Synthesis and Catalytic Ability of Diazaphospholenes

By

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To My Loved Ones

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Abstract

This thesis presents a facile entry into diazaphospholene catalysis, harnessing pre-catalysts formed through the reaction of diazaphospholene-bromide compounds with neopentyl alcohol, to afford crystalline pre-catalysts. Their application in the hydroboration of imines and 1,4-reductions gives novel insight into their reactivity, as these heterocycles had yet to be employed in these catalyzed reactions. Mechanistic insights into the role of the catalyst, as well as potential decomposition pathways were explored.

Next, enantioenriched diazaphospholene pre-catalysts were developed. These chiral pre-catalysts were applied in the asymmetric hydroboration of imines, to afford amines with enantiomeric ratios of up to 88:12. The monoamine oxidase inhibitor drug Rasagiline (employed in the treatment for Parkinson's disease) was synthesized through these methods affording high selectivity and is the first asymmetric synthesis of this drug.

Finally, efforts towards the use of diazaphospheniums as Lewis acids in the splitting of dihydrogen, and hydrogenation of imines are described.

List of Abbreviations and Symbols Used

α	alpha (carbon position)
β	beta (carbon position)
σ^*	sigma-star (anti-bonding orbital)
δ	delta (chemical shift)
>	greater than
<	less than
λ	lambda (wavelength)
Å	angstrom(s)
°C	degrees Celsius
9-BBN	9-borabicyclo[3.3.1]nonane
AB	second order coupling
ap.	apparent
APCI	atmospheric pressure chemical ionization
aq	aqueous
Ar	aryl
BArF$_{24}$	tetrakis(3,5-*bis*trifluoromethylphenyl)borate
BCF	*tris*-pentafluorophenylborane
Binap	2,2'-*bis*(diphenylphosphino)-1,1'-binaphthyl
Binol	1,1'-Bi-2-naphthol
Bn	benzyl
Boc	*tert*-butyloxycarbonyl
br.	broad

c	concentration
CAAC	cyclic alkyl amino carbene
Conv.	conversion
CPME	cyclopentyl methyl ether
Cy	cyclohexyl
d	day (time) or doublet (coupling)
DABCO	1,4-diazabicyclo[2.2.2]octane
DAP	diazaphospholene
DCM	dicholoromethane
Dipp	2,6-diisopropyaniline
DMAP	dimethylaminopyridine
dq	doublet of quartets
dt	doubet of triplets
E	entgegen
e.e.	enantiomeric excess
e.r.	enantiomeric ratio
ESI	electrospray ionization
EtOAc	ethyl acetate
Equiv.	equivalent
EWG	electron withdrawing group
FLP	frustrated Lewis pair
HB(cat)	catechol borane
HB(pin)	pinacol borane

HPLC	high-performance liquid chromatography
HRMS	high-resolution mass spectrometry
J	coupling constant
LA	Lewis acid
LB	Lewis base
LiHMDS	lithium *bis*(*tri*methylsilyl)amide
m	multiplet
MeOH	methanol
Mes	mesityl
MTBE	methyl *tert*-butyl ether
n.a.	not applicable
n.d.	not determined
NHC	*N*-heterocyclic carbene
NHP	*N*-heterocyclic phosphine
NMR	nuclear magnetic resonance (spectroscopy)
NPS R-568	2-chloro-*N*-[(1*R*)-1-(3-methoxyphenyl)ethyl]-benzenepropanamine
OMe	methoxy
p-	*para*
p	pentet
Ph	phenyl
PMB	*para*-methoxybenzyl
PMP	*para*-methoxyphenyl
ppm	parts per million

R	*rectus*
RT	room temperature
S	*sinister*
sext	sextet
t	triplet
td	triplet of doublets
TEA	triethylamine
TFT	trifluorotoluene
THF	tetrahydrofuran
t_{maj}	time of elution of major peak (HPLC)
t_{min}	time of elution of minor peak (HPLC)
TMS	trimethylsilane
Triflyl	trifluoromethylsulfonyl
Ts	*p*-toluenesulfonyl
tt	triplet of triplets
q	quartet
Z	zusammen

Acknowledgements

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To Mallory, thank you for being here for me through my time at Dalhousie. No matter what you were always willing to help me with my work, and keep me motivated to become a better person. Your unfailing support has been crutial to any of my successes and joys. The past six years have been amazing, and I can't wait to spend our lives together, I love you.

Finally, thank you to my parents for their constant support and encouragement throughout my education; I could not have done it without you.

Chapter 1 : Introduction

1.1: Diazaphospholenes

1.1.1: Synthesis of Diazaphospholenes

In the early 1990's *N*-heterocyclic carbenes (NHCs) became important in synthesis, catalysis, and as ligands for metal complexes.[1] NHCs are typically readily accessible and highly modular, which allow for the syntheses of a vast variety of analogues (Scheme 1.1). The idea of an easily modified scaffold is attractive to chemists as it allows for a general set of procedures to synthesize a library of compounds that may have varying steric, electronic, and reactivity profiles.
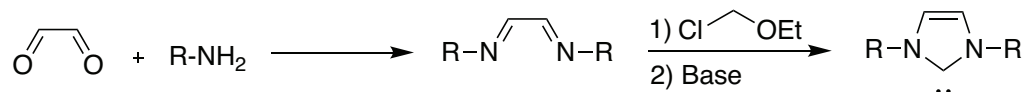
Scheme 1.1: General synthesis of a *N*-heterocyclic carbene

Valence isoelectronic analogues of NHCs have also been of interest to chemists, bringing the use of *N*-heterocyclic phosphines (NHPs), also known as 1,3,2-diazaphospholenes (DAPs), to light. Although examples of NHPs predate NHCs,[2] developments in NHC chemistry have led to more widespread applications in the field of NHPs. Since the isolation of NHCs in the late 1990's, a considerable amount of research has led to their widespread use. This research was then applied to NHPs to further develop their chemistry. The initial challenge when designing NHPs was the incorporation of the phosphorus atom through means of cyclization reactions, an area of much research in the early days of diazaphospholene chemistry.[3,4,5,6] It was found that phosphorus halides provide a good entry point in the synthesis of NHPs, due to the ability

of phosphorus to access a variety of oxidation states, and the high lability of the phosphorus-halide bond.[7] The first reported method of cyclizing a diimine to form a diazaphospholene involves the use of Li metal, PCl_3, and base, as seen in Scheme 1.2.
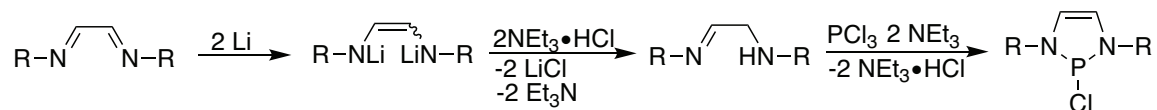
Scheme 1.2: Initial synthesis of a diazaphospholene heterocycle

This method was developed initially by Kibardin and co-workers in 1990,[8] and further developed by Gudat and co-workers.[5] Although this method does give access to diazaphospholene chlorides, over-reduction of the diamine to result in a saturated backbone could occur, as opposed to the desired unsaturated analogue. These methods are harsh and not functional group tolerant; the only variants known are where R= tBu, Mes, or 2,6-^{i}PrC$_6$H$_3$. Since this report, a milder method of forming diazaphospholenes has been reported by Gudat,[5] where a diimine is reacted with PCl_3 and $SnCl_2$ to generate a cationic diazaphosphenium with $SnCl_5^-$ as the counterion, as seen in Scheme 1.3.
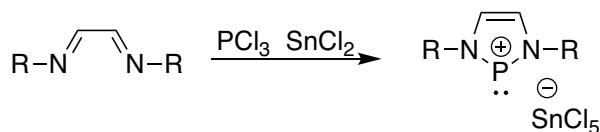
Scheme 1.3: Milder synthesis of diazaphospholenes

Although this route is milder, it generates diazaphospholenes of less synthetic utility, since diazaphosphenium cations are not known to engage in subsequent chemistry. This is not to say that cationic diazaphospholenes may not be useful for chemistry yet to be explored. The Cowley group[3,6] was able to cyclize diimines using PI_3, also generating cationic phosphorus, albeit with an I_3^- anion (Scheme 1.4). This method of cyclization is mild, and encompasses a broader array of diimines, most notably with

bulkier aryl groups, which are of interest for their study in catalysis. These cyclizations are also known to be very clean, usually requiring minimal purification to obtain the desired product. Work recently performed and described in this thesis describes methods to reduce the I_3^- anion after cyclization and access phosphorus iodide bonds, which facilitated the formation of various NHP derivatives.
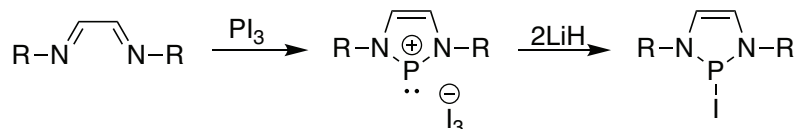
Scheme 1.4: Generation of phosphorus iodide bond

The Macdonald group[4] was the first to report a mild, one-step cyclization reaction using PBr_3 with cyclohexene, as shown in Scheme 1.5.
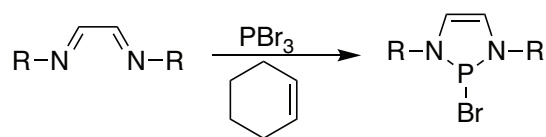
Scheme 1.5: Diazaphospholene synthesis through PBr$_3$ cyclization

This cyclization method directly forms NHPs with desired phosphorus-halide bonds in good yields under mild conditions. This method of cyclization is clean for certain diimines, with a simple work-up procedure involving only trituration and filtration.

The above examples represent modular methods of synthesizing diazaphospholenes, allowing for the synthesis of a variety of scaffolds with differing steric, and electronic profiles.

1.1.2: Reactivity of Diazaphospholenes

Diazaphospholenes were initially studied in their cationic form, but properties observed by the Gudat group,[7] such as unusually long P-Cl bonds in neutral species, were intriguing, because the negative charge density was largely on the Cl, rendering the phosphorus partially cationic as the Cl dissociates. P-H containing diazaphospholenes were synthesized from diazaphospholene-halides with $LiAlH_4$. These displayed hydridic reactivity. Due to donation of electron density from the nitrogen atoms in the C_2N_2 backbone into the σ^* P-H orbital, the P-H bond becomes weak, putting negative charge density onto H, allowing it to behave as a hydride (H^-) as opposed to the usual reactivity of secondary phosphines as weak acids.[2,7,9]

The Gudat group[9] was the first to report the reductive ability of NHP-hydrides. A diazaphospholene-hydride was used to stoichiometrically reduce benzaldehyde, followed by an aqueous work-up to form the corresponding alcohol (Scheme 1.6). This was the first example of diazaphospholenes being used as reagents for organic transformations, displaying hydridic reactivity, with potential applications in synthesis.
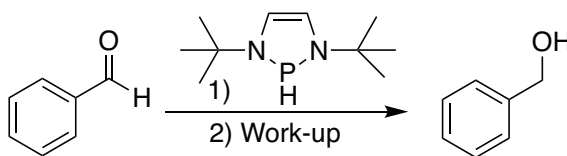
Scheme 1.6: Reduction of benzaldehyde

The Kinjo group[10] subsequently showed that diazaphospholenes could be employed as catalysts. Diazaphospholenes were used for the catalytic hydrosilylation of CO_2, followed by the catalytic *N*-formylation of primary and secondary amines as seen in Scheme 1.7. Utilizing small abundant molecules from large feedstocks, such as CO_2, in synthesis is an important goal for atom economy.
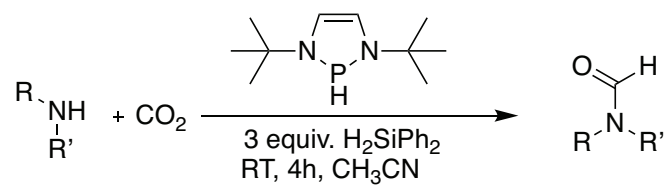
Scheme 1.7: *N*-Formylation of amines using CO_2

The Kinjo group,[11] merged the ideas of reducing carbonyl-containing species with using a terminal reductant to turn over the system, rendering it catalytic. Using aldehydes and ketones as substrates, diazaphospholenes were competent catalysts for reductions using HB(pin) as the terminal reductant. Through a four-membered transition state, a sigma-bond metathesis regenerates the catalyst affording borylated alcohols as products (Scheme 1.8).
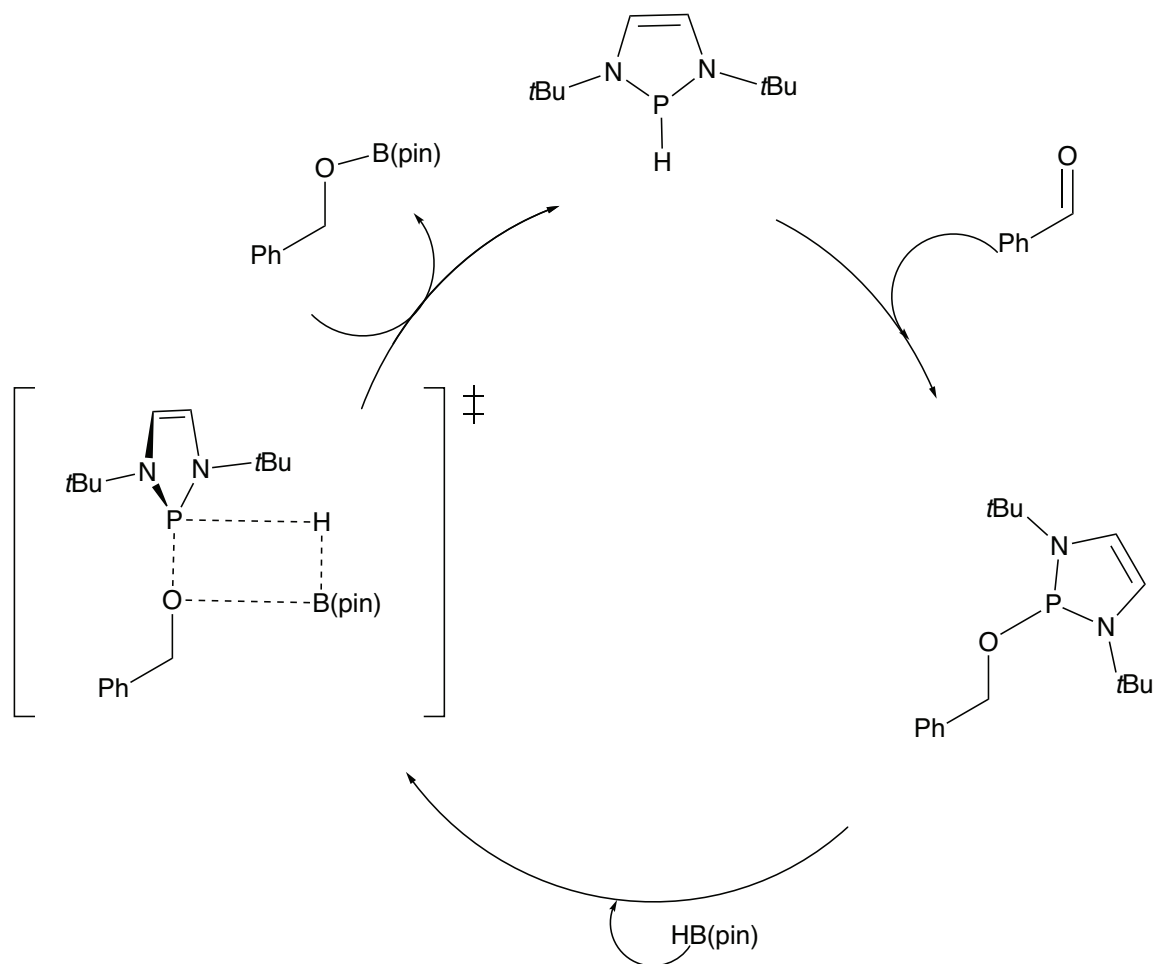
Scheme 1.8: Reduction of benzaldehyde via a diazaphospholene

Two years after Kinjo's first report regarding NHP-catalyzed reactions, the group[12] disclosed yet another diazaphospholene-mediated conjugate reduction of α,β-unsaturated esters to the corresponding borylated enolates (almost immediately after the disclosure of our conjugate reduction studies in *Angewandte Chemie International Edition*). These enolates could then attack nitriles to form new C-C bonds (Scheme 1.9).
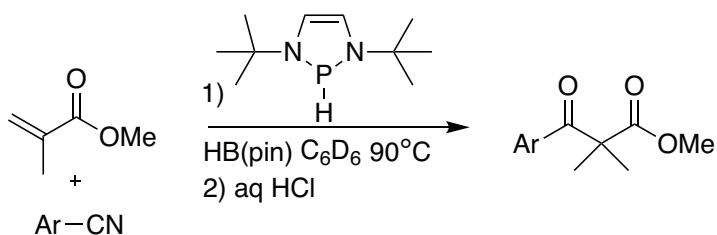
Scheme 1.9: C-C bond formation via diazaphospholenes

The field of diazaphospholene synthesis and catalysis represents a growing subset of main group chemistry. These modular NHPs are made from widely available starting materials in very few steps and with high modularity, making them attractive for the study of catalysis.

1.2: Reductive Catalysis

1.2.1: Frustrated Lewis Pairs (FLPs)

Reductive catalysis, the idea of using a catalyst to break multiple bonds by the addition of a new organic fragment (for example a hydride, a methyl group, etc.), generating products of value, such as pharmaceuticals or fine chemicals, has long been of interest to chemists. In 2006, the Stephan group[13] demonstrated that a Lewis acid, $B(C_6F_5)_3$, and bulky Lewis base, $PHMes_2$, could complex together in an unconventional fashion compared to traditional Lewis adducts, to form what is now known as an FLP (Scheme 1.10).
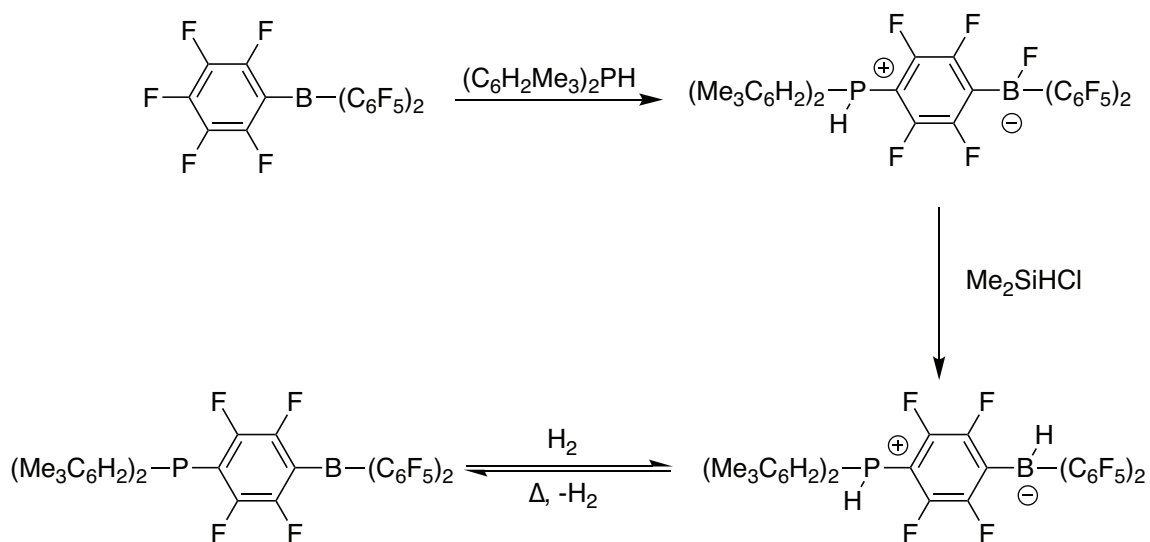
Scheme 1.10: Formation of a FLP

It was shown that the base does not directly complex with the boron center due to steric bulk, but instead nucleophilically attacks the *para*-position of the aromatic ring. After a defluorohydrogenation of the borane reagent with Me_2SiHCl, the product was shown to be able to release as well as split H_2 (Scheme 1.10). Since this seminal example, other FLPs have been developed to activate H_2 and subsequently hydrogenate unsaturated functional groups such as imines (Scheme 1.11).[14] Different FLPs have since been shown to hydrogenate enamines and silyl enol ethers. Also, the activation of other small molecules such as CO_2, SO_2, N_2O, and CO has been reported.[14]

"R–N=C(R)(R') → "R–NH–CH(R)(R')

H–PtBu$_3^{\oplus}$

C_6F_5–B$^{\ominus}$(C$_6F_5$)(C$_6F_5$)H

C_6F_5–B(C$_6F_5$)(C$_6F_5$)   PtBu$_3$

H$_2$
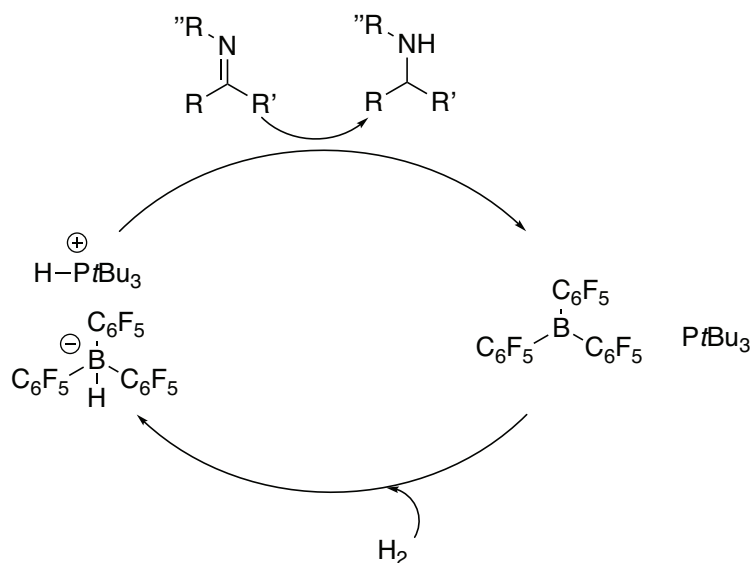
Scheme 1.11: Hydrogenation of an imine by FLPs

The field of reductive catalysis is dominated by transition metals. Since 2006, metal-free reductions and H$_2$ splitting have been an area of rapid development. The idea of utilizing cheaper, less toxic, and more earth abundant elements to perform transformations, especially reductive catalysis, is very attractive. Not only does main group catalysis help reduce the use of transition metals, but research in this area can also uncover new potential reactivity profiles inaccessible by metals. The pioneering work in FLPs has led to the discovery of many other main group-based catalysts for a variety of important chemical transformations.

1.2.2: Phosphorus-Mediated Reductions

The ability of metal compounds to cycle between the n and n+2 oxidation states in oxidative addition and reductive elimination makes metal centers powerful tools for the formation of new covalent bonds. This reversible change in oxidation state has traditionally been viewed as exclusive to transition metals,[15] until Bertrand,[16] Power,[17] Stephan,[18] and Erker[18] demonstrated that p-block elements can also exhibit this reactivity.

The group of Radosevich[19] has made great advances by reporting a catalytic example of a p-block element (in this case phosphorus), alternating between the P^{III} and P^V oxidation states in a transfer hydrogenation reaction (Scheme 1.12). This T-shaped P^{III} heterocycle is converted into a P^V catalyst upon exposure to ammonia borane. The corresponding complex can then undergo transfer hydrogenation of diazenes to regenerate the P^{III} pre-catalyst (Scheme 1.12). This reversibility of oxidation states was previously unknown in main group-catalyzed reductions (phosphine catalysts have been shown to do the III-V cycling in the presence of a silane reductant in catalytic Wittig-type reactions).
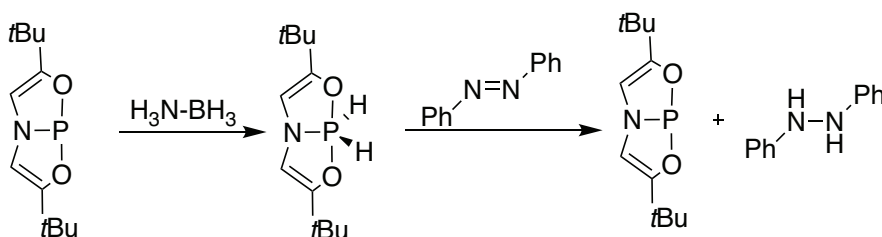
Scheme 1.12: Transfer hydrogenation of azobenzene

This example demonstrates that main group elements may also have access to the key features that allow transition metals to be so powerful in catalysis, showing that there is much room and necessity in developing main group reagents for organic transformations.

The Kawashima group[20] reported an example of an umpolung of water by using a hexacoordinated dihydrophosphate. This umpolung behaviour mediated by a phosphorus based reagent exchanges a proton from water with the reagent, which once attached behaves as a hydride, which as previously mentioned, is rare[9] for the hydrogen of P-H bonds. This air stable phosphorus reagent (Figure 1.1) is able to deliver a hydride to aldehydes and a ketone, affording the corresponding alcohol products, further exploiting the hydridic nature of the P-H bonds via an umpolung of water.
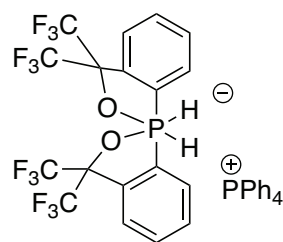
Figure 1.1: Dihydrophosphate reagent

The field of phosphorus-centered catalysis has grown over the past decade with examples of interesting catalytic activity for a range of transformations. These molecules have undergone exquisite reactivity through activation of a number of small molecules such as water, ammonia borane, and HB(pin). There is still much to be done in the field, especially in delivering molecules other than hydrogen atoms, to allow for wider applications in synthesis.

1.3: Chiral Catalysis

1.3.1: Transition Metal Based Catalysis

Chiral metal complexes are very important in the synthesis of optically pure products, due to an array of well-developed ligands affording exquisite enantioselectivity. Many transition metals are used in a variety of C-C and C-H bond-forming reactions to afford enantioenriched chiral molecules. A leading catalyst in the field of chiral hydrogenation is a Ru-based catalyst designed by the Noyori group.[21] The ability of this catalyst to utilize hydrogen gas as a terminal reductant to enantioselectively reduce β-keto esters is of great importance, as these products are of high value. The catalyst shown in Figure 1.2 is able to afford e.e.'s up to >99.9%, which is currently the gold standard in chiral hydrogenation.
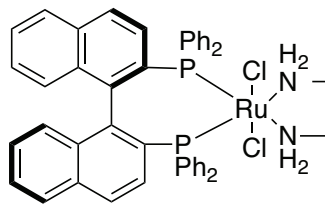
Figure 1.2: Noyori's catalyst

The axially chiral Binap ligand creates a chiral environment, which can selectively engage prochiral substrates in catalysis. The study of ligand design is an important field. Depending on the transformation and metal, the ligand set may vary to accommodate differing steric and electronic profiles. The idea of creating a chiral pocket for the substrate to interact with the catalyst to induce chirality has since been applied to metal-free systems, and is a large field of study. The need to alleviate the use of precious metals is desirable in the process; researchers hope to also observe reactivity that is unique to metal-free systems. To date, metals are still prominent catalysts in these transformations due to their low loadings, high efficiency, and superb selectivity.

1.3.2: Chiral Main Group Catalysis

Main group chemists are interested in further developing metal-free catalysts to access chiral products from prochiral substrates. After the discovery of FLP catalysis, where it was shown that organic molecules could mediate organic transformations, much work has been done on the design of chiral catalysts. The idea behind these transformations is that the burden of high prices and the toxicity of metals can be lessened while continuing to afford products of high value.

The group of List[22] recently developed an axially chiral disulfonimide catalyst for the reduction of imines to amines with high selectivity using Hantzsch esters as a hydrogen source (Scheme 1.13).
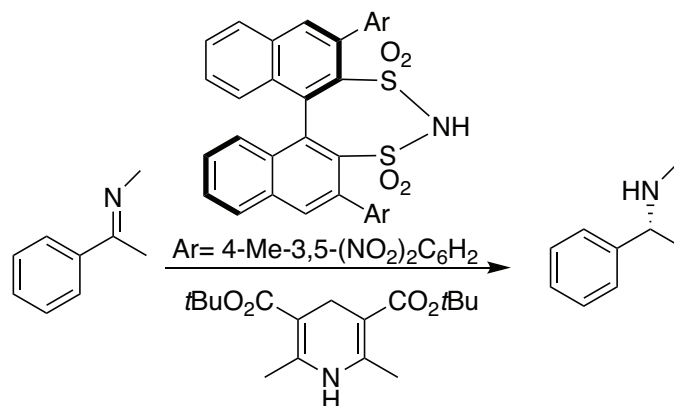
Scheme 1.13: Chiral reduction via a disulfonimide catalyst

This catalyst is able to mediate the reduction of a variety of imine substrates with low catalyst loadings (5 mol %). The utility of this catalyst was highlighted when List demonstrated the synthesis of (S)-Rivastigmine (e.r.= 99.6:0.4) and NPS R-568 hydrochloride (e.r.= 99.7:0.3), which are drugs for Alzheimer's and hyperparathyroidism, respectively. One major shortcoming of this catalyst is that eight steps are required for its synthesis. Nonetheless, the enantioselectivity afforded is superb.

The Enders group[23] explored the idea of Brønsted acid catalysis in chiral transformations by employing an *N*-triflyl phosphoramide, Figure 1.3, which can act as a catalyst in the hydroboration of imines using catecholborane.
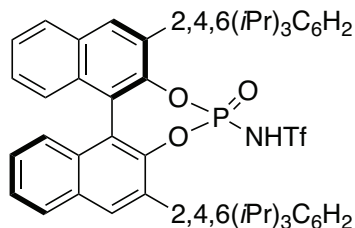
Figure 1.3: Enders' *N*-triflyl phosphoramide

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The Brønsted acid developed by Enders features a Binol-derived backbone that imparts chiral induction. Due to the significant background reaction of catecholborane, these reactions must be conducted at cryogenic temperatures, which is less desirable to pharmaceutical companies for commercial use. This Brønsted acid catalyzed imine reduction is able to impart modest selectivity, with the best example having an e.r. of 86:14. The seminal work on Binol-derived phosphoric acids has paved the way to a large variety of phosphoric acid catalysts, which leads to exquisite induction in the reduction of imines, further expanding chiral main group catalysis. Exa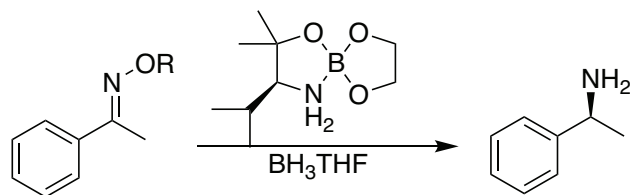mples include Binol-phosphoric acids employed in the reduction of imines with a Hantzch ester, with e.e.'s in the 90's by the group of List.[24]

The group of Ortiz-Marciales[25] designed a chiral spiroborate catalyst from 1,2-amino alcohols and ethylene glycol for the borane reduction of oxime ethers (Scheme 1.14).

Scheme 1.14: Chiral reduction via spiroborate

These catalysts have the potential for a modular synthesis due to the wide availability of 1,2-amino alcohols, where a library of catalysts with different chiral centers can be formed. The reduction products of this method are chiral primary amines, products of high value as pharmaceuticals, chiral auxiliaries, and in catalysis. These spiroborates allow for high enantioinduction, with e.e.'s up to 99% for certain substrates.

The design of differing chiral catalyst scaffolds allows for the synthesis of optically pure organic products that can be further utilized in subsequent chemistry.

In 2016, the Du group[26] made great advances in the field of chiral FLP catalysis. They were able to utilize an adduct between Piers' borane and (R)-*tert*-butylsulfinamide as a catalyst for the asymmetric reduction of imines. Initially they carried out the stoichiometric reduction but sought to render the system catalytic. H_2 gas was not able to regenerate the active catalytic species, unlike in their initially reported FLP system, so the use of ammonia borane as a hydrogen source was explored. Upon using ammonia borane to render the system catalytic, a large breadth of aniline-derived imines was reduced to optically pure amines with e.e.'s of up to 95%. It is proposed that in this catalytic pathway the boron of Piers' borane and the oxygen of the Ellman reagent coordinate. Subsequently, the imine approaches, the boron hydride attacks the imine carbon, and the nitrogen of the imine pulls a proton from the NH_2 of the Ellman reagent (Figure 1.4).
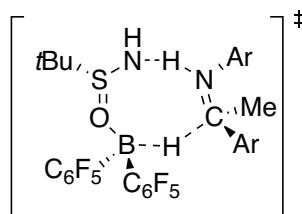
Figure 1.4: Transition state of Piers' borane and Ellman reagent reduction of an imine

A molecule of ammonia borane then regenerates the catalyst. This catalytic system is highly attractive due to the fact that both enantiomers of the Lewis base, namely the sulfonamide, are commercially available, which allows for the control of the absolute configuration in the product. This metal-free system is easy to use, affords great selectivity and yields, and takes few synthetic steps to prepare the catalyst. A downfall to this strategy lies in the difficulty of the synthesis of Piers' borane. Piers' borane is not

commercially available and is difficult to synthesize (C_6F_5Li is explosive, Me_2SnCl_2 is toxic, isolating the product from the starting materials is challenging, and stringent air-free techniques are required). This is not desirable for applications in pharmaceuticals and synthesis. The induction imparted by this system sets high standards for main group chemists working in this field, also, the design of catalytic system should consider how many steps must be taken to prepare the catalyst. It is desirable to have high induction, but also for the catalytic system to be as simple as possible, formed through minimal synthetic steps, which the system by Du accomplishes with the exception of Piers' borane.

1.4: Thesis Chapters

The following chapters in this document are projects I have worked on during my Masters degree. The first project will focus on the synthesis of diazaphospholene pre-catalysts, and their applications in the hydroboration of imines and α,β-unsaturated carbonyls. Mechanistic investigations will be discussed within. As well, the application of a 1,2,4,3 triazaphospholene in the hydroboration of imines will be described.

The second project focuses on the synthesis of the first reported chiral diazaphospholene pre-catalysts, and their applications in chiral imine hydroboration. The synthesis of chiral primary amines, and catalysts optimizations will be discussed.

The third project focuses on phosphorus-based cations and their use as Lewis acids. These cations were applied in the hydrogenation, and hydrosilylation of imines and ketones.

Chapter 2 : Synthesis and Catalytic Ability of Achiral Diazaphospholenes

2.1: Contributions

Dr. Alex Speed is thanked for the preparation of compound **2.42**, and his efforts in the mechanistic study. Chieh Hung Tien is thanked for the synthesis of compound **2.48**. Mass spectrometric data were acquired by Mr. Xiao Feng (Mass Spectrometry Laboratory, Dalhousie University). Dr. Michael Ferguson at the University of Alberta, X-Ray Crystallography Laboratory, performed the acquisition and refinement of structure **2.10**.

2.2: Introduction

Amine functional groups are a common moiety in natural products and drug molecules. The reduction of an imine is a facile route to synthesize amines from readily available starting materials. The hydrogenation of imines using frustrated Lewis pair chemistry[14] has proven to be an important field of research in main group catalysis. Although utilizing H_2 gas has its advantages, the hydroboration of an imine serves as a convenient method for small drug molecule exploratory work in the lab, due to ease of handling HB(pin) compared to high-pressure vessels containing H_2 gas. Coinage metals[27] were used in the seminal reports of the hydroboration of imines, while a later example by Enders[23] demonstrated the use of main group catalysts to facilitate this transformation.

Phosphorus-based reductive catalysts possess the ability to access neutral phosphorus[III] centers, which are low in Lewis acidity, and therefore are not sensitive to Lewis basic reaction components and impurities. The Gudat group[9] was the first to show

that the 2-hydrodiazaphospholene, shown in Figure 2.1, behaves hydridically in stoichiometric reactions.
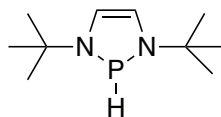
Figure 2.1: 1,3,2-Diazaphospholene

These reactions include the reduction of benzaldehyde and cinnamaldehyde.[9] The ability of electrons in the diazaphospholene backbone to hyperconjugate with the P-H bond reduces the typical acidic nature of this compound, rendering the hydrogen hydridic. With this phosphorus[III] diazaphospholene, the Kinjo group[10] has shown that HB(pin) can regenerate the catalyst from the P-O species resulting from carbonyl reductions, allowing the reduction process to be catalytic. The diazaphospholene catalyst used in these carbonyl reductions was formed from the reaction of a diazaphospholene bromide with LiAlH$_4$. Although this method does form the catalyst, it is harsh and leads to a product that readily decomposes over time (even in a glove box under an inert atmosphere).

During my studies I set out to create a more stable diazaphospholene pre-catalyst, by intercepting the P-O species observed in carbonyl reductions. The idea was to react the diazaphospholene bromide with an alcohol to form a pre-catalyst that can generate the active catalyst when reacted with HB(pin). Upon the generation of these stable pre-catalysts, I sought to investigate their potential in the hydroboration of imines and α,β-unsaturated compounds. These efforts proved to be fruitful, with the design of a stable pre-catalyst and large reduction scope published in *Angewandte Chemie International Edition.*[28]

Since the publication of this chemistry, my coworker Chieh Hung Tien was able to develop a triazaphospholene catalyst (Figure 2.2) for the hydroboration of imines derived from anilines that were challenging for the diazaphospholene system.
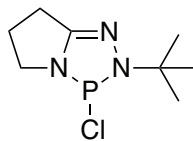

Figure 2.2: Triazaphospholene catalyst

Due to the difficulty of synthesizing non C_2-symmetric diimines for diazaphospholenes, triazaphospholenes became of interest. Since diazaphospholenes are similar to *N*-heterocyclic carbenes, we thought to extend the notion that triazaphospholenes would be similar to triazolium carbenes. These have never been explored before in catalysis.[29] The modularity of these catalysts proved useful in the reduction of challenging substrates, I was able to assist in the screening of substrates, leading to a publication in *Organic Letters*.[30]

2.3: Results and Discussions

2.3.1: Synthesis of Diazaphospholene Pre-catalysts

Based on the initial studies by Gudat and Kinjo on diazaphospholenes, our goal of synthesizing a more convenient pre-catalyst for hydride-delivering reactions began with the synthesis of a variety of diimine backbones. These diimines are typically formed by mixing glyoxal and a primary amine in DCM with Na_2SO_4 and a catalytic amount of formic acid (Scheme 2.1).

R= **2.1**) *t*Bu, **2.2**) Mes, **2.3**) Cy, **2.4**) 3,5-OMe-C_6H_3
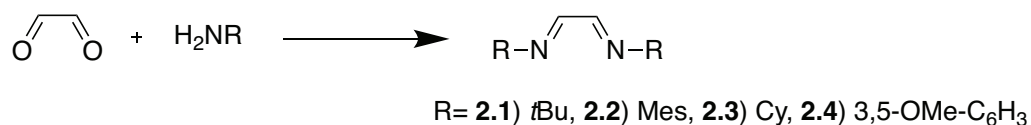
**Scheme 2.1: Syntheses of diimines**

Diimines **2.1-2.3** were all synthesized by the above method, although when trying to form more electron-donating substrates from 2,3-butanedione instead of glyoxal, the corresponding products were not observed (due to the reduced electrophilic nature of this compound). As well, when trying to form a diimine from 3,5-dimethoxyaniline **2.4**, no product formation was observed, which is consistent with the results of Macdonald.[4] With a library of diimines in hand, the next step in the syntheses involved cyclization with phosphorus[III] halides to form the P[III] halogen DAPs. A variety of cyclization methods for diazaphospholenes are known, but based on ease of reaction and products produced, a cyclization with PBr_3, and cyclohexene, developed by Macdonald was employed (Scheme 2.2).

R= **2.5**) *t*Bu, **2.6**) Mes, **2.7**) Cy
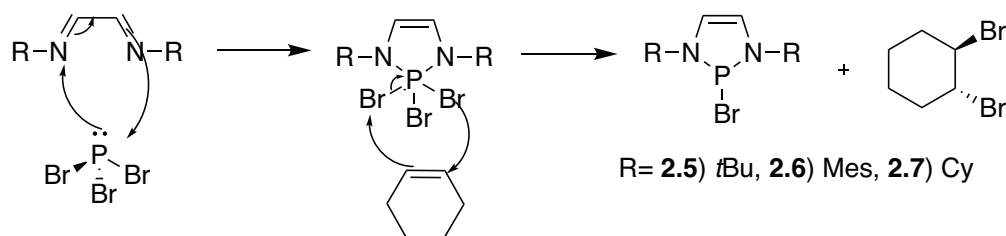
**Scheme 2.2: Macdonald cyclization of diimines**

This method was applicable to several diimines to afford clean cyclized products upon filtration, and trituration with ether in the glovebox. The formation of these products was easily monitored by ^{31}P NMR spectroscopy with the appearance of singlets at δ 186.6, 174.6, and 191.6 ppm for compounds **2.5**, **2.6**, and **2.7**, respectively.

With these diazaphospholene-bromides in hand, the synthesis of novel pre-catalysts was next pursued. The use of benzyl alcohol and triethylamine was employed to afford P-O bonds and intercept the P-O intermediate in the catalytic cycle proposed by Kinjo. This method was successful in forming the benzyloxy-diazaphospholenes **2.8** and **2.9** (Figure 2.3). Compound **2.9** was obtained as a thick oil, and compound **2.8** was a sticky oil that was difficult to handle and purify. Due to crystallization being the main method of NHP purification, formation of pre-catalysts with benzyl alcohol was not further pursued.
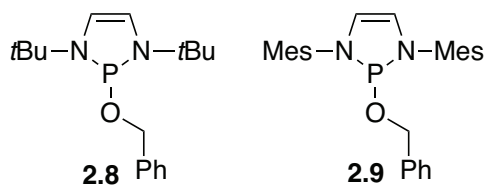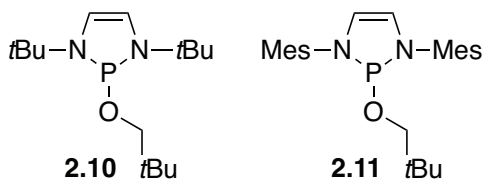

Figure 2.3: Benzyloxy diazaphospholene pre-catalysts

Subsequently, pre-catalysts **2.10** and **2.11** derived from neopentyl alcohol were synthesized from the reaction of diazaphospholene bromide with neopentyl alcohol and triethylamine. To our delight a crystal structure of 1,3-di-*tert*-butyl-2-neopentyloxy-1,3,2-diazaphospholene, **2.10**, was obtained (Figure 2.4).
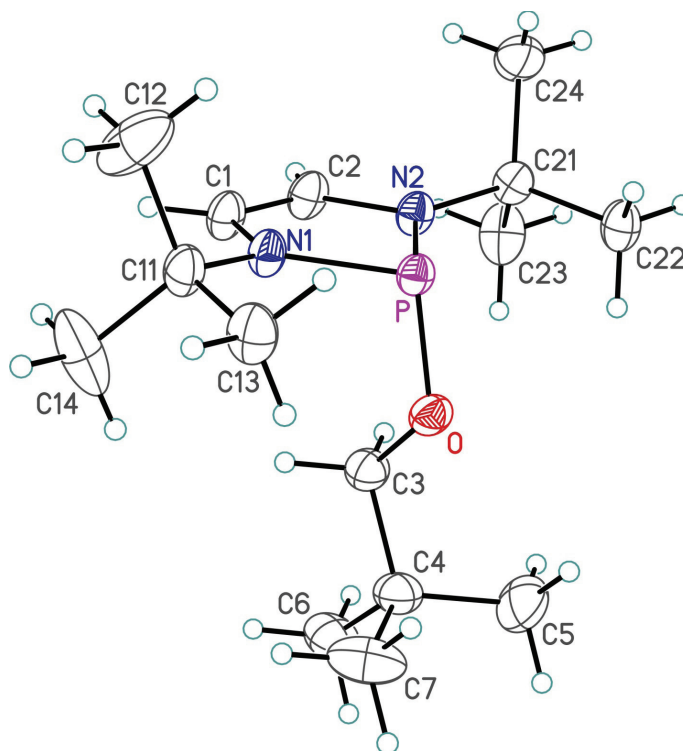
Figure 2.4: Crystal structure of 1,3-di-*tert*-butyl-2-neopentyloxy-1,3,2-diazaphospholene

As can be seen in the crystal structure of **2.10** (data acquired and structure solved and refined by Dr. Ferguson, University of Alberta), the ring of the diazaphospholene is puckered. The ring is puckered due to the P-N^1-C^1-C^2 torsion angle being 6.33°, as opposed to 0° for a planar heterocycle. When the diazaphospholenes are in their cationic form they become planar, and therefore aromatic. Crystalline diazaphospholene pre-catalysts **2.10** and **2.11** were made with *t*butyl and mesityl backbones, seen in Figure 2.5, with characteristic ^{31}P NMR signals as singlets at δ 92.3, and 114.7 ppm, respectively.


Figure 2.5: Diazaphospholene pre-catalysts

We were also interested in investigating the synthesis and properties of scaffolds with saturated backbones, derived from diamines. To begin with, diimines were reduced in methanol with NaBH$_4$, to give diamines **2.12** and **2.13** (Scheme 2.3).

R−N=CH−CH=N−R $\xrightarrow[\text{MeOH}]{\text{NaBH}_4}$ R−NH HN−R

R= **2.12**) *t*Bu, **2.13**) Mes
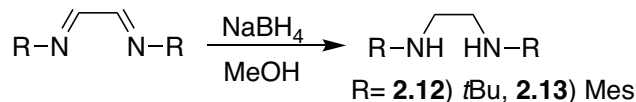
Scheme 2.3: Synthesis of diamines

These diamines were cyclized using PBr$_3$ and triethylamine to afford the corresponding diazaphospholes **2.14** and **2.15** (Figure 2.6).

*t*Bu−N P(Br) N−*t*Bu   Mes−N P(Br) N−Mes

2.14   **2.15**
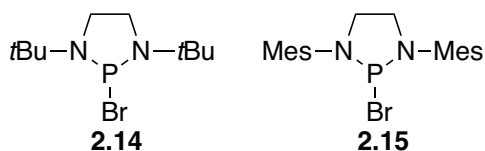
**Figure 2.6: Diazaphosphole bromides**

Triethylamine and neopentyl alcohol were reacted with **2.14** and **2.15** generating **2.16** and **2.17** with ^{31}P NMR signals as singlets at δ 109.9 and 121.5 ppm, respectively (Figure 11).

*t*Bu−N P(O−*t*Bu) N−*t*Bu   Mes−N P(O−*t*Bu) N−Mes

2.16 *t*Bu   **2.17** *t*Bu
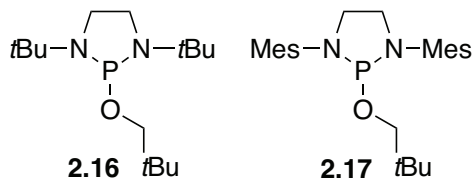
Figure 2.7: Diazaphospholidine pre-catalysts

With these potential pre-catalysts synthesized, the next step in the project was to see if they could be turned into the active P-H catalysts by the use of a terminal reductant. Accordingly, HB(pin), HB(cat), 9-BBN, borane morpholine, and diphenyl silane were investigated. The clean pre-catalysts were mixed 1:1 with the source of hydride in CD$_3$CN, and subsequent NMR studies were performed. When HB(pin) was used, the formation of P-H bonds were observed, evidenced by the formation of a doublet in the

^{31}P NMR spectra with shifts of δ 58.4 ppm for 1,3-di-*tert*-butyl-2-*H*-1,3,2-diazaphospholene **2.18** and δ 64.6 ppm for 1,3-dimesityl-2-*H*-1,3,2-diazaphospholene **2.19** (Figure 2.8).
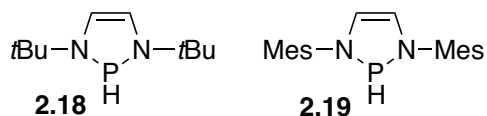

Figure 2.8: Diazaphospholene hydrides

Upon addition of HB(pin) to the compounds with saturated backbones, no conversion to the P-H compound was observed, indicating that they would not be viable in catalytic reactions (for hydride delivery). The lack of catalyst formation may be due to the fact that when the backbone is unsaturated, cationic intermediates formed in this reaction would be aromatic NHP cations, where as removing the double bond in the backbone renders the intermediates non-aromatic, and less stabilized. The formation of the P-H bond was observed more readily for the 1,3-di-*tert*-butyl-2-neopentoxy-1,3,2-diazaphospholene,[28] **2.10**, suggesting it could be more active in catalytic reductions, which was also proposed by the Gudat group while assessing these scaffolds as reductants. The increased electron donating ability of the *t*Bu group compared to Mes may be responsible for the enhanced reactivity of these diazaphospholenes. The increased electron density on phosphorus may render the hydrogen on the phosphorus atom more hydridic.

2.3.2: Imine Hydroborations *via* Diazaphospholenes

The idea of using imines as precursors to amines has long been of interest to chemists. The hydroboration of an imine is a potentially facile method of generating molecules of value in catalyst design and pharmaceuticals. After the Kinjo group

demonstrated that diazaphospholene hydrides were competent reducing agents for carbonyl species, we sought to apply the pre-catalysts developed above to the hydroboration of imines. Based on our initial studies, it was concluded that the 1,3-di-*tert*-butyl-2-neopentoxy-1,3,2-diazaphospholene **2.10** was the most active pre-catalyst developed, and therefore should be used in the hydroboration of imines with HB(pin). Upon the synthesis of several aldimines and ketimines with differing functional groups, I began investigating the potential for the hydroboration of imines with diazaphospholene pre-catalysts and HB(pin). The first substrate assessed was the imine derived from benzylamine and acetophenone, due to its ease of synthesis and wide use in other hydroboration studies. The reduction of this imine to amine **2.20** was accomplished overnight with a 10 mol % loading of catalyst **2.10** at room temperature. This was the first example of an imine hydroboration mediated by a diazaphospholene. Upon this discovery, conditions were optimized (Table 1) before a more exhaustive suite of substrates was assessed.
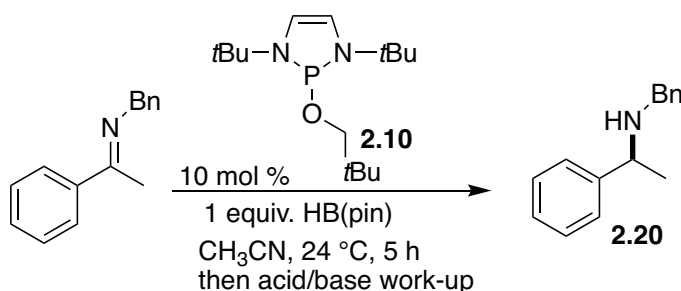
Table 2.1: Optimization of imine hydroboration

Entry	Deviation from standard conditions	Conversion[a] (%)	Yield[b] (%)
1	None	>98	95
2	No catalyst	<2	n.a.
3	Catalyst + HB(pin) aged 24 h before imine	36	n.d.
4	HB(cat) instead of HB(pin)	67	n.d.

5	2 mol % loading of catalyst (12 h)	>98	95
6	1 mol % loading of catalyst (12 h)	66	n.d.
7	2 mol % loading of catalyst (12 h, gram scale)	>98	97
8	**2.11** instead of **2.10**	25	n.d.

[a]Conversion determined by integrating the product versus starting material in ^{1}H NMR.
[b]Yield refers to amount of product isolated following an aqueous work-up and column chromatography.

No background reaction was observed between the substrate and HB(pin) (entry 2, Table 1). Pre-catalyst loading of as low as 2 mol % could be achieved while still observing complete conversion of the imine under the given conditions (entry 5, Table 1). Further decrease of the loading to 1 mol %, resulted in the lowering of the conversion to 66% (entry 6, Table 1). By using **2.11** instead of **2.10** the conversion was substantially reduced, confirming the utility of the *t*Bu diazaphospholene. The above system is also applicable to larger scale reactions, tested on a gram scale, entry 7 (Table 1). In conclusion, the optimized condition was determined to be one presented in entry 5 (Table 1).

I further expanded the scope of imine reductions using the optimized conditions above, as seen in Figure 2.9.
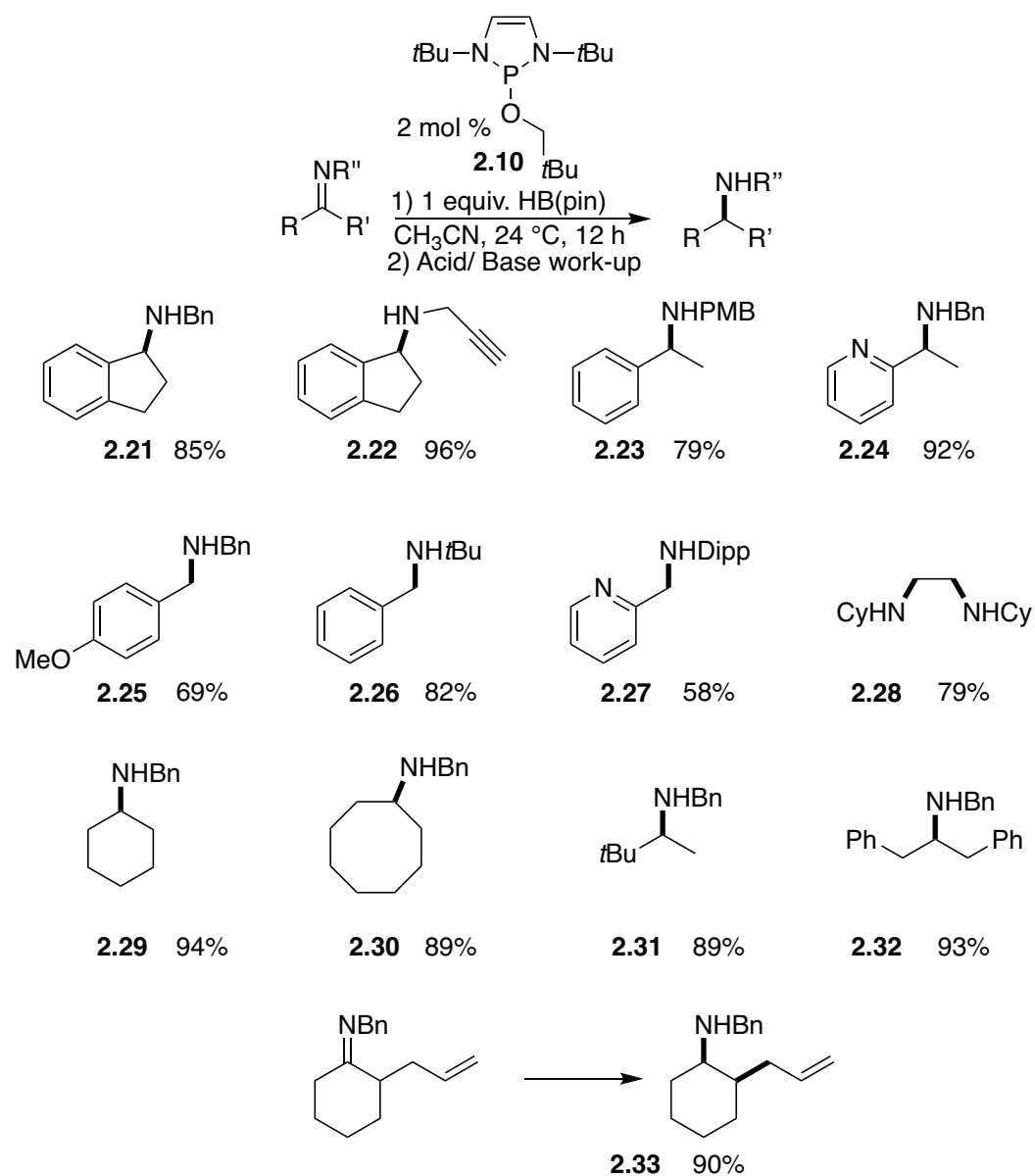
Figure 2.9: Amines successfully formed through imine reductions, with their isolated yields

After the reduction of an acetophenone-derived imine, we sought to explore more sterically hindered substrates, such as those derived from indanone. When condensed with benzylamine or propargyl amine, the corresponding imines were easily reduced in high yields to amines **2.21** and **2.22** (Figure 2.10). The amine **2.22** is the monoamine oxidase inhibitor Rasagiline, used in the treatment of Parkinson's disease, which was

produced cleanly in high yield. The alkyne group was not hydroborated, as this reduction was selective for the imine, obviating a common selectivity issue seen in metal catalysis for these types of substrates.[31] The reduction of an imine with a *p*-methoxybenzyl protecting group was also tolerated, allowing for the hydroboration of the imine affording **2.23**, subsequent removal of the protecting group is possible to afford primary amines if so desired. Pyridyl derived substrates are also tolerated with this strategy, with selective hydroboration of the imine leaving the pyridine intact, forming products **2.24** and **2.27**. This class of substrates is known to be challenging, with the coordination of the basic nitrogen to metal centers, or catalyst poisioning being a common problem in catalysis. Aldimines with different steric profiles all produced amine products, **2.25**, **2.26**, and **2.27**. The reduction of a diimine was performed to afford diamine **2.28**, a monoreduction was attempted but proved to be unsuccessful. Imines derived from cyclic aliphatic ketones were hydroborated to afford amines **2.29** and **2.30**. An imine from a racemic chiral cyclic starting material was formed; the hydroboration of this particular substrate was successful as well, with high diastereoselectivity affording product **3.33** as one detectable diastereomer.

Other substrates were amenable to hydroboration but required longer reduction times, as well as higher catalyst loadings and suffered from poor conversion and yields. For these reasons, they were not pursued further. These substrates can be seen in Figure 2.10.
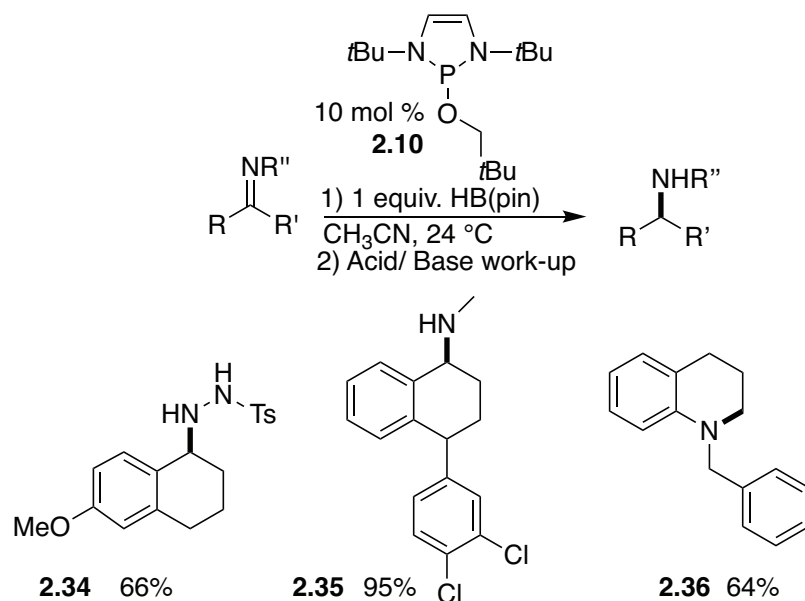
Figure 2.10: More challenging substrates for hydroboration with their isolated yields

The hydrazone substrate was hydroborated to afford amine **2.34**. This reaction required high loadings and 24 h reaction times. Furthermore, the crude product was more difficult to isolate than substrates from Figure 2.13. The hydroboration product **2.35** was obtained in high yields, and is the drug sertraline (Zoloft), which is used in the treatment of depression. This reaction suffered from poor diastereoselectivity, providing a 1.5:1 mixture of diastereomers. An iminium ion was also able to be reduced to afford **2.36**, demonstrating the tolerance of the diazaphospholene catalyst. Some substrates were not reduced by the diazaphospholene catalyst; examples of this can be seen in Figure 2.11.
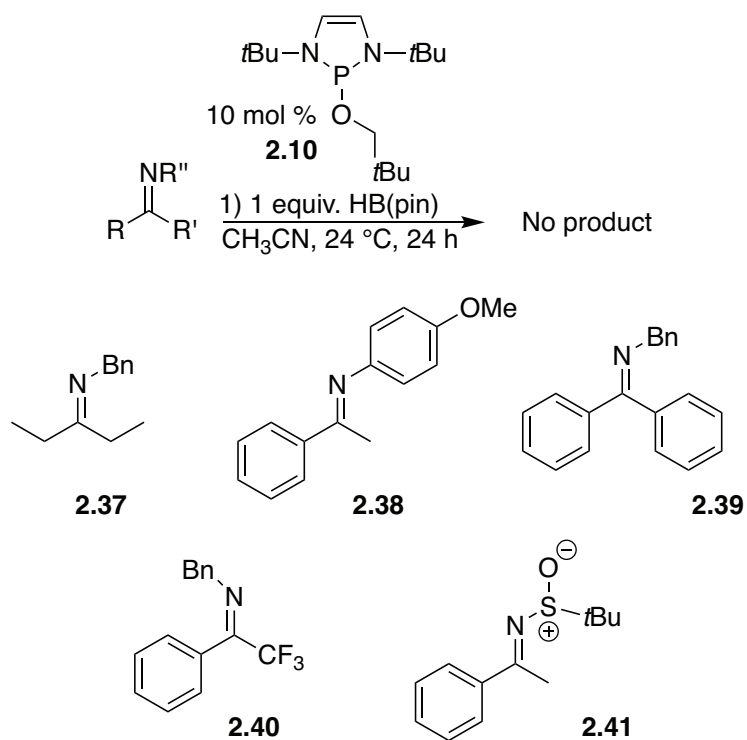
Figure 2.11: Failed hydroboration attempts

It is proposed that when the imine is sterically encumbered, such as **2.39**, the approach of the catalyst is hindered. When the imine possesses electron withdrawing functional groups, such as in **2.40,** and **2.41**, it is proposed that the regeneration of the P-H bond from the P-N intermediates is slow, based on computational studies, which determined that electron poor diazaphospholenes possess less polarized exocyclic bonds.[32] Aniline derived substrates such as **2.38** are not able to be reduced by this catalyst. This pre-catalyst has a wide range of applicability in imine hydroboation reactions, but has more difficulty with substrates that are sterically encumbered around the C=N bond, or those with electron withdrawing groups (Figure 2.11).

2.3.3: Mechanistic Investigation

After the use of **2.10** in the first reported case of diazaphospholene-mediated imine hydroboration reactions, studies into the mechanism of this transformation were undertaken (Scheme 2.4).
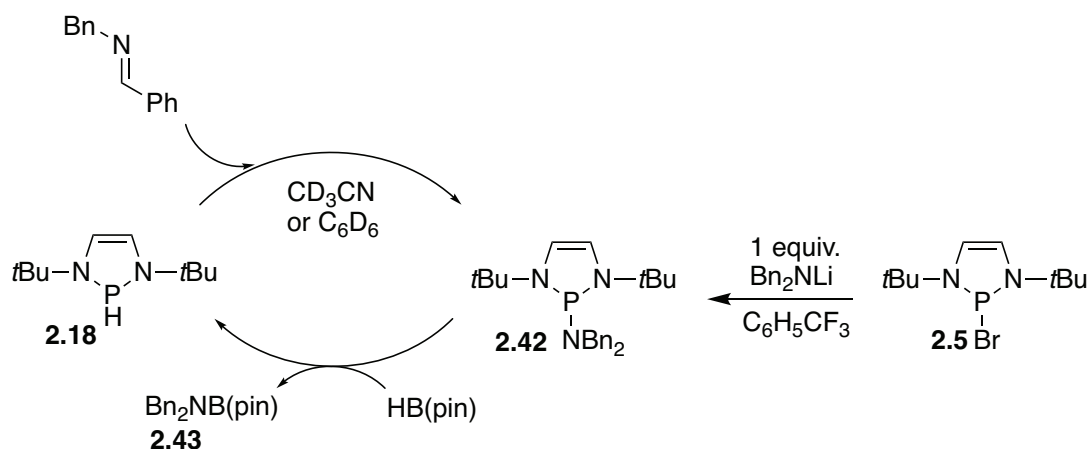
Scheme 2.4: Mechanistic investigation

A sample of **2.18** was exposed to the aldimine made from benzaldehyde and benzylamine. Conversion to compound **2.42** was observed by ^{31}P and ^{1}H NMR spectroscopy. To this, HB(pin) was added to afford the borylated amine product **2.43**, while regenerating active catalyst **2.18**. An authentic sample of **2.42** was generated from **2.5** by mixing it with LiNBn$_2$ (performed by Dr. Alex Speed). Samples of **2.42** prepared from **2.5** or generated *in situ* by the addition of the imine to **2.18** showed identical chemical shifts in the NMR spectra, suggesting it is an intermediate in the catalytic cycle. The mechanistic study backs up the proposal that a P-N bond is generated from the reduction of an imine with P-H **2.18**. Upon addition of HB(pin), the borylated amine is produced, and the P-H bond is reformed. This proposed mechanism is analogous to that proposed by Kinjo,[11] for the hydroboration of carbonyl-containing species. During the study it was also noted that upon the addition of excess HB(pin) compound **2.18**

decomposes to PH$_3$, observed as a quartet at δ -243.6 ppm in the ^{31}P NMR spectrum. As well, when exposed to air, the diazaphospholene decomposes to the P^V oxide, which appears at δ 0 ppm as a doublet of triplets in the ^{31}P NMR spectrum.

2.3.4: Hydroboration of α,β-Unsaturated Substrates

The Gudat group demonstrated that **2.18** could effect a stoichiometric reduction of cinnamaldehyde in a 1,4-fashion, so we next examined conjugate reductions. Conjugate, or 1,4-reductions, provide a selective route for reducing olefins while leaving carbonyl groups intact. This can be challenging, as many catalysts will reduce both the double bond and carbonyl. Upon the reduction of cinnamaldehyde with **2.10** and HB(pin) a complex mixture was obtained. It is postulated that the borylated enolate product of the reduction could react with the reactive cinnamaldehyde starting material. Upon the use of less reactive starting materials, 1,4-reduction products using **2.10** were afforded (Figure 2.12).
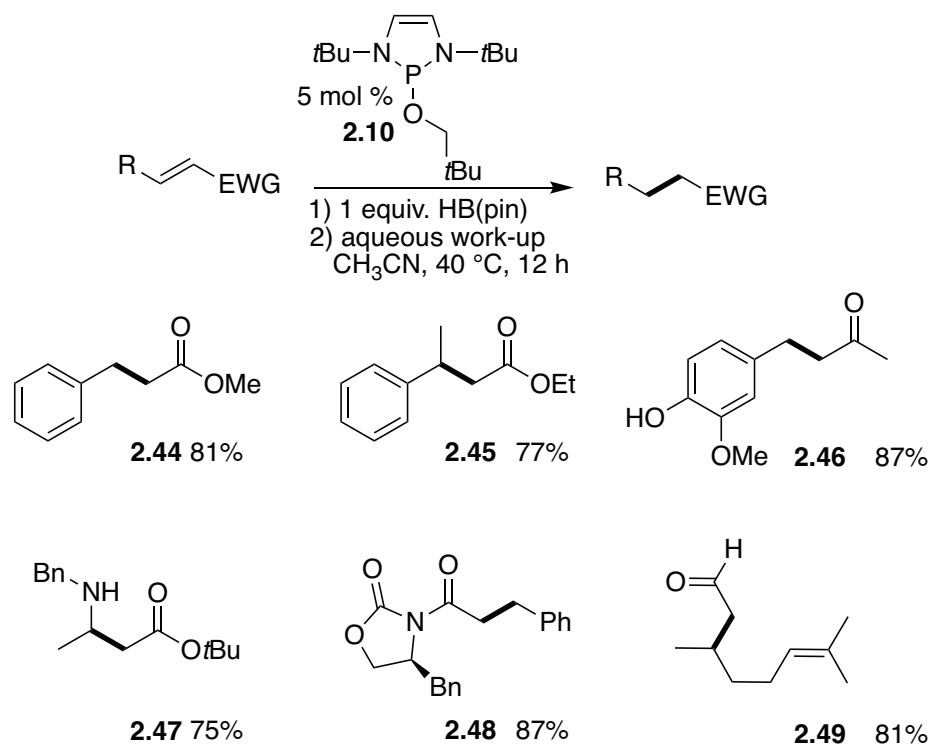
Figure 2.12: Substrate scope of the conjugate reduction. Percentages indicate isolated yields after chromatography

Product **2.46** was obtained in high yield; this is the natural product zingerone, which comes from ginger root, first isolated in Japan.[33] A variety of substrates, namely a ketone, an aldehyde, an amide, and esters could be reduced in a 1,4-fashion, with no reduction of the carbonyl functional group (1,2-reduction). Basic functionality shown in **2.47** is tolerated in the reduction, as no catalyst inhibition was observed. Substrate **2.48**, dihydrocinnamoyloxazolidione, was prepared in high yield. This substrate can be useful as it could undergo a further directed aldol reaction due to the attached Evans auxiliary. The natural product citronellal, **2.49**, could be synthesized through these methods with no hydroboration of the isolated olefin. The substrate screening of conjugate reductions was done in part with my lab mate Chieh Hung Tien.

Not all conjugate acceptors could be reduced successfully. Figure 2.13 shows the conjugate acceptors that were reduced in very low yields, or not at all. It should be noted

that some products were unable to be separated by column chromatography from the corresponding starting materials.
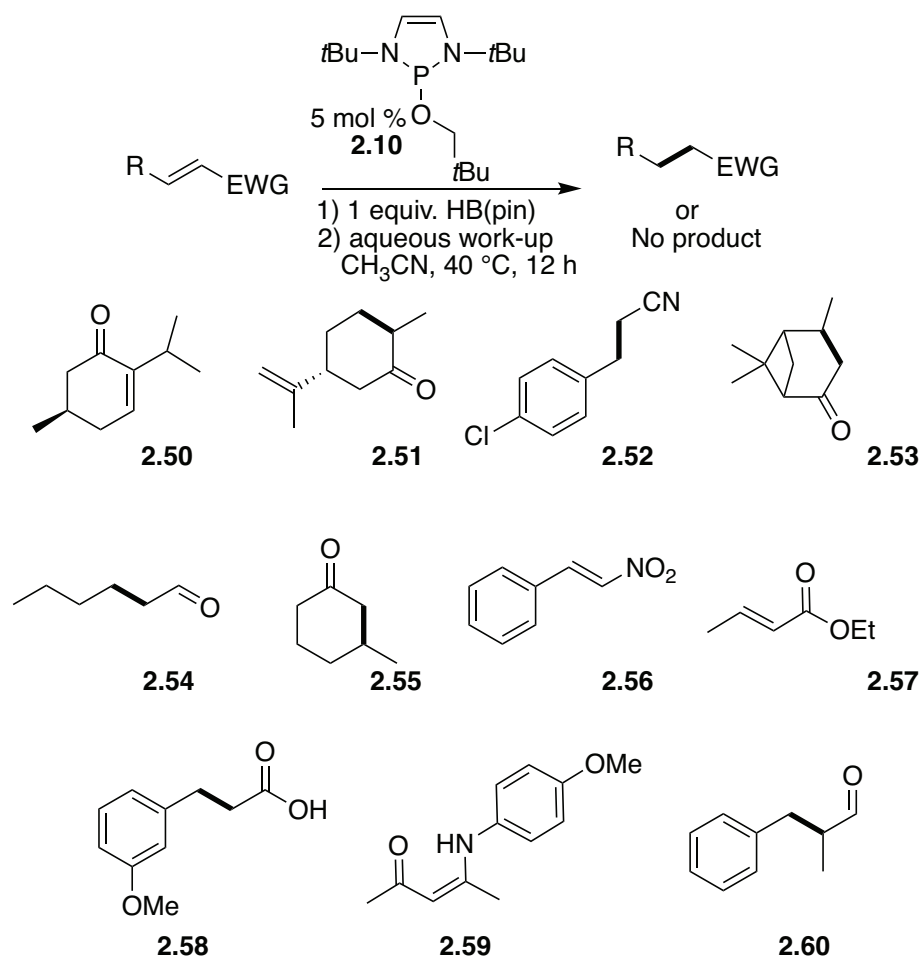
Figure 2.13: Unsuccessful conjugate reductions. Products were inseparable or had low conversion, those drawn as substrates were not reduced

Linear and cyclic aliphatic groups shown in examples **2.50**, **2.51**, **2.53**, **2.54**, **2.55**, and **2.57** were not good substrates for the 1,4-reductions with pre-catalyst **2.10**. These substrates reduced to low conversions, and were inseparable from their starting materials, except for **2.57**, which showed no sign of conversion. The basic substrate **2.47** could be reduced, but more steric bulk such as **2.59** hinders the reduction completely, showing that steric hindrance around the region of the double bond should be considered. Carboxylic acids were unable to undergo 1,4-reduction, as was the case in example **2.58**. Compounds

2.52, and **2.56** bear electron-withdrawing cyano and nitro groups, which were unreactive substrates. These compounds are highly polarized, directing addition of the hydride in an unproductive fashion.

As can be seen, a wide variety of electron-withdrawing groups were tolerated by this method of reduction, allowing for the facile reduction of the double bond, and no reduction of the carbonyl component, affording a very regioselective method of reductions under mild conditions affording products in high yields.

2.3.5: Imine Hydroboration *via* Triazaphospholenes

Since the publication of a stable diazaphospholene pre-catalyst,[28] used in the reduction of imines and conjugate acceptors, the development of more modular scaffolding was desired. The idea is that a third nitrogen in the backbone allows for another basic site, which could help modulate the hydricity of these catalysts. My lab-mate Chieh Hung Tien was able to develop a novel set of triazaphospholene catalysts, with the catalyst shown in Scheme 2.5, for the hydroboration of imines, most notably, some imine substrates that were inaccessible to the diazaphospholene system.
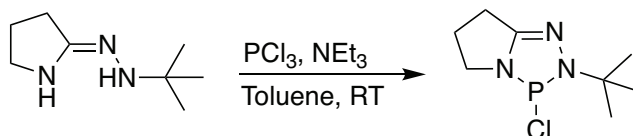
Scheme 2.5: Synthesis of triazaphospholene bromide

My lab mate discovered that the triazaphospholene-halides were viable Lewis acidic catalysts when reacted with HB(pin) and imines. My role in this project was to assist in a comprehensive substrate screening for the hydroboration of imines. The substrates I reduced are shown in Figure 2.14.
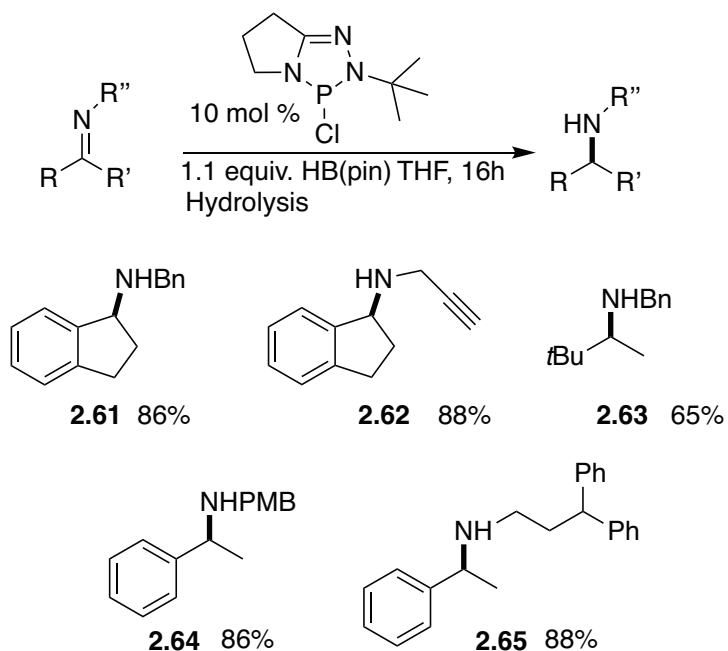
Figure 2.14: Hydroboration of imines mediated by triazaphospholene-chloride, isolated yields reported as percentages

The rest of the scope and more reactivity can be seen in our paper.[30] It should be noted that this catalyst could reduce aniline-derived imines, substrates that proved challenging for the diazaphospholene system.

2.4: Conclusions and Future work

In conclusion, the development of the first reported 1,3,2-diazaphospholene pre-catalyst was synthesized in good yield. An assessment of the optimal pre-catalyst for imine hydroborations was done, and it was found that unsaturation in the backbone of the pre-catalyst is necessary for reactivity.

The first reported example of imine hydroboration mediated by a 1,3-di-*tert*-butyl-2-neopentyloxy-1,3,2-diazaphospholene pre-catalyst was shown. Medically active drugs such as Rasagiline and Sertraline were explored. Reduction using this method is tolerant to ketone impurities, basic functional groups, propargyl groups, and pyridine

substrates. Mechanistic studies were performed, highlighting that from the pre-catalyst a P-H bond is formed upon the addition of HB(pin) and is also reformed after reductive chemistry in the catalytic cycle.

The first catalytic 1,4-conjugate reductions mediated by a 1,3-di-*tert*-butyl-2-neopentyloxy-1,3,2-diazaphospholene pre-catalyst were discovered. These reductions functioned on a variety of electron-withdrawing groups such as ketones, aldehydes, and esters. The synthesis of the natural products Zingerone and Citronellal was performed in high yield. This method proved to be highly regioselective for alkene as opposed to carbonyl reductions.

The development of stable diazaphospholene pre-catalysts and their applications in hydroborations was published in *Angewandte Chemie International Edition*[28] in 2017. This paper has been highlighted by *Organic Process Research and Development*,[34] and *Synfacts*, for its applicability to industrial and pharmaceutical processes.

Future applications of diazaphospholene pre-catalysts would include utilizing allyl-B(pin) in forming new C-C bonds via metal-free methods. Based on the finding that triazaphospholene-halogens act as Lewis acids, it would be feasible to assess diaza- and triaza-phospholenes as Lewis acids for the Diels-Alder reaction of substrates that do not spontaneously undergo [4+2] cyclization.

2.5: Experimental Section

2.5.1: General Considerations

Synthesis of diazaphospholene derivatives was carried out in a fume hood using oven dried Schlenk glassware under nitrogen. Filtration and crystallization of

diazaphospholene derivatives was conducted in a 2001 issue IT Glovebox (O_2 levels typically 4 ppm, H_2O levels typically 5 ppm). Reduction reactions were carried out in 4-dram oven dried scintillation vials equipped with magnetic stir bars and green Qorpak[®] PTFE lined caps. Substrates, reagents and solvents were loaded into vials inside the IT Glovebox. Reactions at ambient temperature were stirred within the glovebox, while reactions that were heated were removed from the glovebox and heated in an oil bath behind a blast shield (precautionary, no rupture was ever observed). ^{1}H, ^{13}C, and ^{31}P NMR data were collected at 300K on Bruker AV-500 or AV-300 NMR spectrometers. Standard NMR tubes and caps were used. Caps on sensitive samples were overwrapped with PTFE tape. Chemical shifts are reported in parts per million from phosphoric acid (for ^{31}P NMR). ^{1}H NMR spectra are referenced to residual non-deuterated NMR solvent ($CHCl_3$ = 7.26 ppm). ^{13}C NMR spectra are referenced to the central $CDCl_3$ peak (77.0 ppm). Melting points were acquired using an Electrothermal[®] apparatus and are uncorrected.

Reagents:

3 Å Molecular Sieves were purchased from Aldrich, and dried at 200 °C at 0.5 torr for 36 hours prior to use. Catecholborane was purchased from Aldrich, stored at -35 °C and used as received. Celite[®] was purchased from Aldrich and dried in an oven at 180 °C for seven days. All other reagents were used as received without any further purification.

Solvent:

Acetonitrile was purchased from VWR in a 1L EMD Drisolv[®] bottle. This bottle was taken into the glovebox, and activated 3 Å molecular sieves were added to the bottle.

Toluene and pentane were deoxygenated and dried by sparging with dinitrogen gas, followed by passage through a double-column solvent purification system purchased from mBraun Inc. The solvents were stored over activated 3 Å molecular sieves in the glovebox. Diethyl ether was purchased from Fisher and was distilled from a purple solution of benzophenone/sodium ketyl, and stored over activated 3 Å molecular sieves in the glovebox. Dichloromethane (ACS grade) was purchased from Fisher and distilled from calcium hydride immediately before use. Deuterochloroform (Cambridge Isotopes) was stored over activated 3 Å molecular sieves, but otherwise used as received.

Imines:

Imines were prepared by a 1:1 combination of the appropriate ketone/aldehyde and amine in dichloromethane, in the presence of 1 equivalent of titanium ethoxide for 96 hours. The reactions were quenched by addition of aqueous KOH (15 %), filtered over Celite onto Na_2SO_4, refiltered and concentrated. Purification of solid imines was accomplished by taking up the obtained solids in warm pentane, and cooling the resulting clear pentane solutions of the imine to -15 °C. The resulting crystals were collected in air by suction filtration and were dried for 12 hours in a vacuum desiccator at approximately 30 torr over P_2O_5 before being brought into the glovebox. Liquid imines were isolated by distillation. Yields of imines were typically > 60% by this method.

Crystallographic Solution and Refinement Details:

Crystallographic data for **2.10** was obtained at -80 °C on a Bruker PLATFORM/Apex II CCD diffractometer using graphite-monochromated Mo Kα (λ=0.71073 Å) radiation, employing a sample that was mounted in inert oil and transferred to a cold gas stream on the diffractometer. Programs for diffractomer

operation, data collection, data reduction and absorption correction were supplied by Bruker. Gaussian integration (face-indexed) was employed as the absorption correction method for **2.10**. The structure of **2.10** was solved by use of intrinsic phasing methods, and was refined by use of full-matrix least-squares procedures (on F^2) with a R_1 of (0.0397) based on $F_o^2 \geq 2\sigma(F_o^2)$.

General Procedure for Imine Reduction

Inside the glovebox, the imine to be reduced was dissolved in CH_3CN in a 4-dram vial (0.1 to 1 M, dependent on scale). HB(pin) was added as a liquid, and the catalyst was added, either as a solid, or a stock solution in CH_3CN (for masses below 5 mg). The resulting mixture was stirred for 12 h. Product amines were separated from pinacol as their sulfate salts, which were highly water soluble: After completion of the reaction, the CH_3CN was removed *in vacuo,* and the products were purified by dissolving the compound in a minimal amount of ether, and adding an excess of concentrated sulfuric acid. Deionized water was added to dissolve the resulting product-sulfate salt, and pincaol was removed by washing this aqueous solution with diethyl ether. The aqueous layer was made basic with 2M KOH, and the product amine was extracted into ether, which was then removed *in vacuo*. The resulting amine was further purified by flash column chromatography with grade I basic alumina using 15 % ether/hexanes and then pure ethyl acetate to elute the amine. Removal of solvent generally resulted in the pure amine. The exchangeable NH proton was occasionally not visible in ^{1}H NMR spectra of the products.

General Procedure for Conjugate Reduction:

General procedure: In a glove box under inert atmosphere, using oven dried vials equipped with magnetic stir bars, conjugate acceptors were dissolved in CH_3CN, then the pre-catalyst and HB(pin) were added and stirred for the prescribed time at 40 °C. The solvent was removed *in vacuo*, the solid product was washed with 1M HCl and extracted with ether, and purified by silica column chromatography, the column was packed with hexanes and eluted with a mixture of 5:1 hexanes/ether.

2.4.2 Synthesis and Characterization

1,4-Di(*tert*-butyl)-1,4-diazabutadiene (2.1) :
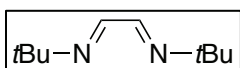
tert-Butylamine (28.7 mL, 273.40 mmol, 2 equiv.) was dissolved in DCM (200 mL) with Na_2SO_4 and stirred. To the solution, glyoxal solution (15.6 mL, 136.70 mmol, 1 equiv.) was added drop wise followed by the addition of formic acid (5 drops). The reaction was stirred for 16 h followed by the removal of solvent *in vacuo* to afford the product[35] as a yellow solid (18.2 g, 91%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.95 (s, 2H), 1.27 (s, 18 H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 157.8, 58.1, 29.4.

HRMS(APCI): 191.1524, $[C_{10}H_{20}N_2Na]^+$ requires 191.1519.

1,4-Di(mesityl)-1,4-diazabutadiene (2.2) :
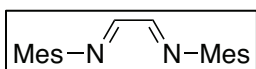
2,4,6-Trimethylaniline (25 mL, 178.10 mmol, 2 equiv.) was dissolved in ethanol (100 mL) and stirred. To the solution, glyoxal solution (10.2 mL, 89.0 mmol, 1 equiv.) was added and stirred for 16 h. A yellow precipitate formed during the reaction; which was collected by suction filtration, washed with hexanes and dried *in vacuo* to afford the product[36] as a yellow solid (24.1 g, 93%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 8.16 (s, 2H), 6.96 (s, 4H), 2.35 (s, 6H), 2.21 (s, 12H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 163.5, 147.5, 134.3, 129.0, 126.6, 20.8, 18.2.

HRMS(APCI): 315.1824, $[C_{20}H_{24}N_2Na]^+$ requires 315.1832.

1,4-Di(cyclohexyl)1,4-diazabutadiene (2.3) :
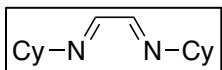
Cyclohexylamine (5.78 mL, 50.4 mmol, 2 equiv.) was dissolved in DCM (20 mL) and Na_2SO_4 was added (14.0 g, 100.8 mmol, 4 equiv.) and stirred. To this solution, glyoxal solution (2.88 mL, 25.2 mmol, 1 equiv.) and formic acid (5 drops) were added and stirred for 16 h. The solvent was removed *in vacuo* and the white solid was washed with pentane, and dried, to afford the product[35] as a beige solid (4.6 g, 83%).

¹H NMR (500 MHz, CDCl₃): δ 7.97 (s, 2H), 3.22-3.17 (m, 2H), 1.86-1.82 (m, 4H), 1.77-1.68 (m, 6H), 1.58-1.50 (m, 4H), 1.42-1.34 (m, 4H), 1.30-1.25 (m, 2H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 160.1, 69.4, 34.0, 25.5, 24.5.

HRMS(APCI): 221.2007, $[C_{14}H_{25}N_2]^+$ requires 221.2012.

1,4-Di(3,5-methoxyphenyl)1,4-diazabutadiene (2.4) :
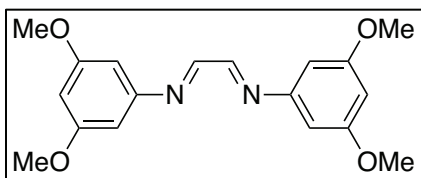
3,5-Dimethoxyaniline (0.50 g, 3.3 mmol, 2 equiv.) was dissolved in a flask with DCM (5 mL) and Na_2SO_4 was added (1.0 g) and stirred. To this solution, glyoxal solution (0.19 mL, 1.6 mmol, 1 equiv.) was added and stirred for 16 h. The Na_2SO_4 was removed by suction filtration and the solvent was removed *in vacuo* to afford a dark oil. NMR revealed no conversion to product, and unreacted starting materials.

2-Bromo-1,3-di-*tert*-butyl-1,3,2-diazaphospholene (2.5):
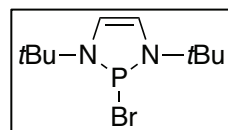
1,4-Di(*tert*-butyl)-1,4-diazabutadiene **2.1** (10.0 g, 59.4 mmol, 1 equiv.) was dissolved in DCM (100 mL) under N_2 in a Schlenk flask

and stirred. To this mixture was added cyclohexene (18.1 mL, 178.0 mmol, 3 equiv.), and PBr$_3$ (5.65 mL, 59.4 mmol, 1 equiv.). The mixture was stirred for 48 h. The solvent was removed *in vacuo,* and the resulting yellow/orange solid was brought into the glovebox where it was washed with ether and filtered to afford the product[35] as a yellow powder (14.5 g, 87%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.29 (d, *J*= 2.6 Hz, 2H), 1.76 (s, 18H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 124.9 (d, *J*= 6.9 Hz), 59.4 (d, *J*= 7.2 Hz), 30.2 (d, *J*= 10.1 Hz).

^{31}P NMR (202 MHz, CDCl$_3$): δ 186.6 (s).

2-Bromo-1,3-di-mesityl-1,3,2-diazaphospholene (2.6):
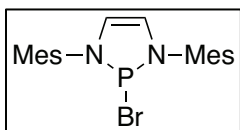
1,4-Di(mesityl)-1,4-diazabutadiene **2.2** (10.0 g, 34.2 mmol, 1 equiv.) was dissolved in DCM (50 mL) under N$_2$ in a Schlenk flask and stirred. To this mixture was added cyclohexene (10.38 mL, 102.6 mmol, 3 equiv.) and PBr$_3$ (34.2 mL, 34.2 mmol, 1 equiv.). The mixture was stirred for 48 h. The solvent was removed *in vacuo*, and the resulting green solid was brought into the glovebox where it was washed with ether and filtered to afford the product[36] as a green powder (11.5 g, 83%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.03 (s, 4H), 6.70 (s, 2H), 2.47 (s, 12H), 2.36 (s, 6H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 138.7, 135.6 (d, *J*= 4.2 Hz), 133.3 (d, *J*= 8.0 Hz), 130.0, 123.3 (d, *J*= 8.0 Hz), 21.0, 14.2 (d, *J*= 2.6 Hz).

^{31}P NMR (202 MHz, CDCl$_3$): δ 174.6 (s).

2-Bromo-1,3-di-cyclohexyl-1,3,2-diazaphospholene (2.7):
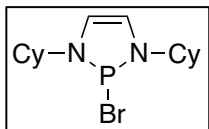
1,4-Di(cyclohexyl)1,4-diazabutadiene **2.3** (1.34 g, 6.1 mmol, 1 equiv.) was dissolved in DCM (20 mL) under N_2 in a Schlenk flask and stirred. To the solution cyclohexene (1.85 mL, 18.3 mmol, 3 equiv.) and PBr_3 (0.58 mL, 6.1 mmol, 1 equiv.) were added and stirred for 48 h. The solvent was removed *in vacuo*, and the solid was brought into the glovebox, washed with ether and the product[35] was collected by suction filtration (1.4 g, 69%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.15 (s, 2H), 4.11-4.05 (m, 2H), 2.44-2.42 (m, 4H), 1.96-1.64 (m, 16H).

^{31}P NMR (202 MHz, CDCl$_3$): δ 191.6 (s).

1,3-Di-*tert*-butyl-2-(benzyloxy)-1,3,2-diazaphospholene (2.8):
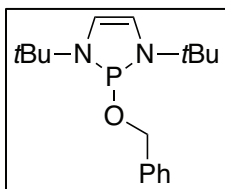
2-Bromo-1,3-di-*tert*-butyl-1,3,2-diazaphospholene **2.5** (0.25 g, 0.896 mmol, 1 equiv.) was dissolved in DCM (2 mL) under N_2 in a Schlenk flask and stirred. To this mixture was added benzyl alcohol (0.093 mL, 0.896 mmol, 1 equiv.) and triethylamine (0.125 mL, 0.896 mmol, 1 equiv.). The mixture was stirred for 16 h. The solvent was removed *in vacuo* and the resulting orange solid was brought into the glovebox where it was dissolved in toluene (5 mL) and filtered over a pad of Celite to remove salts. The toluene was removed *in vacuo* to afford the product as an orange solid. This was then recrystallized from CH_3CN by cooling a saturated solution to -35 °C to afford the product as a white powder (0.21 g, 77%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.38-7.28 (m, 5H), 6.10 (s, 2H), 4.25 (d, *J*= 4.8 Hz, 2H), 1.43 (s, 18H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 128.1, 127.1, 126.9, 112.2 (d, *J*= 9.6 Hz), 63.6 (d, *J*= 3.8 Hz), 52.9 (d, *J*= 16.5 Hz), 31.1 (d, *J*= 9.9 Hz), 30.1 (d, *J*= 4.1 Hz).

³¹P NMR (202 MHz, CDCl₃): δ 94.4 (s).

1,3-Di-mesityl-2-(benzyloxy)-1,3,2-diazaphospholene (2.9):
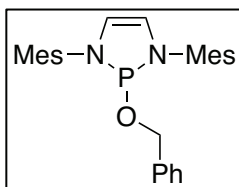
2-Bromo-1,3-di-mesityl-1,3,2-diazaphospholene **2.6** (15 mg, 0.037 mmol, 1 equiv.) was dissolved in DCM (5 mL) in a Schlenk flask under N_2 and stirred. To the solution, NaOBn (5 mg, 0.037 mmol, 1 equiv.) was added and stirred for 16 h. The solvent was removed *in vacuo* and the formation of product was monitored by ^{31}P to observe full conversion to the product. *Full purification and characterization was not pursued due to the reduced reactivity of the mesityl side chain, and the discovery of neopentoxy as a better alcohol to synthesize the pre-catalyst from.

³¹P NMR (202 MHz, CDCl₃): δ 114.2 (s).

1,3-Di-*tert*-butyl-2-neopentyloxy-1,3,2-diazaphospholene (2.10):
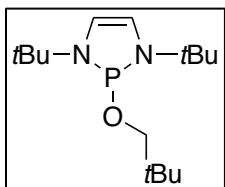
2-Bromo-1,3-di-*tert*-butyl-1,3,2-diazaphosphole **2.5** (2.00 g, 7.16 mmol, 1 equiv.) was dissolved in DCM (15 mL) under N_2 in a Schlenk flask and stirred. To this mixture was added neopentyl alcohol (0.632 g, 7.16 mmol, 1 equiv.) and NEt₃ (1.0 mL, 7.16 mmol, 1 equiv.). The mixture was stirred 24 h. The solvent was removed *in vacuo* and the resulting brown solid was brought into the glovebox where it was dissolved in pentane (10 mL) and filtered over a pad of Celite. The pentane was removed *in vacuo*. The resulting residue was dissolved in minimal acetonitrile (approx. 5 mL) and cooled to -35 °C, then filtered, yielding **2.10** as off white needles (1.51 g, 74%). A colourless crystal suitable for single crystal X-ray analysis was grown by slow evaporation of a pentane solution of **2.10** under a N_2 atmosphere. The data has been deposited with the Cambridge Crystallographic Data

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Centre under deposition number CCDC 1517952. Compound **2.10** can also be readily sublimed at 15 torr with modest heating (40- 50 °C).

MP: 40-42 °C.

^{1}H NMR (500 MHz, CDCl[3]): δ 6.02 (s, 2H), 2.81 (d, *J*= 4.2 Hz, 2H), 1.43 (s, 18H), 0.87 (s, 9H).

^{13}C{^{1}H} NMR (125 MHz, CDCl[3]): δ 119.9 (d, *J*= 9.3 Hz), 70.9 (d, *J*= 6.1 Hz), 52.7 (d, *J*= 17.2 Hz), 31.6 (d, *J*= 1.9 Hz), 31.1 (d, *J*= 10.1 Hz), 26.8.

^{31}P NMR (202 MHz, CDCl[3]): δ 92.3 (s).

HRMS(APCI): 287.2243, $[C_{15}H_{32}N_2OP]^+$ requires 287.2247.

1,3-Di-mesityl-2-(neopentyloxy)-1,3,2-diazaphospholene (2.11):
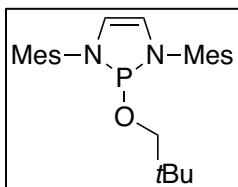
2-Bromo-1,3-di-mesityl-1,3,2-diazaphosphole **2.6** (0.500 g, 1.23 mmol, 1 equiv.) was dissolved in DCM (5 mL) under N$_2$ in a Schlenk flask and stirred. To this mixture was added neopentyl alcohol (0.109 g, 1.23 mmol, 1 equiv.), and NEt$_3$ (0.17 mL, 1.23 mmol, 1 equiv.). The mixture was stirred for 4 h. The solvent was removed *in vacuo* and the resulting brown solid was brought into the glovebox where it was dissolved in toluene (5 mL), filtered over Celite, and then the toluene is removed *in vacuo* to afford the product as a brown solid. (0.50 g, 98%).

MP: 120-121 °C.

^{1}H NMR (500 MHz, CDCl[3]): δ 6.99 (s, 4H), 5.96 (s, 2H), 3.23 (d, *J* = 8.3 Hz, 2H), 2.49 (s, 6H), 2.36-2.34 (m, 12H), 0.71 (s, 9H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 137.6, 137.4 (d, J= 12.3 Hz), 136.7, 135.9 (d, J= 1.8 Hz), 129.0 (d, J= 27.6 Hz), 115.5 (d, J= 7.2 Hz), 73.5 (d, J= 22.3 Hz), 32.5 (d, J= 5.3 Hz), 26.2, 21.0.

^{31}P NMR (200 MHz, CDCl$_3$): δ 114.7 (s).

HRMS(APCI): 411.2576, [C$_{25}$H$_{36}$N$_2$OP]$^+$ requires 411.2560.

N, N-Di-*tert*-butylethane-1,2-diamine (2.12):

tBu−NH HN−tBu   1,4-Di(*tert*-butyl)-1,4-diazabutadiene **2.1** (0.500 g, 2.97 mmol, 1 equiv.) was dissolved in MeOH (10 mL) and stirred. To the mixture was added NaBH$_4$ (0.562 g, 14.85 mmol, 5 equiv.) and stirred for 2 h. The reaction was quenched with Na$_2$CO$_3$ (saturated aqueous solution) and extracted with ether. The solvent was removed *in vacuo* to afford the product as a clear oil (0.4 g, 78%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 3.69 (s, 4H), 2.69 (s, 2H), 1.13 (s, 18H).

N, N-Di-mesityl-ethane-1, 2-diamine (2.13):
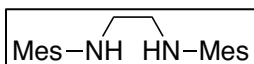
Mes−NH HN−Mes   1,4-Di(mesityl)-1,4-diazabutadiene **2.2** (4.0 g, 13.68 mmol, 1 equiv.) was dissolved in MeOH (20 mL) and stirred. To the mixture was added NaBH$_4$ (2.07 g, 54.72 mmol, 4 equiv.) and stirred for 24 h. The reaction was quenched with Na$_2$CO$_3$ (saturated aqueous solution) and extracted with DCM. The solvent was removed *in vacuo* to afford the product as a yellow oil (3.3 g, 81%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 6.87 (s, 4H), 3.19 (s, 4H), 2.32 (s, 12H), 2.27 (s, 6H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 143.4, 131.5, 129.8, 129.5, 49.2, 20.6, 18.4.

2-Bromo-1,3-di-*tert*-butyl-1,3,2-diazaphospholidine (2.14):
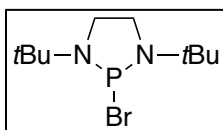
tBu−N P N−tBu Br   *N,N*-Di-*tert*-butylethane-1,2-diamine **2.12** (0.880 g, 5.10 mmol, 1 equiv.) was dissolved in DCM (5 mL) in a Schlenk tube under N$_2$ and

stirred. To the solution NEt₃ (1.50 mL, 10.7 mmol, 2.1 equiv.) and PBr₃ (0.480 mL, 5.10 mmol, 1 equiv.) were added and stirred for 24 h. The solvent was removed *in vacuo* and the flask was brought into the glovebox where toluene (5 mL) was added. The resulting suspension was filtered and the toluene was removed *in vacuo* to afford the product as a brown solid (0.99 g, 67%).

MP: 105-107 °C.

¹H NMR (500 MHz, CDCl₃): δ 3.45 (d, *J*= 6.5 Hz, 4H), 1.47 (d, *J*= 2.2 Hz, 18H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 54.7 (d, *J*= 10.2 Hz), 46.3 (d, *J*= 10.2 Hz), 28.3 (d, *J*= 11.2 Hz).

³¹P NMR (200 MHz, CDCl₃): δ 193.0 (s).

2-Bromo-1,3-di-mesityl-1,3,2-diazaphospholidine (2.15):
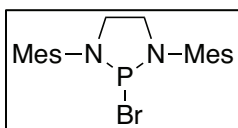
N,N-Di-mesityl-ethane-1,2-diamine **2.13** (0.490 g, 1.65 mmol, 1 equiv.) was placed in a Schlenk flask under N₂ dissolved in DCM (5 mL) and stirred. To the solution PBr₃ (0.16 mL, 1.65 mmol, 1 equiv.) and NEt₃ (0.49 mL, 3.47 mmol, 2.1 equiv.) were added and stirred for 16 h. The solvent was removed *in vacuo*, and the pale yellow precipitate was washed with ether and filtered to afford the product as a white powder (0.40 g, 60%).

¹H NMR (500 MHz, CDCl₃): δ 6.97 (s, 4H), 3.88-3.87 (m, 4H), 2.52 (s, 12H), 2.32 (s, 6H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 137.2 (d, *J*= 4.8 Hz), 134.8 (d, *J*= 12.1 Hz), 130.0, 52.8 (d, *J*= 9.2 Hz), 20.9, 19.6 (d, *J*= 2.3 Hz).

³¹P NMR (200 MHz, CDCl₃): δ 178.6.

1,3-Di-*tert*-butyl-2-neopentyloxy-1,3,2-diazaphospholidine (2.16):

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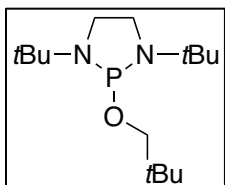
2-Bromo-1,3-di-*tert*-butyl-1,3,2-diazaphospholidine **2.14** (0.10 g, 0.35 mmol, 1 equiv.) was dissolved in DCM (5 mL) and stirred with NEt$_3$ (0.048 mL, 0.35 mmol, 1 equiv.) and neopentyl alcohol (0.031 g, 0.35 mmol, 1 equiv.) for 12 h in a Schlenk flask under N$_2$. The solvent was removed *in vacuo* and the flask was brought into the glovebox where toluene (5 mL) was added. The resulting suspension was filtered and the toluene was removed *in vacuo* to afford the product as a white powder (0.82 g, 82%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 3.26-3.25 (m, 4H), 3.09-3.08 (m, 2H), 1.32 (s, 18H), 0.92 (s, 9H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 71.7, 51.9 (d, *J*= 15.5 Hz), 45.5 (d, *J*= 9.8 Hz), 29.7 (d, *J*= 10.2 Hz), 26.9, 26.4.

^{31}P NMR (200 MHz, CDCl$_3$): δ 109.8 (s).

HRMS (APCI): 289.2408 [C$_{15}$H$_{34}$N$_2$OP]$^+$, requires 289.2403.

1,3-Di-mesityl-2-neopentyloxy-1,3,2-diazaphospholidine (2.17):
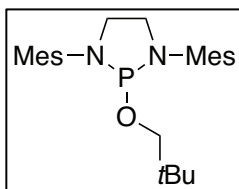
1,3-Di-mesityl-2-bromo-1,3,2-diazaphospholidine **2.16** (0.50g, 1.23 mmol, 1 equiv.) was dissolved in DCM (5 mL) in a Schlenk flask under N$_2$. To the solution NEt$_3$ (0.172 mL, 1.23 mmol, 1 equiv.) and neopentyl alcohol (0.109 g, 1.23 mmol, 1 equiv.) were added and stirred for 16 h. The solvent was removed *in vacuo*, and the crude was brought into the glovebox, dissolved in toluene (10 mL), filtered and concentrated *in vacuo* to afford the product as a yellow oil (0.39 g, 77%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 6.87 (s, 4H), 3.19 (s, 4H), 2.49 (s, 2H), 2.32 (s, 18H), 2.27 (s, 9H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 143.3, 131.5, 129.8, 129.5, 49.2, 26.4, 26.3, 20.9, 20.5, 18.4.

^{31}P NMR (200 MHz, CDCl$_3$): δ 121.5 (s).

HRMS (APCI): 413.2716 [C$_{25}$H$_{38}$N$_2$OP]$^+$, requires 413.2720.

1,3-Di-*tert*-butyl-2-*H*-1,3,2-diazaphospholidine (2.18):
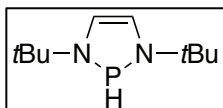
Activation of 2.10: The following is an adaptation of a literature procedure.[9] Under a N$_2$ atmosphere in a glovebox, pre-catalyst **2.10**, (30 mg, 0.170 mmol, 1 equiv.) was dissolved in 0.7 mL CH$_3$CN and a capillary of C$_6$D$_6$ was added. Pinacolborane (13 mg, 0.170 mmol, 1 equiv.) was added, and the NMR tube was shaken and sealed by overwrapping with Teflon tape prior to removal from the glovebox. A ^{31}P NMR spectrum acquired after 5 minutes showed the presence of both **2.10** and **2.18**. Integration was not attempted for the ^{31}P NMR spectrum.

Exhaustive Activation of 2.10: Under a N$_2$ atmosphere in a glovebox, pre-catalyst **2.10**, (30 mg, 0.170 mmol, 1 equiv.) was dissolved in 0.7 mL CH$_3$CN and a capillary of C$_6$D$_6$ was added. Pinacolborane (65 mg, 0.850 mmol, 5 equiv.) was added, and the NMR tube was shaken and sealed by overwrapping with Teflon tape prior to removal from the glovebox. A ^{31}P NMR spectrum acquired after 1 hour showed the consumption of **2.10**. While a clean doublet was not observed for **2.18**, a broad peak in the correct area was observed. In our hands an authentic sample of **2.18** in CD$_3$CN exhibits either a doublet or broad peak in the ^{31}P NMR spectrum, which is apparently dependent on concentration. Kinjo reported similar broadening of the peak for **2.18**.[10] A triplet at -42.9 ppm is attributed to a phosphorus species containing 2 P-H bonds, representing an endocyclic cleavage of a P-N bond, while a quartet at -243.6 ppm is attributed to phosphine (PH$_3$).

Reacquisition of the spectrum after 1 day showed extensive formation of phosphine.

^{31}P NMR (202 MHz, CH₃CN, C₆D₆ capillary): δ 57.5 ppm (d, $^1J_{\text{P-H}}$= 182.9 Hz).

1,3-Di-mesityl-1,3,2-diazaphospholidine (2.19):
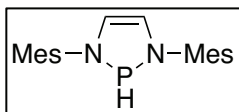
Activation of 2.19: Under a N₂ atmosphere in a glovebox, pre-catalyst **2.11**, (30 mg, 0.07 mmol, 1 equiv.) was dissolved in 0.7 mL CH₃CN and a capillary of C₆D₆ was added. Pinacolborane (11 mg, 0.084 mmol, 1.2 equiv.) was added, and the NMR tube was shaken and sealed by overwrapping with Teflon tape prior to removal from the glovebox. A ^{31}P NMR spectrum acquired after 1 hour showed the presence of **2.19**.

^{31}P NMR (202 MHz, CH₃CN, C₆D₆ capillary): δ 64.2 ppm, ($^1J_{\text{P-H}}$ = 136.6 Hz).

N-**Benzyl-1-phenylethanamine (2.20):**
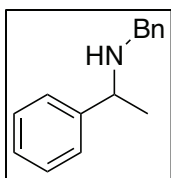
N-Benzyl-1-phenylethanimine (1.0 g, 4.8 mmol, 1 equiv.) was dissolved in CH₃CN (5 mL) and stirred. Pre-catalyst **2.10** (27 mg, 0.095 mmol, 0.02 equiv.) and HB(pin) (0.70 mL, 4.8 mmol, 1 equiv.) were added to the reaction mixture and stirred for 12 h. The solvent was removed *in vacuo* and the work up from the general procedure was performed to afford the product[37] (0.98 g, 97%).

^{1}H NMR (500 MHz, CDCl₃): δ 7.40-7.30 (m, 7H), 3.85 (q, *J*= 6.6 Hz, 1H), 3.69 (second order dd, 2H), 1.59 (s, 1H), 1.42 (d, *J*= 6.6 Hz, 2H).

^{13}C{^{1}H} NMR (125 MHz, CDCl₃): δ 128.5, 128.4, 128.1, 126.9, 126.9, 126.7, 57.5, 51.7, 24.9, 24.5.

N-**Benzyl-2,3-dihydro-1*H*-inden-1amine (2.21):**
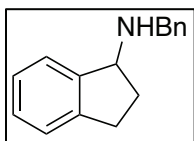
N-(2,3-Dihydroinden-1-ylidene)(phenyl)methanamine (50 mg, 0.23 mmol, 1 equiv.) was dissolved in CH₃CN (1 mL) and stirred. Pre-

catalyst **2.10** (1.3 mg, 0.0045 mmol, 0.02 equiv.) and HB(pin) (0.03 mL, 0.23 mmol, 1 equiv.) were added to the mixture and stirred for 12 h. The solvent was removed *in vacuo* and the work up from the general procedure was performed to afford the product[38] (43 mg, 85%).

¹H NMR (500 MHz, CDCl₃): δ 7.46-7.25 (m, 9H), 4.36 (t, *J*= 6.6, 1H), 3.97 (second order dd, 2H), 3.09-3.05 (m, 1H), 2.89-2.86 (m, 1H), 2.51-2.47 (m, 1H), 1.96-1.92 (m, 1H), 1.58 (s, 1H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 145.3, 143.7, 140.7, 128.4, 128.2, 127.4, 126.9, 126.25, 124.8, 124.1, 62.8, 51.4, 33.7, 30.4.

N-(Prop-2-ynyl)-2,3-dihydro-1H-inden-1-amine (2.22):
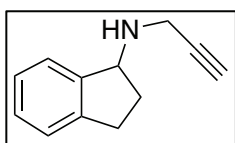
N-(2,3-Dihydroinden-1-ylidene)prop-2-yn-1-amine (200 mg, 1.18 mmol, 1 equiv.) was dissolved in CH₃CN (2 mL) and stirred. Pre-catalyst **2.10** (7 mg, 0.024 mmol, 0.02 equiv.) and HB(pin) (0.17 mL, 1.18 mmol, 1 equiv.) were added and stirred for 12 h. The solvent was removed *in vacuo* and the work up from the general procedure was performed to afford the product[83] (195 mg, 96%).

¹H NMR (500 MHz, CDCl₃): δ 7.39-7.23 (m, 4H), 4.45 (t, *J*= 1.2 Hz, 1H), 3.11-3.05 (m, 1H), 2.90 (m, 1H), 2.48-2.41 (m, 1H), 2.29 (t, *J*= 2.4 Hz, 1H), 1.93-1.88 (m, 1H), 1.53 (s, 1H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 144.5, 143.8, 127.6, 126.3, 124.9, 124.2, 82.5, 71.4, 61.9, 36.2, 33.4, 30.5.

N-(4-Methoxybenzyl)-1-phenylethanamine (2.23):
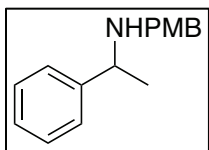
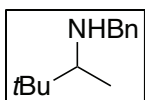(4-Methoxyphenyl)-*N*-(1-phenylethylidene)methanamine (50 mg, 0.210 mmol, 1 equiv.) was dissolved in CH₃CN (1 mL) and stirred.

Pre-catalyst **2.10** (1.2 mg, 0.0042 mmol, 0.02 equiv.) and HB(pin) (0.03 mL, 0.0210 mmol, 1 equiv.) was added to the mixture and stirred for 12 h. The solvent was removed *in vacuo* and the work up from the general procedure was performed to afford the product[37] (40 mg, 79%).

¹H NMR (500 MHz, CDCl₃): *δ* 7.39-7.21 (m, 7H), 6.89-6.86 (m, 2H), 3.84 (q, *J*= 6.6 Hz, 1H), 3.82 (s, 3H), 3.60 (ABq, 2H), 1.39 (d, *J*= 6.6 Hz, 3H).

¹³C{¹H} NMR (125 MHz, CDCl₃): *δ* 158.6, 145.5, 132.6, 129.3, 128.5, 126.9, 126.8, 113.8, 57.4, 55.3, 51.0, 24.4.

N-**Benzyl-1-(pyridin-2-yl)ethanamine (2.24):**
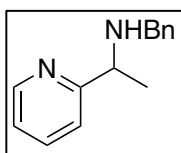
Phenyl-*N*-(1-(pyridin-2-yl)ethylidene)methanamine (50 mg, 0.250 mmol, 1 equiv.) was dissolved in CH₃CN (1 mL) and stirred. Pre-catalyst **2.10** (1.4 mg, 0.005 mmol, 0.02 equiv.) and HB(pin) (0.04 mL, 0.250 mmol, 1 equiv.) were added to the mixture and left to stir for 12 h. The solvent was removed *in vacuo*, and the work up in the general procedure was performed to afford the product (46 mg, 92%).

¹H NMR (500 MHz, CDCl₃ *δ* 8.60 (dq, *J*= 1.8, 0.9 Hz, 1H), 7.67 (td, *J*= 7.6, 1.8 Hz, 1H), 7.38-7.16 (m, 7H), 3.95 (q, *J*= 6.7, 1H), 3.67 (ABq, *J*= 7.9, 14.4 Hz, 2H), 1.99 (s, 1H), 1.44 (d, *J*= 6.7 Hz, 3H).

¹³C{¹H} NMR (125 MHz, CDCl₃): *δ* 164.6, 149.4, 140.5, 136.5, 128.3, 128.2, 126.8, 121.9, 121.2, 58.7, 51.8, 24.9, 22.9.

HRMS(ESI): 213.1386, [C₁₄H₁₇N₂]⁺ requires 213.1377.

N-**Benzyl(4-methoxyphenyl)methanamine (2.25):**
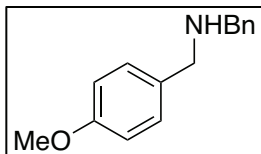
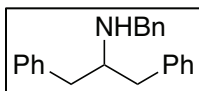*N*-(4-Methoxybenzylidene)(phenyl)methanamine (50 mg, 0.22 mmol, 1 equiv.) was dissolved in CH$_3$CN (1 mL) and stirred. Pre-catalyst **2.10** (1.3 mg, 0.0044 mmol, 0.02 equiv.) and HB(pin) (0.03, 0.22 mmol, 1 equiv.) were added to the mixture and stirred for 12 h. The solvent was removed *in vacuo* and the work up from the general procedure was performed to afford the product[39] (35 mg, 69 %).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.37-7.35 (m, 4H), 7.30-7.27 (m, 3H), 6.91-6.88 (m, 2H), 3.82 (s, 5H), 3.78 (s, 2H), 1.96 (br. s, 1H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 158.7, 129.4, 128.4, 128.3, 127.0, 113.8, 55.3, 52.9, 52.4.

N-Benzyl-2-methylpropan-2-amine(2.26):
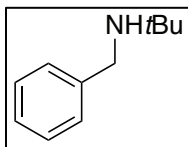
(*E*)-*N*-Benzylidene-2-methylpropan-2-amine (200 mg, 1.24 mmol, 1 equiv.), was dissolved in CH$_3$CN (2 mL) and stirred. Pre-catalyst **2.10** (7 mg, 0.025 mmol, 0.02 equiv.) and HB(pin) (0.18 mL, 1.24 mmol, 1 equiv.) were added to the mixture and stirred for 12 h. The solvent was removed *in vacuo* and the workup from the general procedure was performed to afford the product[40] (155 mg, 82%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.35-7.28 (m, 5H), 3.75 (s, 2H), 1.20 (s, 9H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 128.4, 128.3, 126.8, 47.3, 29.1.

2,6-Diisopropyl-N-(pyridin-2-ylmethyl)benzenamine (2.27):
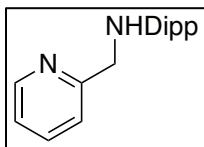
(E)-2,6-Diisopropyl-*N*-(pyridin-2-ylmethylene)aniline (50 mg, 0.19 mmol, 1 equiv.) was dissolved in CH$_3$CN (1 mL) and stirred. Pre-catalyst **2.10** (1.1 mg, 0.0038 mmol, 0.02 equiv.) and HB(pin) (0.03

mL, 0.19 mmol, 1 equiv.) were added to the mixture and stirred for 12 h. The solvent was removed *in vacuo* and the work up in the general procedure was performed to afford the product[41] (29 mg, 58%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 8.66-8.63 (m, 1H), 7.67 (td, *J*= 7.7, 1.8 Hz, 1H), 7.34-7.31 (m, 1H), 7.24-7.20 (m, 1H), 7.16-7.10 (m, 3H), 4.21 (s, 2H), 3.38 (p., *J*= 6.9 Hz, 2H), 1.26 (d, *J*= 6.9 Hz, 12H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 159.1, 149.4, 143.1, 142.7, 136.4, 123.9, 123.6, 122.1, 122.0, 56.9, 27.7, 14.3.

N-(2-(Cyclohexylamino)ethyl)cyclohexanamine (2.28):
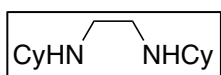
CyHN⌒NHCy N-(2-(Cyclohexylimino)ethylidene)cyclohexanamine (50 mg, 0.23 mmol, 1 equiv.) was dissolved in CH$_3$CN and stirred. Pre-catalyst **2.10** (7 mg, 0.0023 mmol, 0.1 equiv.) and HB(pin) (0.06 mL, 0.23 mmol, 2 equiv.) were added and the mixture was stirred for 12 h. The solvent was removed *in vacuo* and the work up from the general procedure was performed to afford the product[42] (40 mg, 79%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 2.80 (s, 4H), 2.49-2.43 (m, 2H), 1.93-1.89 (m, 4H), 1.78-1.72 (m, 4H), 1.64-1.61 (m, 2H), 1.30-1.09 (m, 10H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 56.9, 47.0, 33.7, 26.2, 25.1.

N-Benzylcyclohexanamine (2.29):
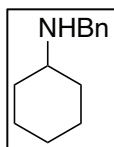
NHBn N-Cyclohexylidene(phenyl)methanamine (50 mg, 0.27 mmol, 1 equiv.) was dissolved in CH$_3$CN. Pre-catalyst **2.10** (1.5 mg, 0.0054 mmol, 0.02 equiv.), and HB(pin) (0.04 mL, 0.027 mmol, 1 equiv.) were added to the mixture and stirred for 12 h. The solvent was removed *in vacuo*, and the work up from the general procedure was performed to afford the product[43] (47 mg, 94%).

¹H NMR (500 MHz, CDCl₃): δ 7.35-7.28 (m, 5H), 3.80 (s, 2H), 3.14 (p, *J*= 6.7 Hz, 1H), 1.90-1.85 (m, 3H), 1.75-1.70 (m, 3H), 1.58-1.53 (m, 2H), 1.44-1.39 (m, 2H), 1.28 (s, 1H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 140.5, 128.4, 128.2, 126.9, 59.1, 52.7, 33.1, 24.1.

***N*-Benzylcyclooctanamine (2.30):**
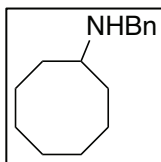
N-Cyclooctylidene(phenyl)methanamine (50 mg, 0.23 mmol, 1 equiv.) was dissolved in CH₃CN (1 mL) and stirred. Pre-catalyst **2.10** (1.3 mg, 0.0046 mmol, 0.02 equiv.) and HB(pin) (0.03 mL, 0.23 mmol, 1 equiv.) were added and stirred for 12 h. The solvent was removed *in vacuo* and the work up from the general procedure was performed to afford the product (45 mg, 89%).
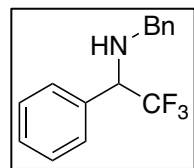
¹H NMR (500 MHz, CDCl₃): δ 7.36-7.30 (m, 5H), 3.82 (s, 2H) 2.78-2.75 (m, 1H), 1.84-1.74 (m, 4H), 1.63-1.55 (m, 7H), 1.51-1.47 (m, 3H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 128.4, 128.2, 126.8, 57.2, 51.5, 32.5, 27.3, 25.8, 24.1.

***N*-Benzyl-3,3-dimethylbutan-2-amine (2.31):**

N-(3,3-Dimethylbutan-2-ylidene)(phenyl)methanamine (50 mg, 0.26 mmol, 1 equiv.), was dissolved in CH₃CN (1 mL) and stirred. Pre-catalyst **2.10** (1.6 mg, 0.0052 mmol, 0.02 equiv.) and HB(pin) were added to the mixture and stirred for 12 h. The solvent was removed *in vacuo* and the work up from the general procedure was performed to afford the product[44] (45 mg, 89%).

¹H NMR (500 MHz, CDCl₃): δ 7.39-7.28 (m, 5H), 3.97 (d, *J*= 13.2 Hz, 1H), 3.70 (d, *J*= 13.2 Hz, 1H), 2.34 (q, *J*= 6.4 Hz, 1H), 1.06 (d, *J*= 6.4 Hz, 3H), 0.93 (s, 9H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 141.3, 128.6, 128.2, 128.2, 128.2, 127.3, 127.1, 126.7, 61.3, 52.7, 34.5, 26.5, 26.4, 14.7.

N-Benzyl-1,3-diphenylpropan-2-amine (2.32):

N-(1,3-Diphenylpropan-2-ylidene)(phenyl)methanamine (50 mg, 0.17 mmol, 1 equiv.) was dissolved in CH$_3$CN (1 mL) and stirred. Pre-catalyst **2.10** (0.94 mg, 0.0033 mmol, 0.02 equiv.) and HB(pin) (0.03 mL, 0.17 mmol, 1 equiv.) were added to the mixture and stirred for 12 h. The solvent was removed *in vacuo* and the work up from the general procedure was performed to afford the product[45] (47 mg, 93%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.33-7.23 (m, 9H), 7.18 (d, *J*= 7.1 Hz, 4H), 7.09 (d, *J*= 7.9 Hz, 2H), 3.81 (s, 2H), 3.12 (ap. p, *J*= 6.6, 2H), 2.85-2.75 (m, 4H), 1.91 (s, 1H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 139.1, 129.5, 129.3, 128.7, 128.4, 128.4, 128.1, 127.0, 126.3, 59.7, 51.1, 40.5.

(1*R**,2*R**)-2-Allyl-*N*-benzylcyclohexanamine (2.33):
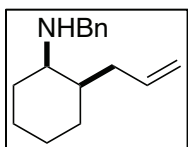
N-(2-Allylcyclohexylidene)(phenyl)methanamine (50 mg, 0.44 mmol, 1 equiv.) was dissolved in CH$_3$CN and stirred. Pre-catalyst **2.10** (1.9 mg, 0.0088 mmol, 0.02 equiv.) and HB(pin) (0.08 mL, 0.44 mmol, 1 equiv.) were added to the mixture and stirred for 12 h. The solvent was removed *in vacuo* and the work up from the general procedure was performed to afford to afford the product[46] (45 mg, 90%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.39-7.34 (m, 4H), 7.29-7.28 (m, 1H), 5.85-5.77 (m, 1H), 5.05 (m, 1H), 5.01 (dd, *J*= 10.0 Hz, 1H), 3.85 (d, *J*= 13.1 Hz, 1H), 3.74 (d, *J*= 13.1

Hz, 1H), 2.79-2.77 (m, 1H), 2.28-2.26 (m, 1H), 2.07-2.05 (m, 1H), 1.75-1.54 (m, 5H), 1.43-1.35 (m, 4H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 138.2, 128.3, 128.2, 126.8, 115.3, 56.4, 51.3, 28.7, 27.3.

N-Toluenelsulfonhydrazine-6-methoxytetralamine (2.34):
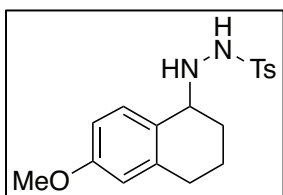
N-Toluenesulfonhydrazine-6-methoxytetralamine (60 mg, 0.18 mmol, 1 equiv.) was dissolved in CH$_3$CN (1 mL) and stirred. To the mixture was added pre-catalyst **2.10** (0.010 g, 0.035 mmol, 0.02 equiv.), and HB(pin) (0.03 mL, 0.18 mmol, 1 equiv.). The solution was stirred for 48 h, the solvent was removed *in vacuo*. NMR data showed some conversion to the product. This substrate was not further pursued due to lower conversions, difficulties with purification, and long reaction times (40 mg, 88% conversion).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.85 (m, 4H), 7.75 (s, 1H), 7.28 (t, *J*= 7.0 Hz, 3H), 6.55 (m, 1H), 3.74 (s, 3H), 3.46 (s, 1H), 2.83 (s, 1H), 2.77 (dt, *J*= 5.9 Hz, 2H), 2.63 (t, *J*= 5.8 Hz, 1H), 2.40 (t, *J*= 8.0 Hz, 2H), 2.36 (s, 2H), 2.08 (s, 1H), 1.12 (s, 3H).

(1S,4S)-4-(3,4-Dichlorophenyl)-N-methyl-1,2,3,4-tetrahydronaphthalen-1-amine (Sertraline) (2.35):
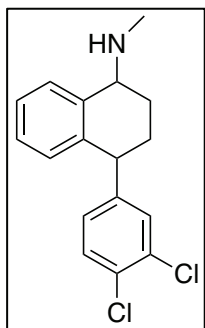
N-[4-(3,4-Dichlorophenyl)-3,4-dihydro-1(2H)-naphthalenylidene]me-thanamine (0.100 g, 0.33 mmol, 1 equiv.) was dissolved in CH$_3$CN (1 mL) and stirred. To the solution pre-catalyst **2.10** (19 mg, 0.066 mmol, 0.05 equiv.), and HB(pin) (0.05 mL, 0.33 mmol, 1 equiv.) were added and stirred for 18 h. The solvent was removed *in vacuo* and the

workup from the general procedure was performed to afford the product[47] (0.095 g, 95%) with a 1.5:1 d.r.

¹H NMR (500 MHz, CDCl₃): δ 7.48-7.45 (m, 1H), 7.38-7.33 (m, 2H), 7.28-7.22 (m, 3H), 7.14-7.12 (m, 1H), 4.17-4.13 (m, 1H), 3.83-3.80 (m, 1H) 2.54 (3H, s), 2.39-2.33 (m, 1H), 2.05-1.97 (m, 2H), 1.85 (br. s, 4H).

N-Benzyltetrahydroquinoline (2.36):
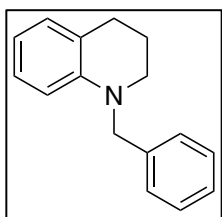
Quinolinium-PF⁶ (64 mg, 0.18 mmol, 1 equiv.) was dissolved in CH₃CN (1 mL) and stirred. To the solution pre-catalyst **2.10** (10 mg, 0.035 mmol, 0.05 equiv.), and HB(pin) (0.05 mL, 0.18 mmol, 1 equiv.) were added and stirred for 16 h. The solvent was removed *in vacuo* and the conversion was determined by NMR. This product[48] was not further pursued due to issues in purification (0.055 g, 86 %).

¹H NMR (500 MHz, CDCl₃): δ 7.28 (m, 5H), 6.99 (m, 2H), 6.59 (m, 2H), 4.50 (s, 2H), 3.38 (t, *J*= 5.6 Hz, 2H), 2.84 (t, *J*= 6.3 Hz, 2H), 2.03 (pent, *J*= 5.8 Hz, 2H).

HRMS(ESI): 222.1277, $[C_{16}H_{16}N]^+$ requires 222.1274.

N-Pentylbenzylamine (2.37):
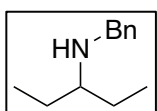
N-Benzyl-3-pentylamine (62 mg, 0.35 mmol, 1 equiv.) was dissolved in CH₃CN (1 mL) and stirred. To the solution pre-catalyst **2.10** (0.010 g, 0.035 mmol, 0.1 equiv.), and HB(pin) (0.05 mL, 0.35 mmol, 1 equiv.) were added and stirred for 24 h. NMR showed unreacted starting material.

N-3-Methoxyphenyl-1-phenylethanamine (2.38):
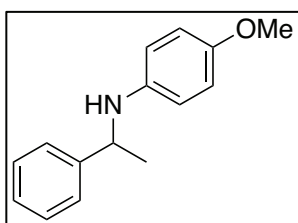
N-3-Methoxyphenyl-1-phenylethanimine (39 mg, 0.18 mmol, 1 equiv.) was dissolved in CH₃CN (1 mL) and stirred. To the

solution pre-catalyst **2.10** (10 mg, 0.035 mmol, 0.05 equiv.), and HB(pin) (0.03 mL, 0.18 mmol, 1 equiv.) were added and stirred for 18 h. The NMR showed unreacted starting material.

Benzenemethanamine, α-phenyl-*N*-(phenylmethyl) (2.39):
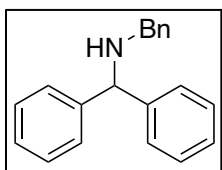
Benzenemethanamine, α-phenyl-*N*-(phenylmethylene) (48 mg, 0.18 mmol, 1 equiv.) was dissolved in CH$_3$CN (1 mL) and stirred. To the solution pre-catalyst **2.10** (10 mg, 0.035 mmol, 0.05 equiv.), and HB(pin) (0.03 mL, 0.18 mmol, 1 equiv.) were added and stirred for 24 h. The NMR showed unreacted starting material.

N-Benzyl-1-(trifluoromethyl)phenylethanamine (2.40):

N-Benzyl-1-(trifluoromethyl)phenylethanimine (50 mg, 0.19 mmol, 1 equiv.) was dissolved in CH$_3$CN (1 mL) and stirred. To the solution pre-catalyst **2.10** (10 mg, 0.0038 mmol, 0.1 equiv.) and HB(pin) (0.028 mL, 0.19 mmol, 1 equiv.) were added and stirred for 16 h. The NMR showed unreacted starting material.

N-(S)-*tert*-Butylsulfinamide-phenylethanamine (2.41):
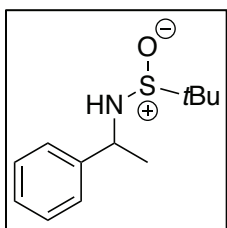
N-(*S*)-*tert*-Butylsulfinamide-phenylethanimine (0.050 g, 0.24 mmol, 1 equiv.) was dissolved in CH$_3$CN (1 mL) and stirred. To the solution pre-catalyst **2.10** (1.3 mg, 0.0047 mmol, 0.02 equiv.) and HB(pin) (0.035 mL, 0.24 mmol, 1 equiv.) were added and stirred for 16 h. The NMR showed unreacted starting material.

2-Dibenzylamido-1,3-di-*tert*-butyl-1,3,2-diazaphosphole (2.42):

60
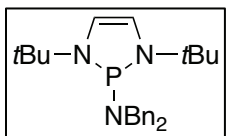
2-Bromo-1,3-di-*tert*-butyl-1,3,2-diazaphosphole **2.5** (600 mg, 2.15 mmol, 1 equiv.) was suspended in dry trifluorotoluene (10 mL), and cooled to -35 °C. Solid lithium dibenzylamide (prepared by the treatment of dibenzylamine with 1 equiv. 2.1 M n-BuLi in pentane, followed by solvent removal) was added to the suspension, which was allowed to warm naturally to ambient temperature and stirred vigorously for 2 days. The resultant suspension was filtered on a frit, and the solvent removed *in vacuo*. The resultant solid was taken up in pentane, and filtered. The filtrate concentrated to yield **2.42** as an extremely air sensitive amber oil, which was contaminated with approximately one equivalent of dibenzylamine. NMR spectra in $CDCl_3$ and CH_3CN were acquired immediately, while NMR spectra in C_6D_6 were acquired after approximately two months of storage at -35 °C. In the intermediate time, a small amount of inconsequential hydrolysis was observed. The hydrolysis product is a known compound.

^{1}H NMR (500 MHz, CDCl[3]): δ 7.38-7.17 (m, 10H), 5.88 (s, 2H), 3.89-3.86 (m, 4H), 1.37 (s, 18H).

^{31}P NMR (202 MHz, CDCl[3]): δ 97.5.

N-**Benzyl-phenylmethanamine (2.43):**
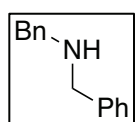
1,3-Di-*tert*-butyl-2-(hydro)-1,3,2-diazaphospholidine **2.18** (40 mg, 0.2 mmol, 1 equiv.) was placed in a 4-dram vial and dissolved in CD_3CN. *N*-Benzyl-phenylmethanimine (43 mg, 0.22 mmol, 1.1 equiv.) was added. The reaction was stirred for 24 h, then placed in an NMR tube, sealed with Teflon tape, and ^{1}H and ^{31}P spectra were acquired. Diagnostic peaks were identical with **2.42**. The reaction was also conducted in C_6D_6.

^{1}H NMR (500 MHz, CDCl[3]): δ 7.36- 7.22 (m, 10H), 3.81 (s, 4H), 2.22 (s, 1H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 140.5, 128.5, 128.3, 127.1, 53.4.

Methyl 3-phenylpropanoate (2.44):
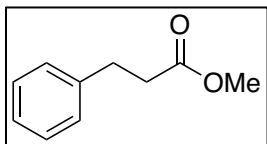
Methyl cinnamate (100 mg, 0.62 mmol, 1 equiv.) was dissolved in CH₃CN (1 mL) and stirred. Pre-catalyst **2.10** (8.8 mg, 0.031 mmol, 0.05 equiv.) and HB(pin) (0.09 mL, 0.62 mmol, 1 equiv.) were added and stirred for 12 h at 40 °C. The work up from the general procedure was performed to afford the product[49] (82 mg, 81%).

¹H NMR (500 MHz, CDCl₃): δ 7.34-7.20 (m, 5H), 3.69 (s, 3H), 2.98 (t, *J*= 7.5 Hz, 2H), 2.66 (t, *J*= 6.8 Hz, 2H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 173.3, 140.5, 128.5, 128.3, 126.3, 51.6, 35.7, 31.0.

Ethyl 3-phenylbutanoate (2.45):
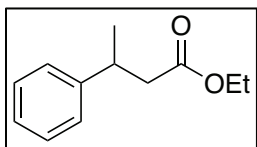
(*E*)-Ethyl 3-phenylbut-2-enoate (100 mg, 0.53 mmol, 1 equiv.) was dissolved in CH₃CN (1 mL) and stirred. Pre-catalyst **2.10** (15 mg, 0.053 mmol, 0.1 equiv.) and HB(pin) (0.0076 mL, 0.53 mmol, 1 equiv.) were added and stirred for 12 h at 40 °C. The work up from the general procedure was performed to afford the product[50] (78 mg, 77%).

¹H NMR (500 MHz, CDCl₃): δ 7.34-7.21 (m, 5H), 4.10 (q, *J*= 7.2 Hz, 2H), 3.30 (ap. sext., *J*= 7.0 Hz, 1H), 2.67-2.51 (m, 2H), 1.32 (d, *J*= 7.0 Hz, 3H), 1.20 (t, *J*= 7.3 Hz, 3H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 145.8, 128.5, 126.8, 126.4, 60.2, 43.0, 36.5, 21.8, 14.2.

4-(4-Hydroxy-3-methoxyphenyl)butan-2-one (Zingerone) (2.46):
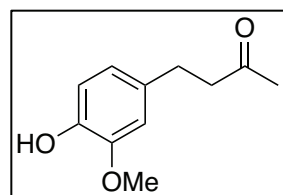
(*E*)-4-(4-Hydroxy-3-methoxyphenyl)but-3-en-2-one (100 mg, 0.66 mmol, 1 equiv.) was dissolved in CH₃CN (1 mL) and stirred.

Pre-catalyst **2.10** (3 mg, 0.013 mmol, 0.02 equiv.) and HB(pin) (0.08 mL, 0.66 mmol, 1 equiv.) were added and stirred for 12 h at room temperature. The work up from the general procedure was performed to afford the product[51] (88 mg, 87%).

¹H NMR (500 MHz, CDCl₃): δ 6.84 (d, J= 8.0 Hz, 1H), 6.71-6.67 (m, 2H), 5.54 (s, 1H), 3.89 (s, 3H), 2.87-2.82 (m, 2H), 2.77-2.72 (m, 2H), 2.15 (s, 3H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 208.2, 146.4, 143.9, 132.9, 120.8, 114.4, 111.1, 55.9, 45.6, 30.1, 29.5.

tert-Butyl-3-(benzylamino)butanoate (2.47):
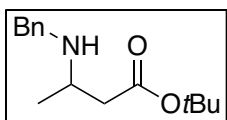
(*Z*)-*tert*-Butyl-3-(benzylamino)but-2-enoate (50 mg, 0.20 mmol, 1 equiv.) was dissolved in CH₃CN (1 mL) and stirred. Pre-catalyst **2.10** (2.9 mg, 0.010 mmol, 0.05 equiv.) and HB(pin) (0.03 mL, 0.20 mmol, 1 equiv.) were added and stirred for 16 h at 50 °C. The work up from the general procedure was performed, using Brockman grade I basic alumina instead of silica for column chromatography to afford the product[52] (0.038 g, 75%).

¹H NMR (500 MHz, CDCl₃): δ 7.36-7.30 (m, 5H), 3.83 (q, J= 12.9, Hz, 2H), 3.16 (ap sext., J= 6.4 Hz, 1H), 2.45 (m, 1H), 2.33 (m, 1H), 1.48 (s, 9H), 1.18 (d, J= 6.4 Hz, 3H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 171.8, 128.4, 128.1, 126.9, 80.5, 51.2, 51.2, 50.0, 42.9, 28.1, 20.4.

(*S*)-4-Benzyl-3-(3-phenylpropanoyl)oxazolidin-2-one (2.48):
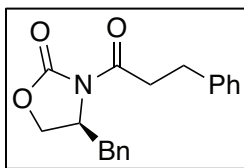
(*4S*)-4-Benzyl-3-[(2*E*)-3-phenylprop-2-enoyl]oxazolidin-2-one (85 mg, 0.28 mmol, 1 equiv.) was dissolved in CH₃CN (1 mL) and stirred. Pre-catalyst **2.10** (4 mg, 0.01 mmol, 0.05 equiv.) and HB(pin) (0.04 mL, 0.28 mmol, 1 equiv.) were added and stirred for 16 h at room

temperature. The work up from the general procedure was performed to afford the product[53] (0.074 g, 87%).

^{1}H NMR (300 MHz, CDCl$_3$): δ 7.31-7.15 (m, 10H), 4.69-4.61 (m, 1H), 4.16-4.14 (m, 2H), 3.38-3.18 (m, 3H), 3.05-2.99 (m, 2H), 2.78-2.71 (dd, *J*= 9.3, 13.2 Hz, 1H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 172.5, 153.5, 140.6, 135.3, 129.5, 129.1, 128.7, 128.6, 127.5, 126.4, 66.3, 55.2, 38.0, 37.2, 30.4.

3,7-Dimethyloct-6-enal (Citronellal) (2.49):
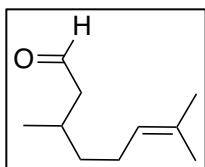
Citral (1:2 mix of *Z* and *E* isomers) (50 mg, 0.33 mmol, 1 equiv.) was dissolved in CH$_3$CN (1 mL) and stirred. Pre-catalyst **2.10** (9.3 mg, 0.033 mmol, 0.1 equiv.) and HB(pin) (0.048 mL, 0.33 mmol, 1 equiv.) were added to the solution and stirred for 12 h at room temperature. The work up from the general procedure was performed to afford the product[54] (41 mg, 81%).

^{1}H NMR (500 MHz, CDCl$_3$): 9.77 (dd, *J*= 2.6, 2.2 Hz, 1H), 5.13-5.08 (m, 1H), 2.43 (ddd, *J*= 16.0, 5.6, 2.1 Hz, 1H), 2.25 (ddd, *J*= 16.0, 7.9, 2.7 Hz, 1H), 2.09-2.0 (m, 2H), 1.71 (s, 3H), 1.62 (s, 3H), 1.42-1.27 (m, 2H), 0.99 (d, *J*= 6.7 Hz, 3H).

(*R*)-2-Isopropylidane-5-methylcyclohexanone (2.50):
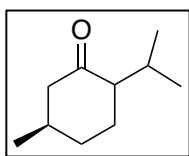
(*R*)-Pulegone (100 mg, 0.066 mmol, 1 equiv.) was dissolved in CH$_3$CN (2 mL) and stirred. To the solution pre-catalyst **2.10** (9.3 mg, 0.033 mmol, 0.05 equiv.) and HB(pin) (0.095 mL, 0.66 mmol, 1 equiv.) were added and stirred for 36 h. No conversion to the product was observed by NMR.

(*R*)-5-Isopropenyl-2-methyl-cyclohexanone (2.51):
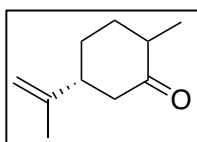
(*R*)-Carvone (100 mg, 0.67 mmol, 1 equiv.) was dissolved in CH$_3$CN (2 mL) and stirred. To the solution pre-catalyst **2.10** (9.4 mg, 0.033

mmol, 0.05 equiv.) and HB(pin) (0.097 mL, 0.67 mmol, 1 equiv.) were added and stirred for 36 h. Minimal conversion to the product was observed by NMR, but was an inseparable mixture.

4-Chloro-benzenepropanenitrile (2.52):
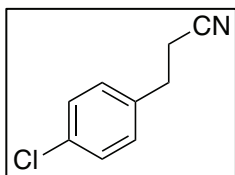
4-Chloro-cinnamonitrile (100 mg, 0.61 mmol, 1 equiv.) was dissolved in CH_3CN (2 mL) and stirred. To the solution pre-catalyst **2.10** (17 mg, 0.061 mmol, 0.1 equiv.) and HB(pin) (0.09 mL, 0.61 mmol, 1 equiv.) were added and stirred for 16 h. Some conversion to the product was observed by NMR, but was an inseparable mixture.

(1*S*, 5*S*)-2-Pinan-4-one (2.53):
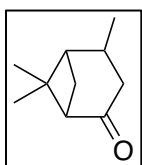
(1*S*,5*S*)-2-Pinen-4-one (50 mg, 0.33 mmol, 1 equiv.) was dissolved in CH_3CN (1 mL) and stirred. To the solution pre-catalyst **2.10** (9 mg, 0.033 mmol, 0.1 equiv.) and HB(pin) (0.048 mL, 0.33 mmol, 1 equiv.) were added and stirred for 36 h. Some conversion to the product was observed by NMR, but was an inseparable mixture.

***Trans*-2-octanal (2.54):**
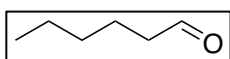
Trans-2-octenal (50 mg, 0.40 mmol, 1 equiv.) was dissolved in CH_3CN (1 mL) and stirred. To the solution pre-catalyst **2.10** (11 g, 0.04 mmol, 0.1 equiv.) and HB(pin) (0.057 mL, 0.40 mmol, 1 equiv.) were added and stirred for 36 h. Some conversion to the product was observed by NMR, but was a volatile, and inseparable mixture.

3-Methyl-2-cyclohexanone (2.55):
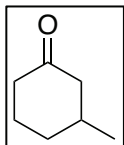
3-Methyl-2-cyclohexenone (50 mg, 0.45 mmol, 1 equiv.) was dissolved in CH$_3$CN (1 mL) and stirred. To the solution pre-catalyst **2.10** (12.8 mg, 0.045 mmol, 0.1 equiv.) and HB(pin) (0.058 mL, 0.45 mmol, 1 equiv.) were added and stirred for 36 h. Some conversion to the product was observed by NMR, but was an inseparable mixture.

1-Phenyl-2-nitroethane (2.56):
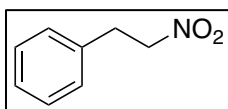
Nitrostyrene (50 mg, 0.34 mmol, 1 equiv.) was dissolved in CH$_3$CN (1 mL) and stirred. To the solution pre-catalyst **2.10** (9 mg, 0.034 mmol, 0.1 equiv.) and HB(pin) (0.05 mL, 0.34 mmol, 1 equiv.) were added and stirred for 16 h. No conversion to the product was observed by NMR.

Ethyl butanoate (2.57):
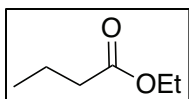
Ethyl crotonate (50 mg, 0.44 mmol, 1 equiv.) was dissolved in CH$_3$CN (1 mL) and stirred. To the solution pre-catalyst **2.10** (12 mg, 0.044 mmol, 0.1 equiv.) and HB(pin) (0.06 mL, 0.44 mmol, 1 equiv.) were added and stirred for 16 h. No conversion to the product was observed by NMR.

3-Methoxybenzenepropanoic acid (2.58):
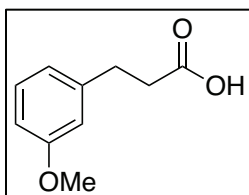
3-Methoxy-cinnamic acid (50 mg, 0.28 mmol, 1 equiv.) was dissolved in CH$_3$CN (1 mL) and stirred. To the solution pre-catalyst **2.10** (8 mg, 0.028 mmol, 1 equiv.) and HB(pin) (0.05 mL, 0.28 mmol, 1 equiv.) were added and stirred for 16 h. Minimal conversion to the product was observed by NMR, and was an inseparable mixture.

3-[(4-Methoxyphenyl)amino]2-butanoic acid methyl ester (2.59):
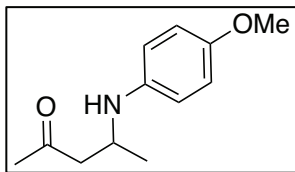
3-[(4-Methoxyphenyl)amino]2-butenoic acid methyl ester (50 mg, 0.23 mmol, 1 equiv.) was dissolved in CH₃CN (1 mL) and stirred. To the solution pre-catalyst **2.10** (6.5 mg, 0.023 mmol, 0.1 equiv.) and HB(pin) (0.033 mL, 0.23 mmol, 1 equiv.) were added and stirred for 48 h. No conversion to the product was observed by NMR.

α-Methyl-benzenepropanal (2.60):
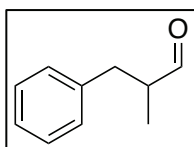
α-Methy-*trans*-cinnamaldehyde (50 mg, 0.34 mmol, 1 equiv.) was dissolved in CH₃CN (1 mL) and stirred. To the solution pre-catalyst **2.10** (9.7 mg, 0.034 mmol, 0.1 equiv.) and HB(pin) (0.05 mL, 0.34 mmol, 1 equiv.) were added and stirred for 16 h. Minimal conversion to the product was observed by NMR, and was an inseparable mixture.

N-Benzyl-2,3-dihydro-1*H*-inden-1amine (2.61):
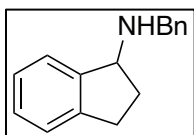
N-[(Indane)ethylidene]benzylamine (50 mg, 0.226 mmol, 1 equiv.) was dissolved in THF (1 mL) and stirred. To the solution 3-chloro-2-(*tert*-butyl)-6,7-dihydro-5*H*-pyrrolo[2,1-c]-1,2,4,3-triazaphospholene (6.6 mg, 0.0226 mmol, 0.1 equiv.) and HB(pin) (0.035 mL, 0.226 mmol, 1 equiv.) were added and stirred for 16 h. The work up from the general procedure was performed to afford the product [28] as a brown oil (43 mg, 85%).

¹H NMR (500 MHz, CDCl₃): δ 7.44-7.23 (m, 10H), 4.33 (t, 1H, *J*= 6.4), 3.98-3.88 (m, 2H), 3.11-3.01 (m, 1H), 2.89-2.81 (m, 1H), 2.48-2.42 (m, 1H), 1.97-1.90 (m, 1H), 1.69 (br. s, 1H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 145.3, 143.7, 140.7, 128.4, 128.2, 127.4, 126.9, 126.3, 124.8, 124.1, 62.8, 51.4, 33.7, 30.4.

_N_-Propargyl-1-indanamine (2.62):
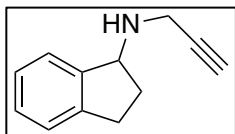
_N_-[Indane]ethylidene]propargylamine (50 mg, 0.295 mmol, 1 equiv.) was dissolved in THF (1 mL) and stirred. To the solution 3-chloro-2-(_tert_-butyl)-6,7-dihydro-5_H_-pyrrolo[2,1-c]-1,2,4,3-triazaphospholene (1.3 mg, 0.0295 mmol, 0.1 equiv.) and HB(pin) (0.043 mL, 0.295 mmol, 1 equiv.) were added and stirred for 16 h. The work up from the general procedure was performed to afford the product[28] as a brown oil (44 mg, 87%).

¹H NMR (500 MHz, CDCl₃): _δ_ 7.38-7.20 (m, 4H), 4.46-4.42 (m, 1H), 3.55-3.54 (m, 2H), 3.12-3.02 (m, 1H), 2.90-2.80 (m, 1H), 2.48-2.37 (m, 1H), 2.28 (t, _J_= 2.4, 1H), 1.94-1.84 (m, 1H), 1.51 (br. s, 1H).

¹³C{¹H} NMR (125 MHz, CDCl₃): _δ_ 144.5, 143.8, 127.6, 126.2, 124.8, 124.2, 82.5, 71.3, 61.9, 36.2, 33.3, 30.5.

_N_-Benzyl-1-(_tert_-butyl)ethylamine (2.63):
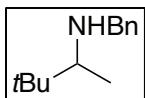
_N_-[(_tert_-Butyl)ethylidene]benzylamine (50 mg, 0.264 mmol, 1 equiv.) was dissolved in THF (1 mL) and stirred. To the solution 3-chloro-2-(_tert_-butyl)-6,7-dihydro-5_H_-pyrrolo[2,1-c]-1,2,4,3-triazaphospholene (5.8 mg, 0.0264 mmol, 0.1 equiv.) and HB(pin) (0.038 mL, 0.264 mmol, 1 equiv.) were added and stirred for 16 h. The work up from the general procedure was performed to afford the product[28] as a yellow oil (33 mg, 65%).

¹H NMR (500 MHz, CDCl₃): _δ_ 7.35-7.21 (m, 5H), 3.94-3.64 (second order dd, 2H), 2.30 (q, _J_= 6.4, 1H), 1.27 (br. s, 1H), 1.02 (d, _J_= 6.4, 3H), 0.89 (s, 9H).

¹³C{¹H} NMR (125 MHz, CDCl₃): _δ_ 141.3, 128.3, 128.2, 126.7, 61.3, 52.7, 34.5, 34.5, 26.5, 14.7.

***N*-Benzyl-1-(4-methoxyphenyl)ethylamine (2.64):**
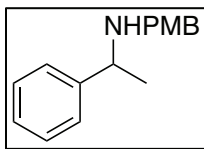
N-[1-(4-Methoxyphenyl)ethylidene]benzylamine (50 mg, 0.209 mmol, 1 equiv.) was dissolved in THF (1 mL) and stirred. To the solution 3-chloro-2-(*tert*-butyl)-6,7-dihydro-5*H*-pyrrolo[2,1-c]-1,2,4,3-triazaphospholene (0.92 mg, 0.0209 mmol, 0.1 equiv.) and HB(pin) (0.030 mL, 0.209 mmol, 1 equiv.) were added and stirred for 16 h. The work up from the general procedure was performed to afford the product[28] as a yellow oil (41 mg, 81%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.31-7.23 (m, 7H), 6.89-6.88 (m, 2H), 6.81 (s, 3H), 3.77 (q, *J*= 6.5 Hz, 1H), 3.54 (ABq, 2H), 1.53 (s, 1H), 1.34 (d, *J*= 6.6 Hz, 3H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 158.6, 140.8, 137.7, 128.4, 128.1, 127.7, 126.8, 113.8, 56.8, 55.3, 51.6, 24.5.

***N*-(1-Phenylethyl)-3,3-diphenylpropylamine (Fendiline) (2.65):**
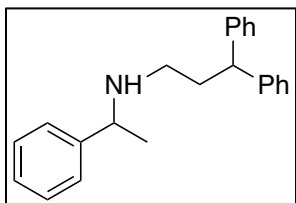
N-(1-Phenylethylidene)diphenylpropylamine (50 mg, 0.159 mmol, 1 equiv.) was dissolved in THF (1 mL) and stirred. To the solution 3-chloro-2-(*tert*-butyl)-6,7-dihydro-5*H*-pyrrolo[2,1-c]-1,2,4,3-triazaphospholene (3.5 mg, 0.0159 mmol, 0.1 equiv.) and HB(pin) (0.023 mL, 0.159 mmol, 1 equiv.) were added and stirred for 16 h. The work up from the general procedure was performed to afford the product[55] as a brown oil (34 mg, 68%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.30-7.16 (m, 15H), 3.99 (t, *J*= 7.7 Hz, 1H), 3.69 (q, *J*= 6.6 Hz, 1H), 2.51-2.42 (m, 2H), 2.27-2.18 (m, 2H), 1.46 (s, 1H), 1.30 (d, *J*= 6.6 Hz, 3H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 144.9, 144.7, 128.4, 128.3, 127.8, 127.7, 126.7, 126.5, 126.1, 58.1, 49.0, 45.9, 36.1, 24.3.

Chapter 3 : Chiral Diazaphospholenes

3.1: Contributions

Dr. Alex Speed is thanked for the preparation of the diimines used in the attempts of compounds **3.36** and **3.38**. Chieh Hung Tien is thanked for the preparation of compounds **3.58**, **3.66-3.68**, and **3.70**. Mass spectrometric data were acquired by Mr. Xiao Feng (Mass Spectrometry Laboratory, Dalhousie University). Elemental analysis data were acquired by Ms. Patricia Granados (Centre for Environmental Analysis and Remediation, Saint Mary's University) on a Perkin Elmer 2400 Series II CHN analyzer. No precautions were taken to protect **3.32** from air during the preparation of the elemental analysis samples. Data acquisition and structural determination of compound **3.32** was conducted by Dr. McDonald (University of Alberta).

3.2: Introduction

Developing methods of preparing enantioenriched amines is of great importance in the synthesis of pharmaceuticals and agrochemicals.[56] While utilizing enzymes to resolve racemic primary amines is well known, for example through the use of *Candida antarctica* lipase B with an acyl source,[57] these methods are not applicable to the resolution and enantioenrichment of secondary amines.[58,59] Much work has been done to develop methods of enantioselective catalysis to produce enantioenriched secondary amines. In that vein, the hydrogenation of imines to form enantioenriched secondary amines mediated by chiral transition metal complexes is a vast field of study.[60,61,62] Although metal-catalyzed asymmetric hydrogenation of imines is well established, the development of alternative methods employing main group catalysts is a field of rapid

growth. Main group catalysts offer the attractive feature of being metal-free, which helps reduce the use of depleting stocks of rare metals, but also allows for the investigation of alternative reactivity patterns when compared to metal based catalysts.[63,64] A subset of main group catalysts, namely frustrated Lewis pairs, have been developed for the enantioselective hydrogenation of imines to afford chiral amines.[65,66,67] Reductants other than hydrogen gas have also been explored in imine reductions. The activation of trichlorosilane by Lewis bases has allowed for the asymmetric reduction of aniline-derived imine substrates.[68,69,70,71] Chiral Brønsted acid-derived catalysts utilize Hantzsch esters or dihydrobenzothiazoles as the source of terminal reductant, with a chiral sulfonic acid catalyst developed by List and co-workers,[72] which has proven effective for the synthesis of enantiopure secondary alkylamines, a process unamenable to lipase enzymes. To our surprise, reports of employing boranes as a source of terminal reductant in the hydroboration of imines are scarce. The Corey-Bakshi-Shibata (CBS) catalyst has been reported to undergo asymmetric imine reductions, although this usually requires stoichiometric amounts of amino alcohol ligand or very electron poor imines to observe high conversion or enantioselectivity unless the substrate is an oxime.[73,74,75,76] More recently, the group of Du reported the asymmetric reduction of aryl imines with ammonia borane as a terminal reductant, employing an adduct of Ellman's chiral sulfonamide and Piers' borane as the catalyst.[77] This work serves as a pioneering example in the highly selective metal-free hydroboration of imines.

Attracted by the efficiency of the diazaphospholene pre-catalyst described in the previous chapters for imine hydroboration, we sought to develop an asymmetric variant by employing chiral primary amines to design chiral pseudo C_2-symmetric

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diazaphospholene pre-catalysts. This work[78] represents the first synthesis of chiral diazaphospholene pre-catalysts, and highlights their application in the hydroboration of imines to afford enantioenriched secondary amine products.

3.3: Results and Discussion

3.3.1: Synthesis of Chiral Primary Amines

Chiral primary amines are the entry point into the synthesis of chiral diazaphospholene pre-catalysts. Some chiral primary amines are commercially available, but the availability of amines with diverse steric and electronic profiles is limited. Modulating the primary amine side group of the diazaphospholene catalyst represents the most facile method of modifying selectivity. Varying the steric and electronic properties of these side chains allows for the modification of the interaction of the diazaphospholene with substrates in the chiral pocket, and therefore may change the extent of chiral induction produced in the reaction. For the aforementioned reasons, accessing a variety of chiral primary amines is critical in this study.

Initially, we explored commercially available amines shown in Figure 3.1. A more exhaustive list of chiral amines was desired, and so the synthesis of chiral amines was targeted to expand the scope of potential chiral catalysts.
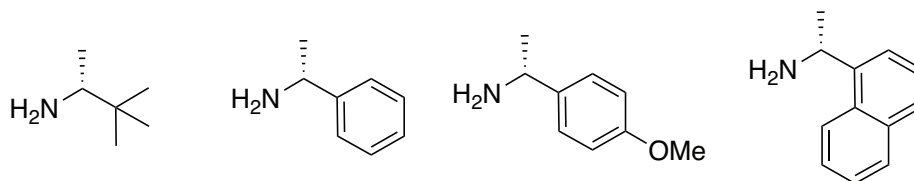
Figure 3.1: Commercially available chiral amines of interest

The available amines shown in Figure 3.1 provide varying steric bulk, which should help differentiate the interaction of substrates within the chiral pocket, to afford varying levels

of enantioselectivity. The commercially available amines (Figure 3.1) fail to vary the bulk of the alkyl group, which hinders a more thorough study of their effects in chiral catalysis. Since chiral diazaphospholene pre-catalysts are novel entities, it is unclear which chiral building blocks would lead to the highest enantiomeric excess in the product of imine hydroboration. For that reason, exploring different chiral building blocks would allow for a more thorough study regarding enantioinduction.

With a subset of commercially available chiral primary amines in hand, I sought to increase the bulk at the alkyl position, vary electronic parameters, as well as introduce a group larger than naphthyl, to study what effects these modifications have on inducing chirality. A facile and functional group tolerant method of synthesizing chiral primary amines, *via* Ellman's auxilliary,[79] was employed (Scheme 3.1). The initial products are diastereomers that were separable by column chromatography, and deprotected to afford the desired chiral primary amines.
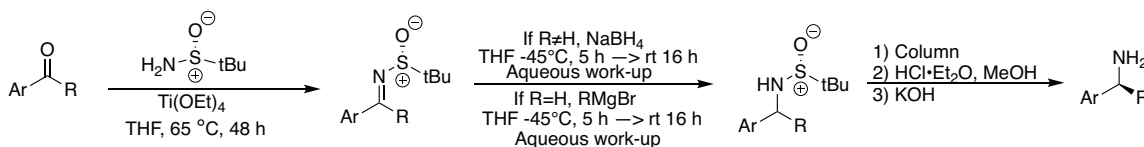
Scheme 3.1: General synthesis of chiral primary amines

Figure 3.2 shows the chiral amines that were synthesized using the Ellman method, with the exception of **3.1,** which was synthesized racemically and resolved with *L*-malic acid.
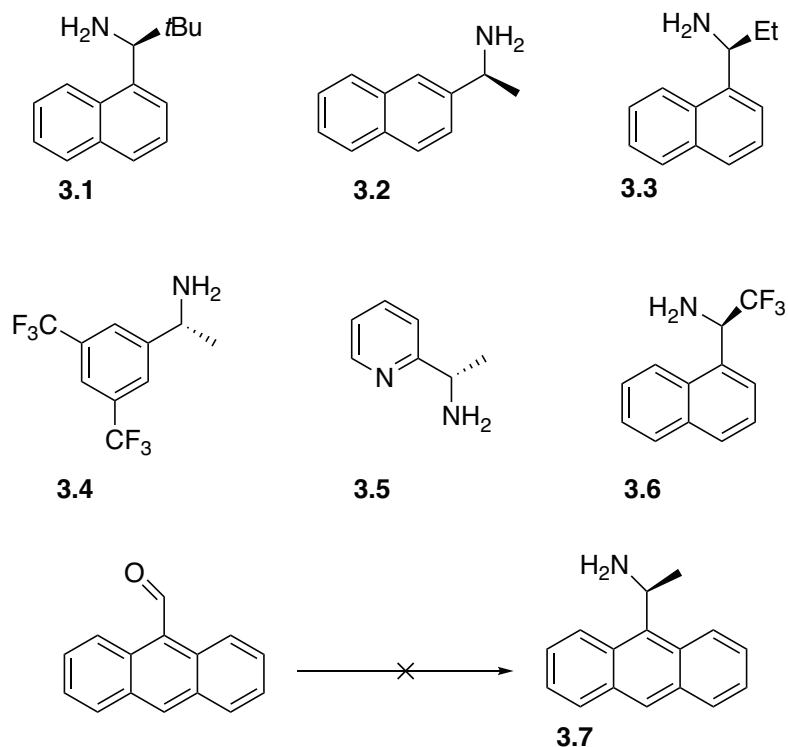
Figure 3.2: Library of synthesized chiral primary amines

Amine **3.1**, which features the 1-naphthyl group while also adding bulk with a *tert*-butyl group in the alkyl position, was made to assess the outcome when both groups are sterically encumbered. Amine **3.2** was synthesized to determine the effect of the position of the naphthyl group, changing it from 1-naphthyl to 2-naphthyl, which moves steric congestion further away from the phosphorus center. Amine **3.3** features the bulky 1-naphthyl group, with an ethyl group of intermediate size between methyl and *tert*-butyl in the alkyl position. When synthesizing amine **3.4**, the goal was to design an amine that would allow for moderate bulkiness, but also study how electron withdrawing CF_3 groups affect enantioinduction. Many ligands for metals feature nitrogen-based chelating groups to form specific sites for reactivity. In the case of diazaphospholenes this could help direct the approach between the imine and catalyst in a controlled manner. For that reason amine **3.5** was synthesized to assess the effects caused by a pyridyl side chain.

Amine **3.6** again features the 1-naphthyl moiety, which we believed would induce high chiral induction based on its steric profile. This amine again modulates what was the methyl group in the commercially available amine in Figure 3.1 by having a bulkier and electron withdrawing CF_3 group at this position. Amine **3.7** was targeted, but could not be synthesized by the Ellman route. It is proposed that due to steric congestion around the anthracene group, the methyl group could not be installed when reacting with a Grignard reagent or MeLi. These products were all purified by column chromatography, and subsequent cleavage of the auxilliary afforded the enantiopure amines (Scheme 3.1).

With a library of 10 enantiopure amines of varying steric and electronic properties to employ in the design of chiral diazaphospholenes, the next step was to synthesize diimines followed by their subsequent conversion to diazaphospholene pre-catalysts.

3.3.2: Synthesis of Chiral Diazaphospholenes

Since their discovery, diazaphospholenes have been synthesized by methods such as cyclizations of diimines with PCl_3 and PBr_3. Only achiral diazaphospholenes have been cyclized from these methods, but it is assumed chiral diimines should behave similarly, and that the work done by Gudat,[9] Kinjo[11] and our group[28] could be applied to this chemistry. In the past years, investigations on the synthesis of diazaphospholenes, and their reactivity have been conducted, showing a variety of methods of synthesis, and the use of diazaphospholenes as catalysts for reduction reactions. There has yet to be an example of chiral diazaphospholene pre-catalysts in the literature. This work represents the first reported synthesis of a library of chiral diazaphospholene pre-catalysts.

The synthesis of diimines from commercial amines as well as amines **3.1-3.6** was the next step in this project. Mixing two equivalents of chiral amine with one equivalent

of glyoxal in DCM, a catalytic amount of formic acid, and Na_2SO_4 afforded the corresponding diimines in high yields (72-94%) (Scheme 3.2).

3.8) Ar= *t*-butyl, R= Me   **3.13**) Ar= 2-naphthyl, R= Me
3.9) Ar= Ph, R= Me   **3.14**) Ar= 1-naphthyl, R= Et
3.10) Ar= 4-OMe(C$_6$H$_4$), R= Me   **3.15**) Ar= 3,5-CF$_3$(C$_6$H$_3$), R= Me
3.11) Ar= 1-naphthyl, R= Me   **3.16**) Ar= 2-pyridyl, R= Me
3.12) Ar= 1-naphthyl, R= *t*-butyl   **3.17**) Ar= 1-naphthyl, R= CF$_3$
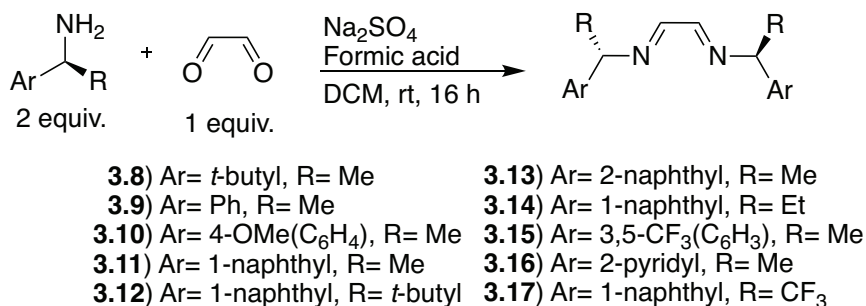
Scheme 3.2: Library of chiral diimines (3.12, 3.13, 3.14, 3.16, and 3.17 are *S*-enantiomers)

By preparing diimines **3.8, 3.9, 3.11,** and **3.13** the role of steric bulk could be assessed by comparing the enantioselectivity afforded when going from *t*Bu, Ph, 1-naphthyl, to 2-naphthyl. In the synthesis of chiral amines Ellman's *tert*-butyl sulfinamide was used to convert aldehydes and ketones to chiral amines. For this reason, it was thought the auxillary itself could be a good candidate to assess as a chiral primary amine for diazaphospholenes, but unfortunately the corresponding diimine could not be synthesized. Diimines **3.10**, **3.15**, and **3.17** bear differing electronic properties that could affect the reactivity and enantioinduction of the diazaphospholenes. It should be noted that diimine **3.16** could not be synthesized by these methods. Finally, compounds **3.12**, **3.14**, and **3.17** will allow for the assessment of enantioinduction when both of the substituent groups are large, as opposed to keeping one of these groups fixed as a smaller methyl group, and varying the bulk of the aryl group.

With chiral diimines in hand, their conversion to chiral diazaphospholenes was explored. Since PBr$_3$ and cyclohexene was the optimal method for work in the previous

chapter,[28] this was the first method assessed for the cyclization of diimines, shown in Scheme 3.3.
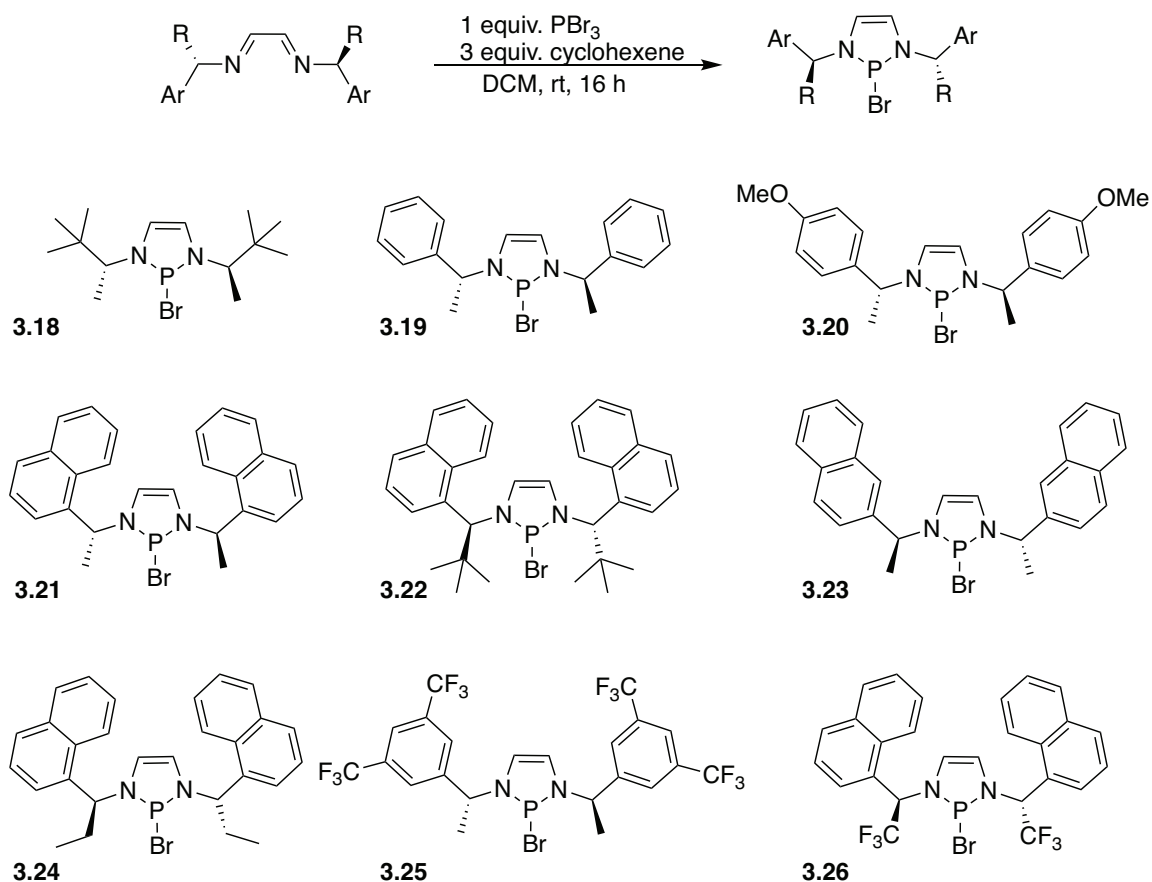
Scheme 3.3: Chiral diazaphospholene bromides

Compounds **3.22**, **3.25**, and **3.26** could not be synthesized using this method, this could be attributed to the sterics of **3.22**, and the electronics of **3.25** and **3.26**. Although this method was successful at cyclizing most diimines to their corresponding diazaphospholene bromides, it failed in cyclizing the most sterically congested diimine, **3.12**, which was of great interest. Cowley reports that reacting PI_3 with diimines forms diazaphospholene cations as triiodide salts.[3] This poses the hurdle of generating a cationic diazaphospholene, which cannot be converted into a pre-catalyst through mixing with triethylamine and neopentyl alcohol or directly engage in catalysis when reacting

with HB(pin) and an imine, as both reactions were attempted. We postulated that a P-I bond would behave similarly to a P-Br bond and undergo pre-catalyst formation to the P-O species when reacted with an alcohol. Diimine **3.12** was cyclized successfully with PI_3 to its corresponding phosphenium triiodide **3.27**. Subjecting **3.27** to LiH in ether afforded the corresponding diazaphospholene iodide **3.28** cleanly (Scheme 3.4).
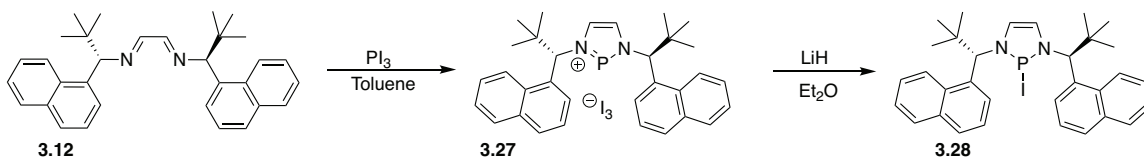
Scheme 3.4: Diazaphospholene iodide synthesis

Since diazaphospholene bromides are able to undergo further conversion to their corresponding pre-catalysts with an alcohol and base, it was proposed that the diazaphospholene iodide would behave comparably. It is postulated that the LiH serves to reduce I_3^-. Attack of a hydride from LiH would form one molecule of HI, one molecule LiI, and one molecule of diazaphospholene iodide. Further reaction of HI with LiH would generate a second equivalent of LiI and one equivalent of H_2, which was observed by the evolution of gas along with the formation of insoluble salts during the reaction. This method was tested with diimines **3.8** and **3.11**, and could also provide their corresponding diazaphospholene iodide species, demonstrating the generality of this method. This shows that triiodide cations can be transformed into diazaphospholene iodides, which can be turned into pre-catalysts by the reaction with an alcohol and base. The cyclization of diimines with PI_3 allowed access to cyclized products that were inaccessible through PBr_3/cyclohexene cyclizations. This method could prove useful in the field of diazaphospholene catalysis to cyclize more challenging diimines, that are inaccessible with current strategies. This is likely the case due to the more reducing nature of PI_3,

compared to PBr$_3$. This method requires only one extra step, but has the added value of accessing alternate catalyst structures.

The chiral diazaphospholene halides were then converted to their corresponding pre-catalysts. Based on my previous work, it was determined that saturated diazaphospholes would not be a good target for this catalysis, as they could not be converted to the active P-H catalyst under the same conditions. Saturated chiral diazaphospholes are more known for their use as ligands, instead of as independent catalytic entities.[80,81] The compounds in Schemes 3.3 and 3.4 were converted to their corresponding pre-catalysts through reaction with neopentyl alcohol and triethylamine (Scheme 3.5), in analogy with work from Chapter 2.
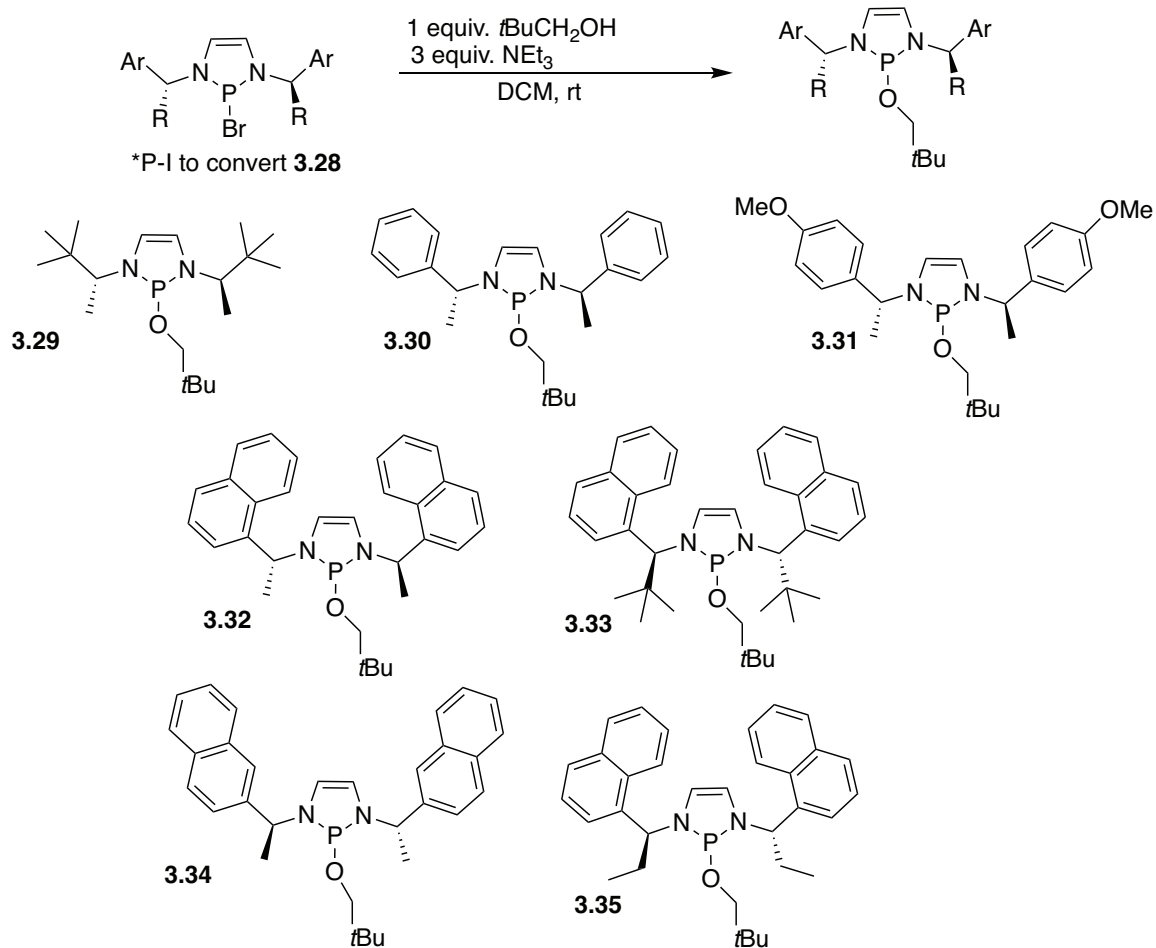
Scheme 3.5: Chiral diazaphospholene pre-catalysts

This novel library of novel pseudo C_2-symmetric diazaphospholene pre-catalysts is the first of its kind in main group synthesis. Compounds **3.29**, **3.30**, **3.32**, and **3.34** allowed the study of different steric profiles in diazaphospholene hydride-delivering reactions and how the afforded enantioselectivity is dependant on catalyst architecture. Compound **3.31** allowed for the assessment of electronic effects when comparing it to the reactivity of **3.30**, which bears a similar steric profile. Compounds **3.32, 3.33,** and **3.35** were useful in assessing the change in enantioinduction when the steric bulk of the alkyl position is systematically increased while keeping the aryl group fixed, in this case 1-naphthyl. Single crystals of pre-catalyst **3.32** were grown, which allowed for the determination of

the structure *via* X-ray analysis. Data acquisition and structural determination was conducted by Dr. McDonald (University of Alberta). As can be seen in Figure 3.3, the 1-naphthyl groups provide large steric bulk, which should allow for a well-defined chiral pocket during catalysis. It should be noted that the conformation of the naphthyl groups likely changes upon the exchange of the neopentoxy group for a hydrogen atom. It is possible that one naphthyl group remains pointing up, while the other naphthyl group rotates down filling the void left by the loss of the neopentoxy group. The crystal structure supports the doubling of peaks observed in the NMR spectrum of **3.32**, as in the X-ray structure (Figure 3.3), the two sides of the catalyst are inequivalent. This catalyst has C_1 symmetry, supporting the observed doubling in NMR.
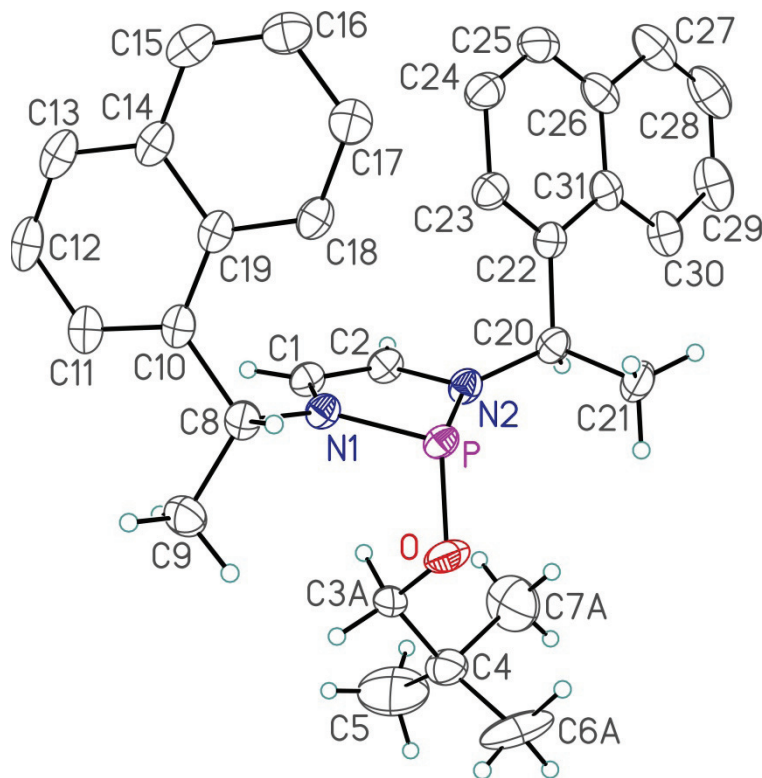
Figure 3.3: X-ray crystal structre of pre-catalyst 3.32

Missing from the list of chiral diazaphospholenes in Scheme 3.5 are pre-catalysts with non-hydrogen substituents in the backbone. Synthesizing molecules of this sort

could reduce rotation about the carbon-nitrogen single bond by imparting steric bulk in the backbone. Based on their precedence as good ligands in metal catalysis, a bisoxazoline ligand was assessed (Scheme 3.6). Not only could this ligand constrain the backbone of the diazaphospholene, but it could allow for the region of steric bulk and chirality to be in a different site relative to the phosphorus center when compared to the diazaphospholenes in Scheme 3.5. However, multiple cyclization methods were attempted but met with no success (Scheme 3.6).
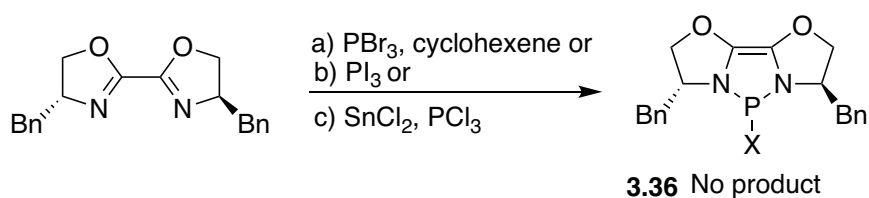
Scheme 3.6: Attempted synthesis of bisoxazoline-derived diazaphospholene

The Macdonald method of cyclization was attempted, but to our disappointment failed to produce the cyclized product **3.36**. Moving forward with the knowledge that PI$_3$ could cyclize more sterically demanding substrates to yield a cationic diazaphospholene, and then subsequent reaction with LiH could afford the P-I compound, this method was attempted. Once again no product was formed from this reaction. Using PCl$_3$ and SnCl$_2$ also led to no cyclized product. It is postulated that the oxygen in the backbone of the diimine hinders the cyclization to the product, being too electron rich to reduce. With the desire to explore substituents in the backbone of the diazaphospholene, an attempt was made to form a diimine from 3-methyl-1,2-cyclopentanone, although with minimal success (Scheme 3.7).

3.37
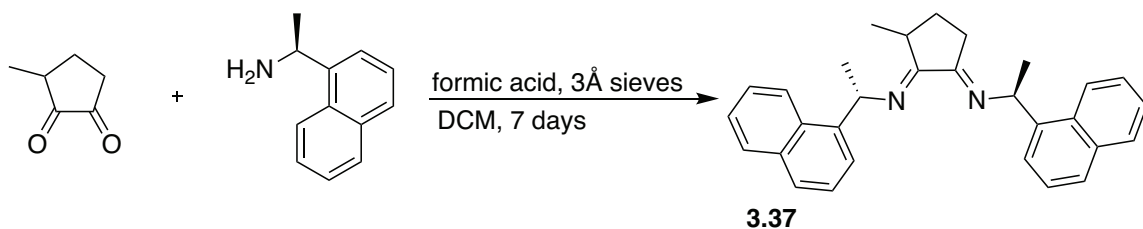
Scheme 3.7: Attempted synthesis of a constrained chiral diimine

So far trying to constrain the backbone of the diazaphospholene has proven unfruitful, although modulating the backbone is an important goal to assess its affects on enantioinduction in hydroboration reactions. Moving to a less substituted backbone scaffolding, using 2,3-dimethylbutanedione would provide less-constraint than the cyclic backbones, but may be possible to synthesize. Since the diimine derived from (*R*)-1-naphthylethylamine was available in our lab, multiple attempts at cyclization were attempted without success (Scheme 3.8).

3.38 No product
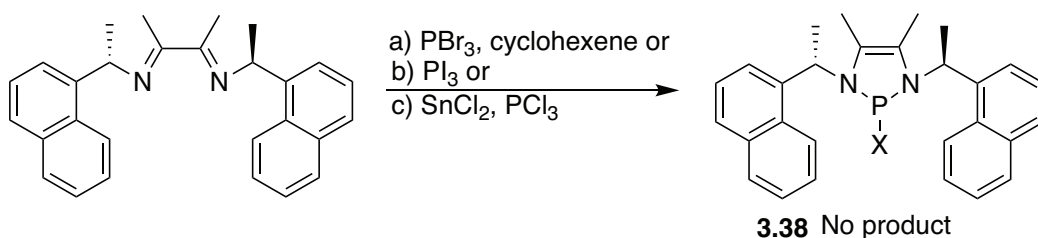
Scheme 3.8: Attempted synthesis of diazaphospholene with methyls in backbone

No current method of cyclization was able to successfully afford diazaphospholene **3.38**. This is still a molecule of interest in our group, since the methyl groups in the backbone could lead to hindered rotation of the naphthyl groups. Furthermore, it could increase the enhanced electron donating properties of methyl groups compared with hydrogens.

All of the diazaphospholene pre-catalysts that were successfully synthesized are pseudo C_2-symmetric. It would be useful to develop a route for the synthesis of non C_2

-symmetric diazaphospholene pre-catalysts to compare their enantioselectivity to C_2-symmetric diazaphospholenes. To synthesize an unsymmetric diimine, one could start from 2,3-butanedione instead of glyoxal. The reason for this is that upon reaction of glyoxal with 1 equivalent of an amine, a mixture of products is formed, as opposed to the desired mono-condensation. When instead using 2,3-butanedione, upon the addition of 1 equivalent of a sterically encumbered primary amine the monocondensation occurs, and then upon the addition of a second primary amine an unsymmetric diimine is afforded.[82] There is literature precedent that using lithium metal and PCl_3 is a viable method for cyclizing diimines with methyls substituting the backbone.[82] An attempt to form a non C_2-symmetric diazaphospholene is shown in Scheme 3.9.
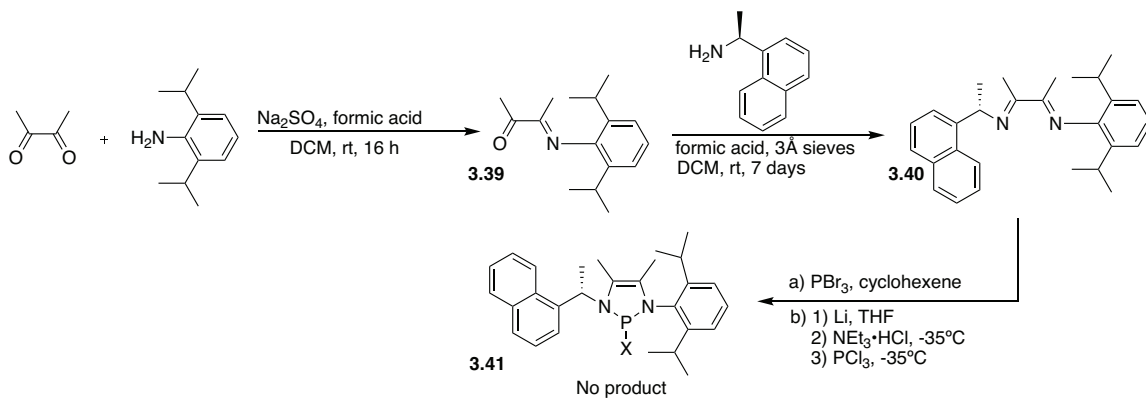
Scheme 3.9: Synthetic route to non C_2-symmetric diazaphospholene

The synthesis of compounds **3.39** and **3.40** was straightforward, although suffered from long reaction times. Although Gudat and coworkers[82] were able to show the cyclization of a diimine featuring *N*-cyclohexyl and *N'*-diisopropylaniline with lithium and PCl_3, the cyclization of **3.40** did not occur through this method, potentially due to its steric bulk.

While attempts at including substituents in the backbone of chiral 1,3,2-diazaphospholenes or forming non C_2-symmetric 1,3,2-diazaphospholenes were unsuccessful, the modularity of 1,2,4,3-triazaphospholenes[30] led to ideas in the design of

diazaphospholenes. Since 1,2,4,3-triazaphospholenes can be readily cyclized and have more points of modularity, perhaps it would be possible to synthesize 1,4,2-diazaphospholenes to impart more rigidity in the structure and afford differing levels of enantioselectivity. The synthetic route for the synthesis of a 1,4,2-diazaphospholene is shown in Scheme 3.10.
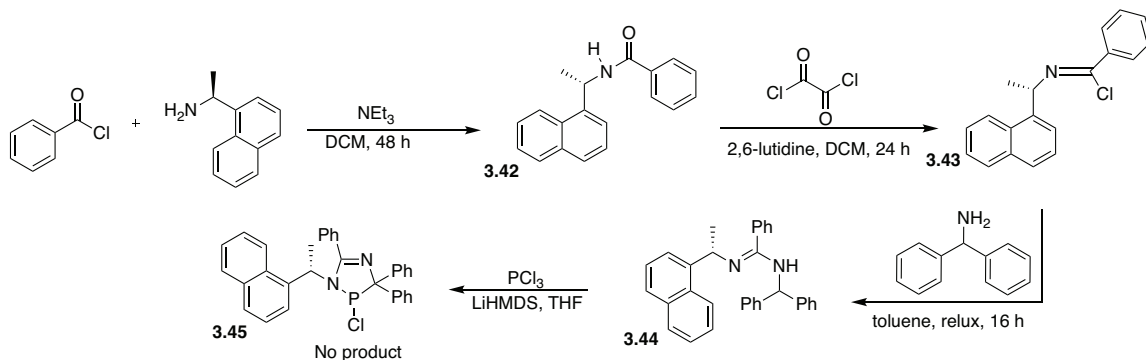
Scheme 3.10: Attempted synthesis of a 1,4,2-diazaphospholene

The synthesis of compounds **3.42** and **3.43** was straightforward, which afforded pure products. The reaction leading to product **3.44** took place with minimal impurities, allowing for an attempted cyclization to compound **3.45**. This critical step in closing the ring has a few potential issues. First of all, the proposed product is very sterically hindered, which could allow for difficulties in cyclizing. One might imagine a single addition of PCl₃ on to the nitrogen of the naphthylethylamine, instead of a ring closure. The second major issue with this synthesis is that both 1,3,2-diazaphospholenes and 1,2,4,3-triazaphospholenes feature a N-P-N fragment, whereas this molecule would bear a N-P-C arrangement, similar to CAAC carbenes that are known to be challenging synthetic targets. To do this, the selective deprotonation of the proton between the two phenyl rings must occur, and then this anion must be stable enough to close the ring,

bonding to phosphorus. For the aforementioned reasons, the synthesis of **3.45** was not successful.

Although the syntheses of alternative diazaphospholene pre-catalysts are still of great interest to our group, with a library of chiral diazaphospholene pre-catalysts in hand we moved our efforts to studying their reactivity. The reaction of interest was the chiral hydroboration of imines. This would be the first reported case of chiral diazaphospholenes and their reactivity, as well as add to the sparse literature of methods of generating chiral secondary amines through metal free techniques.

3.3.3: Imine Hydroborations Mediated by Chiral Diazaphospholenes

The chiral hydroboration of imines would be a facile route for synthesizing optically pure secondary amines, which are products of great value to the pharmaceutical industry. Hydroborations are synthetically accessible means of doing reductive chemistry, as opposed to using high pressure vessels filled with H_2. Since our first report of using diazaphospholenes in the hydroboration of imines,[28] we sought to render this system chiral, in order to afford enantioenriched amines. Few main group methods are able to achieve high stereoselectivity, compared to the well-developed field of metal catalysis. Even fewer systems employ readily available sources of borane as a terminal reductant in the reaction. For this reason, using a novel chiral diazaphospholene as the pre-catalyst, and a borane such as HB(pin) as the reductant is a highly attractive transformation, not only due to the products afforded but the ideas that shall be created by adding to the field of main group chemistry. We sought to evaluate the catalysts on their ability to impart selectivity. The imine precursor to the therapeutic Rasagiline was employed as the test substrate since the alkyne in this substrate may present a selectivity

challenge for many transition metal catalysts. A comparison of enantioinduction afforded

in the hydroboration of imines between pre-catalysts **3.29-3.35** is shown in Table 3.1.

Table 3.1: Catalyst screening for asymmetric induction
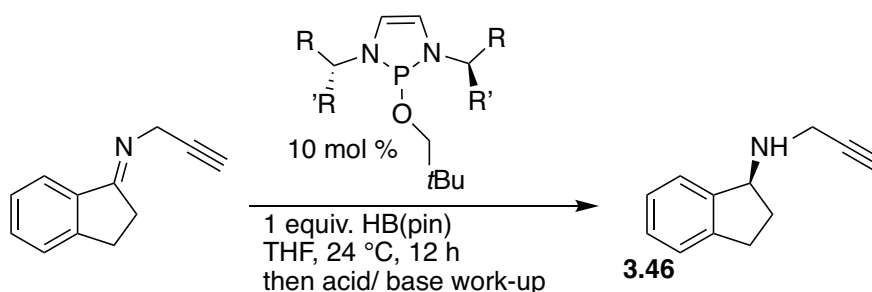
Entry	Catalyst	R	R'	e. r.	e. e.
1	**3.29**	t-Butyl	Methyl	60:40	20
2	**3.30**	Phenyl	Methyl	72:28	44
3	**3.31**	4-OMe-C$_6$H$_4$	Methyl	62:38	24
4	**3.32**	1-Naphthyl	Methyl	85:15	70
5	**3.33**	t-Butyl	1-Naphthyl	29:71	42
6	**3.34**	Methyl	2-Naphthyl	65:35	30
7	**3.35**	Ethyl	1-Naphthyl	29:71	42

An initial reaction with pre-catalyst **3.29** showed a predominantly (*S*)-amine determined

by the sign of the optical rotation, in 60:40 e. r. When increasing the steric bulk at R, the

e. r. increases, going from a 72:28 e. r. for **3.30**, and a 85:15 e. r. for **3.32**. This trend

demonstrates as the group at R increases in size, while keeping R' fixed, the e. r.

increases. An electron rich pre-catalyst **3.31** provided an inferior e.r. of 62:38, compared

to catalyst **3.30**, indicating a potential effect caused by the electronic properties of

substituents. As the R' group increases in size while R is fixed at 1-naphthyl, a decrease

in e. r. is observed. Pre-catalyst **3.32** produced an e. r. of 85:15, going to pre-catalyst **3.35**

the e. r. decreased to 71:29, and then 29:71 moving to pre-catalyst **3.33**. Finally, the

position of the naphthyl group is important to the stereoselection of the product. When

the diazaphospholene has a 1-naphthyl group, pre-catalyst **3.32**, the e. r. is 85:15. When

the position of the naphthyl is moved from 1-naphthyl to 2-naphthyl, pre-catalyst **3.34**,

the e. r. drops to just 65: 35. Overall, the catalyst screen determined that pre-catalyst **3.32** was the most stereoselective and should be applied to the hydroboration reaction to assess its abilities over a variety of different imines. From the catalyst optimization studies it was found that it is best to have sterically differentiated sites, namely one large group and one small group on the amine based side chain. It should also be noted that this system has afforded the best in class method for synthesizing Rasagiline, with the higest e. r. to date from a catalytic reduction of this substrate.[83]

Before applying **3.32** for the reduction of a number of imines to produce a substrate scope for this catalyst, a solvent screen was carried out to determine the effects of solvent on this catalysis (Table 3.2).

Table 3.2: Solvent screen
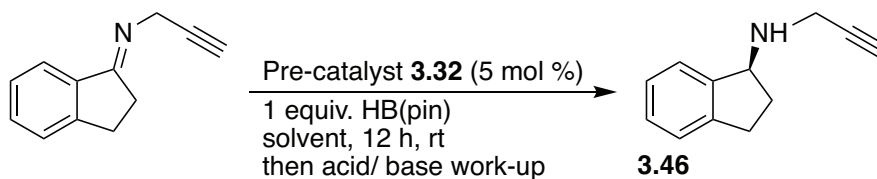
Solvent	Enantiomeric Ratio	NMR Conversion (%)
THF	85:15	>99
CH$_3$CN	62:38	>99
MTBE	73:27	>99
Pentane	50:50	>99
CPME	80:20	>99
Isopropanol	n.d.	38
EtOAc	55:45	67
Toluene	76:24	>99
TFT	66:44	40
DCM	73:27	63
Dioxane	80:20	>99
THF -35 °C	83:17	>99
Ether	85:15	>90

Upon conducting the solvent screen, it was observed that THF is the best solvent to use in the hydroboration of imines using diazaphospholene pre-catalysts. Although ether afforded a similar e. r. when compared to THF, solubility and conversion was inferior. As demonstrated in Table 3.2, the choice of solvent has a great effect on imparting selectivity, as pentane afforded a racemic mixture, where as THF yielded a highly selective reaction for the *S*-enantiomer of the product. The opposite enantiomer of the catalyst is available from the *S*-enantiomer of the amine, which would allow for the synthesis of the *R*-enantiomer of the product if desired. Temperature is known to affect the selectivity of some chiral catalysts,[23] but this was not observed for catalyst **3.32**, as no increase in selectivity was afforded upon cooling the reaction. To ensure that HB(pin) was again transforming the pre-catalyst into the active diazaphosholene catalyst, pre-catalyst **3.32** was reacted with HB(pin) to observe the formation of a doublet in the ^{31}P NMR spectrum at δ 67.3 ppm, representing the formation of the active catalyst (Scheme 3.11).
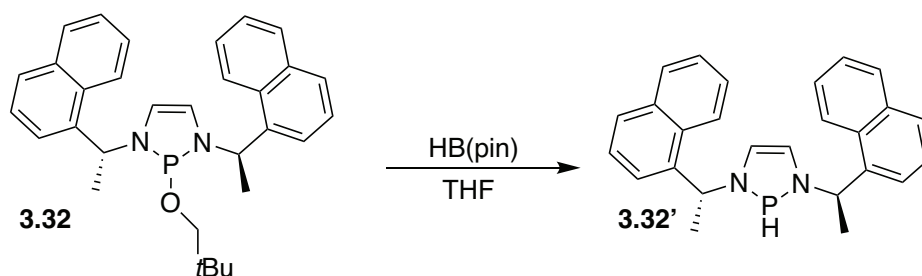
Scheme 3.11: Activation of diazaphospholene catalyst

Finally, another source of terminal reductant was assessed, namely a Hantzsch ester. This reaction gave no conversion to the product and was not further investigated.

A predictive model for induction based on the stereochemical outcome was developed (Figure 3.4). A four-quadrant model was generated such that when the catalyst

is in a conformation where the H substituents on the stereogenic centers point toward the phosphorus, a substrate would approach in a controlled fashion. The approach of the substrate occurs such that the interactions between substituents of the imine and the large aryl groups of the catalyst are minimized. That is to say that two quadrants of the model are empty, and the bulky groups of the incoming substrate may enter here, where as two quadrants are filled by the naphthyl groups of the catalyst precluding the approach of the substrate in these quadrants. This minimization of steric interactions allows for an increased control of stereoselectivity. This model explains the observations for pre-catalyst **3.33**, because adding a *t*-butyl group would fill the void, and diminish the selective interaction with the substrate, pushing the substrate further away from the chiral pocket allowing alternate substrate orientations, diminishing the e. r.
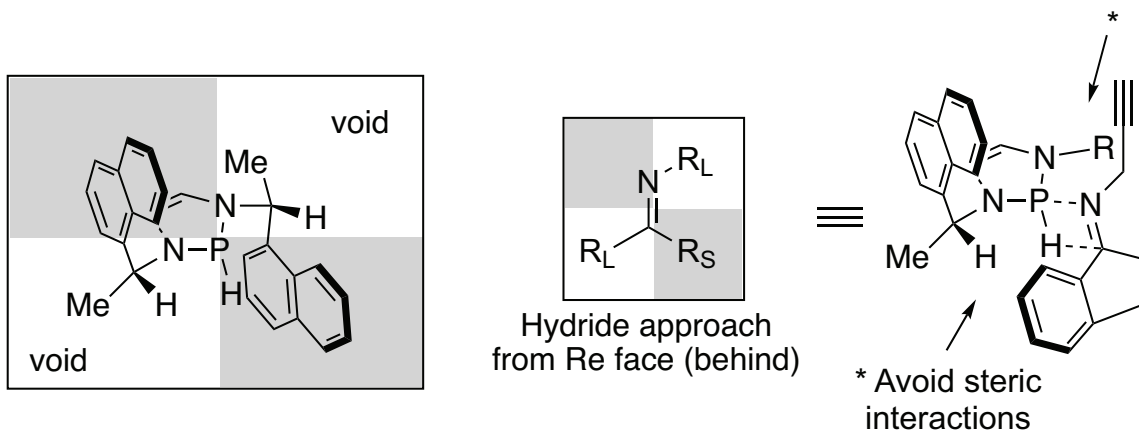
Figure 3.4: Quadrant model for asymmetric induction

A series of enantioenriched amines were afforded through the hydroboration of their corresponding imines (Scheme 3.12). The screening of various imine substrates in the hydroboration reaction was done with pre-catalyst **3.32**, at a loading of 2 mol % in THF with 1 equivalent of HB(pin) for 16 h. All reactions generally afforded high yields and e. r.'s, with all the products having the *S*-configuration.

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Scheme for asymmetric imine hydroboration:

2 mol %
3.32
1 equiv. HB(pin), THF, 16 h, 25 °C
acid/base work-up
alumina chromatography

3.46 84% 85:15

3.47 75% 83:17

3.48 90% 85:14

3.49 66% 82:18

3.50 77% 87:12

3.51 87% 88:12

3.52 68% 84:16

3.53 62% 73:27

3.54 70% 80:20

3.55 84% 84:16

3.56 89% 71:29

3.57 56% 55:45

3.58 83% 67:33

3.59 83% 69:31

3.60 86% 73:27

3.61 79% 84:16

3.62 70% 75:25

3.63 60% 87:13

3.64 70% 84:16

3.65 95% 86:14

3.66 25% 62:38

3.67 10% 56:44

3.68 71% 69:31

3.69 80% 82:18

3.70 46% 66:34

3.71 76% 81:19

3.72 80% 79:21

Scheme 3.12: Substrate scope of asymmetric imine hydroboration. Percentages indicate isolated yield, where ratios indicate the e.r. of the product.

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The hydroboration of 27 imines with pre-catalyst **3.32** was done in part with my co-worker Chieh Hung Tien. Further investigation of imines with propargyl groups was conducted, as this is a functional group that poses some selectivity issues to some metal catalysts. Compounds **3.46**, **3.55**, and **3.56** all bear the propargyl moiety; these products were all formed cleanly in high yields with high levels of stereoselectivity. The addition of electron-withdrawing groups showed a decrease in enantioinduction, as was the case for **3.49**, **3.54**, **3.56**, and **3.69** where cyano and chloro groups reduce the induction observed when compared to their analogues lacking these groups. Amine **3.52** with the 2-naphthyl moieties was afforded in higher selectivity than amine **3.53**, which bears a 1-naphthyl group. This is consistent with the proposed quadrant model of enantioinduction that by having two quadrants completely filled and two quadrants vacant for substrates to approach would afford the highest induction. Substrates with *p*-OMe groups afforded products with high stereoselectivity, as is the case for **3.50** and **3.51**. When substituting the imine with a PMB group enantioselection was again increased, example **3.51** demonstrates the highest enantioinduction achieved in this project with an e. r. of 88:12, an example of some of the highest enantioselectivity in metal-free catalysis. It was found that modifying R_2 from methyl to other groups was detrimental to the induction as was the case for example **3.57**, where the e. r. is 55:45, the lowest induction achieved in this project. This finding further supports the quadrant model of enantioinduction, as the isopropyl group would clash with the bulky 1-naphthyl group of the catalyst. Examples with *ortho*-Cl groups yielded modest e.r.'s, 80:20 for **3.54**, 82:18 for **3.69**. Amine product **3.59** features an *N*-cyclopropyl group, which afforded an e. r. of 69:31. This is a reduction in selectivity compared to amine **3.50** that bears a larger *N*-benzyl group. As

the group attached to nitrogen decreases in size, the selectivity of the diazaphospholene catalyst is reduced, and as this group increases in size, the selectivity also increases. This trend is continued by observing example **3.70** that bears an *N*-methyl group, the smallest example explored, this afforded a reduced e. r. of 66:34. Examples featuring heteroatoms were also tolerated in this catalysis. Modest to good inductions of 69:31, 73:27, and 84:16 were afforded for examples **3.68**, **3.60**, and **3.61**, respectively. Comparing **3.68** and **3.61**, we see that the position of the furyl ring is important in the degree of enantioselectivity achieved, as when it is directly attached to nitrogen, a higher level of selectivity is afforded. Aniline derived products **3.66** and **3.67** both suffered from reduced yields and selectivity, and for these reason scaffolds of this sort were not extensively explored. Metal containing amines could be synthesized though these methods, such as example **3.62**, with modest induction. Examples of this class would be useful in the design of new ligands, as Fe based Josiphos ligands are privileged and commonly used in metal catalysis.[84] By methylating the amine in **3.62**, facile routes to new scaffolds and substitution patterns could arise. A comparison of **3.71** and **3.72** showed that by increasing the steric bulk at the *N*-position too much resulted in a decline in enantiomeric excess, 81:19, 79:21 respectively. This mode of metal-free catalysis afforded the drug Rasagiline **3.46**, a therapeutic for Parkinson's disease, and the drug Fendiline **3.65**, a calcium channel blocker. Upon searching the literature, it is to the best of my knowledge that using chiral diazaphospholene catalysis affords the highest e. r. known for synthesizing Rasagiline.

3.4: Conclusions and Future Work

In conclusion, a variety of optically pure primary amines were synthesized, and their diastereomeric purity was monitored by NMR spectroscopy before they were converted to their corresponding free bases. These amines were employed to develop a library of diazaphospholene pre-catalysts. With many chiral amines in hand, a number of diazaphospholene pre-catalysts were synthesized by cyclization of their corresponding diimines, and subsequent reaction with neopentyl alcohol. A new method of diazaphospholene halide synthesis from diazaphospholene triiodides, employing LiH was developed. This new mode of diazaphospholene synthesis could prove useful in further explorations of these catalysts, especially when accessing diazaphospholenes with diverse sterics and electronic properties

A large number of asymmetric diazaphospholene-catalyzed imine hydroborations was achieved at low catalytic loadings, in good yields, and high (for current main group catalysts) enantiomeric ratios. A pre-catalyst and solvent screen was conducted to afford the optimal conditions for these reductions. A predictive model of induction was provided to explain the observed trends in catalyst selectivity, as well as amount of induction achieved. This model will allow for the design of new catalysts for the assessment of new reactivity.

This work represents the development of the first class of chiral diazaphospholenes and their application in synthesizing secondary amines in high enantiomeric ratios. Due to the novelty of the system, adding to a growing field of main group catalysis, and discovering a good method for inducing chirality in secondary amines, this work was published in *Angewandte Chemie International Edition* in 2017.[78]

Future work in the field of chiral diazaphospholene catalysis includes the development of non C_2-symmetric catalyst variants. By exploring these catalyst scaffolds there should be opportunities to achieve higher levels of enantioinduction as well as increasing selectivity for other classes of substrates. Exploring 1,4-conjugate reductions mediated by asymmetric diazaphospholenes would be of interest as the products would be of value in pharmaceuticals and synthesis. Further extending conjugate reductions to α,β-unsaturated imines would be useful to explore the selectivity between the double bond and the imine, as diazaphospholenes have been proven to undergo very selective reactivity.[28,78]

3.5: Experimental Section

3.5.1: General Considerations

Synthesis of diazaphospholene derivatives was carried out in a fumehood using oven dried Schlenk glassware under nitrogen. Filtration and crystallization of diazaphospholene derivatives were conducted in a 2001 issue IT Glovebox (O_2 levels typically 4 ppm, H_2O levels typically 5 ppm). Reduction reactions were carried out in 4 dram oven dried scintillation vials equipped with magnetic stir bars and green Qorpak® PTFE lined caps. Substrates, reagents and solvents were loaded into vials inside the IT Glovebox. Reactions at ambient temperature were stirred within the glovebox. ^{1}H, ^{13}C, ^{19}F, and ^{31}P NMR data were collected at 300K on a Bruker AV-500 NMR spectrometer. Standard NMR tubes and caps were used. Caps on sensitive samples were overwrapped with PTFE tape. Chemical shifts are reported in parts per million from phosphoric acid (for ^{31}P NMR). ^{1}H NMR spectra are referenced to residual non-deuterated NMR solvent

(CHCl$_3$ =7.26 ppm, CH$_3$CN = 1.94 ppm). ^{13}C NMR spectra are referenced to the central CDCl$_3$ peak (77.0 ppm) and CD$_3$CN methyl peak (1.32 ppm).

Solvents

Acetonitrile, trifluorotoluene, and dioxane was purchased from VWR in 1L EMD Drisolv® bottles. This bottle was taken into the glovebox, and activated 3 Å molecular sieves were added. Isopropanol, and ethylacetate were purchased in drums from chemstores, and stored over activated 3 Å molecular sieves for 3 d.

Toluene and pentane were deoxygenated and dried by sparging with dinitrogen gas, followed by passage through a double-column solvent purification system purchased from mBraun Inc. The solvents were stored in the glovebox and activated 3 Å molecular sieves were added. Diethyl ether, methyl *tert*-butyl ether, cyclopentyl methyl ether, and tetrahydrofuran were purchased from Fisher and was distilled from a purple solution of benzophenone/sodium ketyl, and stored in the glovebox over activated 3 Å molecular sieves were added. Dichloromethane (ACS grade) was purchased from Fisher and distilled from calcium hydride immediately before use.

Deuterochloroform, and deuteroacetonitrile (Cambridge Isotopes) were stored over activated 3 Å molecular sieves, but otherwise used as received.

Reagents

3 Å Molecular sieves were purchased from Aldrich, and dried at 200 °C at 0.5 torr for 36 hours prior to use. Basic alumina was Brockman Grade I alumina purchased from Aldrich and used as received. Neopentyl alcohol was purchased from Aldrich and used as received. Titanium ethoxide was purchased as Technical Grade from Aldrich, and used as received. Triethylamine was purchased from Aldrich in a Sureseal bottle, and used as

received. Pinacolborane was purchased from Oakwood Chemical, stored at ambient temperature in the glovebox, and used as received. Phosphorus[III] halides were purchased as the 99% purity grade from Aldrich in sureseal bottles and used as received.

Chiral amines were purchased from Oakwood chemicals and Aldrich and were used as received, or were made in house.

Synthesis of Reduction Substrates:

Imines: All ketones and amines employed in imine preparation were purchased from Aldrich, and were used as received after purity was verified by ^{1}H NMR.

Imines were prepared by a 1:1 combination of the appropriate ketone and amine in dichloromethane, in the presence of 1 equivalent of titanium ethoxide for 92 hours. The reactions were quenched by addition of aqueous KOH (15 %), filtered onto Na_2SO_4, extracted with dichloromethane, refiltered and concentrated. Purification of solid imines was accomplished by taking up the obtained solids in warm pentane, and cooling the resulting clear pentane solutions of the imine to -15 °C. The resulting crystals were collected in air by suction filtration and were dried for 12 hours in a vacuum dessicator at approximately 30 torr over P_2O_5 before being brought into the glovebox. Liquid imines were distilled before use. Yields of imines were typically > 60% by this method. Diimines were prepared by a 1: 2 combination of glyoxal solution (40% w.t) and appropriate amine in dichloromethane, in the presence of 0.01 equivalent of formic acid and 4 equivalents of Na_2SO_4 for 16 hours. The Na_2SO_4 was filtered out and the solvent was removed in vacuo. Solid diimines were recrystallized from methanol if needed, liquid diimines were used without further purification. Yields of diimines were usually > 85% by this method.

General Reduction Procedure:

The appropriate imine and 2-neopentoxy-1,3-*bis*{(*R*)1-(naphthalen-1-yl)ethyl}-1,3,2-diazaphosphole (**3.32**) (0.02 equiv.) were mixed in THF and HB(pin) (1 equiv.) was added. The reactions were stirred in the glovebox for 16 hours. The solvent was removed in *vacuo* and crude NMRs were taken to assess the conversions. Complete consumption of imine was usually observed, unless otherwise stated. Concentrated sulfuric acid was carefully added to a solution of the crude reaction mixture in diethyl ether, the resulting mixture was carefully poured into water, and washed with ether. The aqueous layer was treated with aqueous 2M KOH, and extracted 3x with ether, then the filtrate was concentrated. The product was further purified by column chromatography on basic alumina (Brockman Grade I), first with 10% ether in hexanes to remove the least polar impurity, and then 100% ether to flush the product from the column. The amine product fractions were concentrated and stored under N_2. HPLC traces of racemates were obtained by first reducing imines with 4 equiv. $NaBH_4$ in MeOH (3 mL), followed by dilution with DCM and washing with aqueous 2M KOH, the organic phase was then concentrated to afford the racemic products. NMR spectra of Boc protected amines were obtained in CD_3CN at 65 °C on a Bruker AV-500MHz NMR. HPLC data was acquired on a Varian Prostar instrument, equipped with detection at 254 nm, using either Astec Cellulose DMP, or Chiralpak ADH columns. A 99:1 hexanes/isopropanol solvent mixture was used as the eluent, with a flow rate of 0.5 mL/min unless otherwise stated. Optical rotations were obtained using a DigiPol 781 Automatic Polarimeter from Rudolph Instruments.

Crystallographic Solution and Refinement Details

Crystallographic data for **3.32** was obtained at -100 °C on a Bruker D8/Apex II CCD diffractometer using microfocus source Cu Kα (λ=1.54178 Å) radiation, employing a sample that was mounted in inert oil and transferred to a cold gas stream on the diffractometer. Programs for diffractomer operation, data collection, data reduction and absorption correction were supplied by Bruker. Gaussian integration (face-indexed) was employed as the absorption correction method for **3.32**. The structure of **3.32** was solved by use of direct methods, and was refined by use of full-matrix least-squares procedures (on F^2) with a R_1 of (0.0417) based on $F_o^2 \geq 2\sigma(F_o^2)$.

The data has been deposited with the Cambridge Crystallographic Data Centre under deposition number CCDC 1576100

3.5.2: Synthesis and Characterization

(S)-1-(1-Naphthyl)-(2,2-dimethyl)propylamine (3.1):

The following is an adaptation of a literature proceudure.[85]
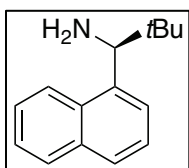
1-Naphthonitrile (15.0 g, 97.9 mmol 1 equiv.) was dissolved in ether (20 mL) and stirred under N_2. The reaction was cooled to 0°C. To the solution, *t*BuMgCl in THF (51.45 mL 2M, 102.8 mmol, 1.05 equiv.) was slowly added, followed by the addition of CuBr-SMe$_2$ (0.56 g, 2.74 mmol, 0.028 equiv.). The solution was heated to reflux for 24 h. Heating was removed and the solution was cooled to room temperature, and then to -78°C, where MeOH (75 mL) followed by NaBH$_4$ (4.8g, 127.3 mmol, 1.3 equiv.) were added and stirred for 2 h. The mixture was allowed to warm to room temperature and stirred for 16 h. Water (50 mL) is slowly added to the green solution, and a precipitate formed which was removed by suction filtration. The solvent was removed from the solution *in vacuo*, and the product was purified by

distillation to a clear liquid. The liquid was suspended in ether and 1M HCl (5 mL), followed by the addition of aqueous 1M NaOH (10 mL). The organic phase was collected and the solvent was removed *in vacuo* to afford the product as the racemic amine (18.5 g, 89%). The racemic amine (25.1 g, 117.8 mmol, 1 equiv.) was dissolved in isopropanol (675 mL) and EtOAc (90 mL) and then L-malic acid (15.8 g, 117.8 mmol 1 equiv.) was added and stirred. The mixture was heated to reflux to dissolve the contents of the mixture. Upon cooling to room temperature the solution was left on the bench for 24 h, and then in the freezer for 24 h. This recrystallization afforded white crystals which were collected by suction filtration, and washed with isopropanol. These crystals were once again recrystallized by the above procedure. To afford the free-base, the crystals were dissolved in excess 2M KOH (20 mL) and shaken, and then extracted with ether. The ether was removed *in vacuo* to afford the chiral primary amine[85] (10.0 g, 40%, one enantiomer).

¹H NMR (500 MHz, CDCl₃): δ 8.26-8.24 (m, 1H), 7.90-7.88 (m, 1H), 7.80-7.79 (m, 1H), 7.75-7.73 (m, 1H), 7.55-7.48 (m, 3H), 4.84 (s, 1H), 1.56 (s, 2H), 1.02 (s, 9H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 140.7, 133.5, 132.4, 128.9, 127.2, 125.4, 125.1, 125.0, 125.0, 123.8, 57.3, 36.4, 26.9.

HRMS (APCI): 214.1594, $[C_{15}H_{20}N_1]^+$ requires 214.1590.

(*S*)-1-(2-Naphthyl)ethylamine (3.2):
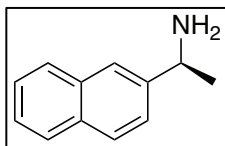
β-Naphthaldehyde (2.82 g, 18.06 mmol, 1.1 equiv.) was dissolved in THF (50 mL) and stirred. To the solution was added (*S*)-*t*-Bu-sulfinamide (1.99 g, 16.4 mmol, 1 equiv.) and Ti(OEt)₄ (6.88 mL, 32.8 mmol, 2 equiv.). The solution was left to stir at room temperature for 14 h. To the

solution was added brine (50 mL) to remove the titanium, this was filtered over a pad of celite. The resulting solution was washed with EtOAc, and dried with Na_2SO_4, the solvent was removed *in vacuo* to afford the imine (3.8 g, 81%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 8.79 (s, 1H), 8.25 (s, 1H), 8.09-8.07 (m, 1H), 8.00-7.98 (m, 1H), 7.95-7.91 (m, 2H), 7.64-7.59 (m, 2H), 1.34 (s, 9H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 162.7, 135.4, 133.0, 132.4, 131.8, 129.2, 128.9, 128.2, 127.9, 126.9, 123.8, 57.9, 53.4, 22.7.

HRMS (ESI): 282.0921, $[C_{15}H_{17}N_1Na_1O_1S_1]^+$ requires 282.0923.

The above imine (3.8 g, 14.65 mmol, 1 equiv.) was dissolved in DCM (100 mL) and stirred under N_2. The reaction was cooled to -78°C and 3M MeMgBr in ether (9.77 mL, 29.3 mmol, 2 equiv.) was added and stirred for 4 h. The reaction was left to warm to room temperature and stirred for 16 h. To the solution sat. NH_4Cl (10 mL) was added, and the product was extracted with EtOAc, dried with Na_2SO_4, and filtered. The solvent was removed *in vaccuo*. The reaction afforded a 4:1 mixture of diastereomers, these diastereomers were separated by silica column chromatography (5% EtOAc/hexanes, then 100% EtOAc). The solvent was removed *in vacuo* to afford the sulfonamide protected amine (2.5 g, 65%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.87-7.81 (m, 4H), 7.52-7.49 (m, 3H), 4.80-4.76 (m, 1H), 3.43 (s, 1H), 1.66 (d, J= 6.7 Hz, 3H), 1.24 (s, 9H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 140.7, 133.3, 132.9, 128.4, 127.9, 127.7, 126.2, 125.9, 125.9, 124.9, 55.6, 54.8, 25.0, 22.6.

The sulfonamide protected amine (2.50 g, 9.08 mmol, 1 equiv.) was dissolved in MeOH (6 mL) and stirred. To this solution was added HCl in ether (4.54 mL, 18.2 mmol, 2

equiv.) and stirred for 30 min. Additional ether (10 mL) was added to the solution to precipitate the amine as the HCl salt, which was collected by suction filtration. To this white solid excess 2M KOH was added, and ether was used to extract the free amine product. The solvent was removed *in vacuo* to afford the product[86] (1.4 g, 90%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.86-7.82 (m, 4H), 7.54-7.48 (m, 3H), 4.34 (q, J= 6.6 Hz, 1H), 2.02 (s, 2H), 1.52 (d, J= 6.6 Hz, 3H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 144.8, 133.5, 132.7, 128.2, 127.8, 127.6, 126.0, 125.5, 124.5, 123.9, 51.5, 25.4.

(*S*)-1-(1-Naphthyl)propylamine (3.3):
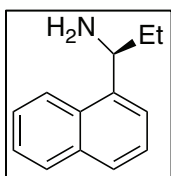
1-Naphthaldehyde (5.0 g, 32.0 mmol, 1 equiv.) was dissolved in THF (80 mL) and stirred under N$_2$. To the solution was added (*S*)-*t*-Bu-sulfinamide (3.88 g, 32.01 mmol, 1 equiv.) and Ti(OEt)$_4$ (7.38 mL, 35.2 mmol, 1.1 equiv.), and the reaction was stirred for 24 h. An aqueous workup was performed with brine (80 mL), and EtOAc (100 mL), and the mixture was filtered over celite to remove titanium residue. The solvent was removed *in vacuo* to afford the imine product (6.5 g, 78%). This intermediate was used without further purification. The imine (6.5 g, 25.1 mmol, 1 equiv.) was dissolved in DCM (150 mL) and stirred, and cooled to -45°C. To the solution EtMgBr (3M in ether)(17.7 mL, 50.1 mmol, 2 equiv.) was added and stirred for 6 h. The solution was warmed to room temperature and stirred for 16 h. The solvent was removed *in vacuo* to afford 8.8 g of the crude mixture, which was purified by column chromatography (30% EtOAc/hexanes, 60%. EtOAc/hexanes, then 100% EtOAc) to afford one diastereomer (2.1 g, 29%). *It should be noted that the EtMgBr can deliver a hydride as opposed to the ethyl group, affording 1-naphthalenemethanamine.

¹H NMR (500 MHz, CDCl₃): δ 8.12-8.09 (m, 1H), 7.91-7.79 (m, 2H), 7.57-7.43 (m, 4H), 4.84-4.69 (m, 2H), 3.53-3.52 (m, 1H), 1.24 (s, 9H), 1.20 (s, 3H).

The sulfonamide protected amine (2.1 g, 0.124 mmol, 1 equiv.) was dissolved in MeOH (5 mL) and stirred. To this solution 2M HCl in ether (7.12 mL, 0.248 mmol, 2 equiv.) was added and stirred for 30 min. Ether (10 mL) was added to precipitate out the amine HCl salt, which was collected by suction filtration. This was dissolved in excess 2M KOH, and extracted with ether. The solvent was removed *in vacuo* to afford the chiral amine[87] (0.97 g, 74%).

¹H NMR (500 MHz, CDCl₃): δ 8.20-8.18 (m, 1H), 7.92-7.90 (m, 1H), 7.80-7.78 (m, 1H), 7.67-7.65 (m, 1H), 7.57-7.50 (m, 3H), 4.76-4.74 (m, 1H), 2.03-1.99 (m, 1H), 1.88-1.82 (m, 3H), 1.04 (t, *J*= 7.4 Hz, 3H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 142.1, 133.9, 131.1, 129.0, 127.4, 125.9, 125.6, 125.4, 123.0, 122.4, 52.6, 31.6, 11.2.

(*R*)-1-(3,5-*Bis*trifluoromethylphenyl)ethylamine (3.4):
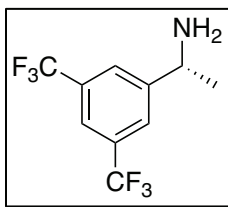
3,5-*Bis*-trifluoromethylacetophenone (2.5 g, 9.76 mmol, 1 equiv.) was dissolved in THF (50 mL) and stirred under N₂. To this solution was added (*S*)-*t*-butylsulfinamide (1.18 g, 9.76 mmol, 1 equiv.). The mixture was refluxed for 48 h to observe full conversion. The mixture was allowed to cool to room temperature, followed by an aqueous extraction with brine (80 mL) and EtOAc (80 mL). The solvent was removed *in vacuo* to afford the imine product as an oil (3.01 g, 86%).

¹H NMR (500 MHz, CDCl₃): δ 8.31 (s, 2H), 8.02 (s, 1H), 2.88 (s, 3H), 1.38 (s, 9H).

HRMS (APCI): 382.0658, $[C_{14}H_{15}F_6N_1Na_1O_1S_1]^+$ requires 382.0671.

The imine (2.0 g, 5.34 mmol, 1 equiv.) was dissolved in THF (15 mL) and cooled to -48°C where NaBH$_4$ (0.84 g, 21.36 mmol, 4 equiv.) was added and stirred for 4 h, and then at room temperature for 16 h. The reaction was quenched with the addition of MeOH (5 mL) and then brine was added, filtered, and the aqueous layer was extracted with EtOAc (20 mL). The solvent was removed *in vacuo*, and the crude was purified by column chromatography on silica gel (20% EtOAc/hexanes, 50% EtOAc/hexanes, then 100% EtOAc), and the solvent was removed *in vacuo* to afford the sulfonamide protected amine as a white solid (0.850 g, 44% of one diastereomer).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.85 (m, 3H), 4.72-4.70 (m, 1H), 3.51 (s, 1H), 1.62 (d, J= 6.3 Hz, 3H), 1.28 (s, 9H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 146.6, 132.2 (q, J= 33.5 Hz, 2C), 127.0 (d, J= 3.4 Hz, 2C), 124.3, 121.9, 55.9, 53.7, 22.9, 22.6.

The sulfonamide protected amine (0.83 g, 2.30 mmol, 1 equiv.) was dissolved in MeOH (10 mL) and stirred. To the solution 2M HCl in ether (2.30 mL, 4.60 mmol, 2 equiv.) was added and stirred for 30 min. Ether (10 mL) was added to precipitate the HCl salt of the amine product as a white solid, which was collected by suction filtration. 2M Aqueous KOH (5 mL) was added to the white solid, and extracted with ether, the solvent was removed *in vacuo* to afford the free amine product[88] (0.49 g, 66%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.87 (s, 2H), 7.77 (s, 1H), 4.31 (q, J= 6.6 Hz, 1H), 1.53 (s, 2H), 1.44 (d, J= 6.6 Hz, 3H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 150.1, 131.9, 131.4, 126.3, 120.8, 50.7, 25.9.

^{19}F NMR (MHz, CDCl$_3$): δ 62.8.

HRMS (ESI): 258.0704, [C$_{10}$H$_{10}$F$_6$N$_1$]$^+$ requires 258.0712.

(S)-2-(Pyridyl)ethylamine (3.5):
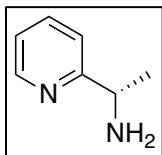
 2-Pyridinecarboxaldehyde (2.22 mL, 23.34 mmol, 1 equiv.) was dissolved in THF (100 mL) and stirred under N_2. To the solution (S)-*t*-butylsulfinamide (2.83 g, 23.34 mmol, 1 equiv.) and Ti(OEt)$_4$ (4.89 mL, 23.34 mmol, 1 equiv.) were added and stirred for 24 h at reflux. The solution was cooled, brine (15 mL) was added, and the mixture was filtered over celite to remove titanium residues, the solvent was removed *in vacuo* to afford the imine product (3.3 g, 68%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 8.80-8.79 (m, 1H), 8.75 (s, 1H), 8.07-8.05 (m, 1H), 7.87-7.84 (m, 1H), 7.45-7.42 (m, 1H), 1.33 (s, 9H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 163.8, 152.6, 150.2, 136.8, 125.9, 123.1, 58.1, 22.7.

HRMS (ESI): 233.0713, [C$_{10}$H$_{14}$N$_2$Na$_1$O$_1$S$_1$]$^+$ requires 255.1985.

The imine product above (3.33 g, 15.83 mmol, 1 equiv.) was dissolved in DCM (50 mL) and stirred under N_2 at -78°C. To the solution 3M MeMgBr in ether (10.56 mL, 31.66 mmol, 2 equiv.) was added and stirred for 5h, then at room temperature for 16 h. The solution was quenched with aqueous NH$_4$Cl (15 mL), and then extracted with EtOAc (50 mL), the solvent was removed *in vacuo* to afford the crude mixture with a 90:10 diastereoselectivity, determined by NMR. The crude was purified by silica column chromatography (30% EtOAc/hexanes, then 70% EtOAc/hexanes, then 100% MeOH), and then solvent was removed *in vacuo* to afford the product as an orange oil (3.0 g, 84%).

¹H NMR (500 MHz, CDCl₃): δ 8.58 (m, 1H), 7.70-7.65 (m, 1H), 7.32-7.29 (m, 1H), 7.21-7.17 (m, 1H), 4.84-4.82 (m, 1H), 4.64-4.60 (m, 1H), 1.53 (d, *J*= 6.7 Hz, 3H), 1.28 (s, 9H).

HRMS (ESI): 249.1040, $[C_{11}H_{18}F_6N_2Na_1O_1S_1]^+$ requires 249.1032.

The sulfonamide protected amine (0.20 g, 0.884 mmol, 1 equiv.) was dissolved in MeOH (4 mL) and stirred for 30 min with 2M HCl in ether (0.88 mL, 1.77 mmol, 2 equiv.). Additional ether (5 mL) was added to precipitate out the HCl salt of the amine which was collected by suction filtration, and washed with a 2M aqueous solution of KOH (10 mL) and extracted with ether, the solvent was removed *in vacuo* to afford the product[89] (0.1 g, 93%).

¹H NMR (500 MHz, CDCl₃): δ 8.59 (d, *J*=4.4 Hz, 1H), 7.67 (td, *J*= 1.8, 7.7 Hz, 1H), 7.34 (d, *J*= 7.8 Hz, 1H), 7.19-7.16 (m, 1H), 4.19 (q, *J*= 6.7 Hz, 1H), 1.73 (s, 1H), 1.47 (d, *J*= 6.7 Hz, 3H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 165.9, 149.2, 136.6, 121.8, 120.1, 52.6, 24.5.

(*S*)-1-(1-Naphthyl)-(trifluoromethyl)methylamine (3.6):
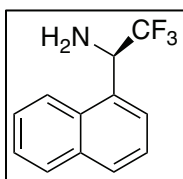
1-Naphthaldehyde (4.35 mL, 32.01 mmol, 1 equiv.) was dissolved in THF (100 mL) and stirred under N₂. To the solution (*S*)-*t*-butylsulfinamide (3.88 g, 32.01 mmol, equiv.) and Ti(OEt)₄ (6.71 mL, 32.01 mmol, 1 equiv.) were added and stirred for 48 h. 2M KOH (25 mL) was added, and the titanium was removed by fitration over Celite. The product was extracted with ether (100 mL), and the solvent was removed *in vacuo* to afford the imine product (6.23 g, 75%).

¹H NMR (500 MHz, CDCl₃): δ 9.16 (s, 1H), 9.03 (d, *J*= 8.6 *Hz*, 1H), 8.06-7.90 (m, 4H), 7.65-7.55 (m, 2H), 4.51-4.32 (m, 2H), 1.33 (s, 9H).

HRMS (ESI): 282.0920, $[C_{15}H_{17}N_1Na_1O_1S_1]^+$ requires 282.0923.

The 1-naphthaldimine (1.0 g, 3.86 mmol, 1 equiv.) was dissolved in THF (20 mL) under N_2 in a Schlenk and stirred at -50 °C. To the solution the Rupert-Parkesh reagent (TMSCF₃) (0.57 mL, 3.86 mmol, 1 equiv.) and Bu₄NOAc (0.232 g, 0.772 mmol, 0.2 equiv.) were added and stirred for 4 h, and then placed in the freezer at -15 °C for 48 h. The reaction was quenched with aqueous NH₄Cl (15 mL) and extracted with EtOAc (80 mL), the solvent was removed *in vacuo* to afford the crude as a yellow oil. The crude was purified by silica column chromatography (20% EtOAc/hexanes, then 100% EtOAc) affording one diastereomer as a white solid (0.5 g, 40%).

¹H NMR (500 MHz, CDCl₃): δ 8.20-8.18 (d, *J*= 8.6 Hz, 1H), 7.95 (t, *J*= 8.3 Hz, 2H), 7.72-7.66 (m, 2H), 7.61-7.54 (m, 2H), 5.79-5.73 (m, 1H), 3.81-3.80 (m, 1H), 1.30 (s, 9H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 134.0, 130.9, 130.4, 129.8, 129.2, 127.4, 126.4, 125.1, 122.5, 57.0, 22.4.

¹⁹F NMR (MHz, CDCl₃): δ 72.7.

HRMS (ESI): 352.0951, $[C_{16}H_{18}F_3N_1Na_1O_1S_1]^+$ requires 255.1985.

The *t*-butylsulfinamide protected amine (0.33 g, 1.00 mmol, 1 equiv.) was dissolved in MeOH (6 mL) and stirred under N_2. To the solution 2M HCl in ether (1.0 mL, 2.00 mmol, 2 equiv.) was added and stirred for 30 min. Ether was added to the solution to precipitate out the HCl salt of the amine, which was collected by suction filtration. To

this aqueous 2M KOH (10 mL) was added, and the organics were extracted with ether, and concentrated to afford the product[90] (0.13 g, 58%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 8.13-8.10 (m, 1H), 7.94-7.89 (m, 2H), 7.81-7.78 (m, 1H), 7.63-7.52 (m, 1H), 1.94-1.92 (m, 2H).

^{19}F NMR (MHz, CDCl$_3$): δ 75.3 (d, J= 7.2 Hz, 3F).

(*S*)-1-(9-Anthracyl)ethylamine (3.7):
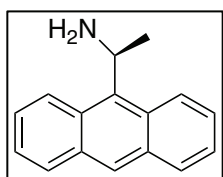
9-Anthracenecarboxaldehyde (5.0 g, 24.24 mmol, 1 equiv.) was dissolved in THF (100 mL) and stirred under N$_2$. To the solution *(S)-t-*butylsulfinamide (2.94 g, 24.24 mmol, 1 equiv.) and Ti(OEt)$_4$ (5.08 mL, 24.24 mmol, 1 equiv.) were added and stirred for 48 h. The solution was washed with brine (100 mL) to precipitate out titanium residues which were filtered over celite. The solvent was removed *in vacuo* to afford the anthracenylimine (6.27 g, 84%). This was used without further purification.

^{1}H NMR (500 MHz, CDCl$_3$): δ 9.97 (s, 1H), 8.94-8.92 (m, 2H), 8.66 (s, 1H), 8.13-8.09 (m, 3H), 7.67-7.56 (m, 4H), 1.42 (s, 9H).

HRMS (ESI): 332.1065, [C$_{19}$H$_{19}$N$_1$Na$_1$O$_1$S$_1$]$^+$ requires 332.1080.

a) The 9-anthracenylimine (0.50 g, 1.62 mmol, 1 equiv.) was dissolved in THF (15 mL) and stirred under N$_2$ at -84°C. To the solution MeLi (1.01 mL, 1.62 mmol, 1 equiv.) and DMPU (1.17 mL, 9.72 mmol, 6 equiv.) were added and stirred for 4 h. The reaction was quenched by the addition of aqueous NH$_4$Cl, extracted with EtOAc, and then solvent was removed *in vacuo*, no product was afforded after multiple attempts, with or without the use of DMPU.

b) The 9-anthracenylimine (0.10 g, 0.323 mmol, 1 equiv.) was dissolved in DCM (15 mL) and stirred under N_2 at -78°C. To the solution MeMgBr (0.215 mL, 0.646 mmol, 2 equiv.) was added and stirred for 5 h, then warmed to room temperature and stirred for 16 h. No product was observed by NMR.

N,N'-Bis-((R)-2-(3,3-dimethyl)butyl)ethane-1,2-diimine (3.8):
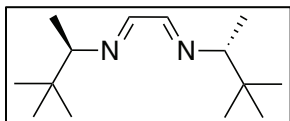
(R)-3,3-Dimethyl-2-butylamine (1.31 mL, 9.88 mmol, 2 equiv.) was dissolved in DCM (10 mL) with Na_2SO_4 and stirred under N_2. To the mixture glyoxal solution (0.564 mL, 4.94 mmol, 1 equiv.) and formic acid (2 drops) were added and stirred for 14 h. The mixture was filtered, and the solvent was removed *in vacuo* to afford the product[91] as a brown solid (1.8 g, 82%).

¹H NMR (500 MHz, CDCl₃): δ 7.94 (s, 2H), 2.99 (q, J= 6.6 Hz, 2H), 1.16 (d, J= 6.6 Hz, 6H), 0.93 (s, 18H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 160.4, 75.5, 34.0, 26.5, 17.1.

HRMS (ESI): 225.2334, $[C_{14}H_{29}N_2]^+$ requires 225.2325.

N,N'-Bis-((R)-1-phenylethyl)ethane-1,2-diimine (3.9):
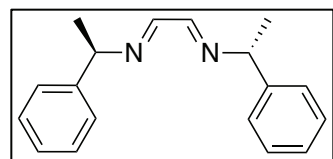
(R)-Phenylethylamine (5.32 mL, 41.26 mmol, 2 equiv.) was dissolved in DCM (20 mL) and stirred under N_2 with Na_2SO_4. To the solution glyoxal solution (2.36 mL, 20.36 mmol, 1 equiv.) and formic acid (0.122 mL, 2.06 mmol, 0.1 equiv.) were added and stirred for 18 h. The solution was filtered over celite, and then the solvent was removed *in vacuo* to afford the product[92] (4.8 g, 88%).

¹H NMR (500 MHz, CDCl₃): δ 8.09 (s, 2H), 7.38-7.36 (m, 10H), 4.55 (q, J= 6.7 Hz, 2H), 1.62 (d, J= 6.7 Hz, 6H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 160.7, 143.7, 128.6, 128.5, 127.3, 126.7, 125.7, 69.7, 24.0.

HRMS (ESI): 265.1707, [C$_{18}$H$_{21}$N$_2$]$^+$ requires 265.1699.

N,N′-Bis-((R)-1-p-methoxyphenylethyl)ethane-1,2-diimine (3.10):
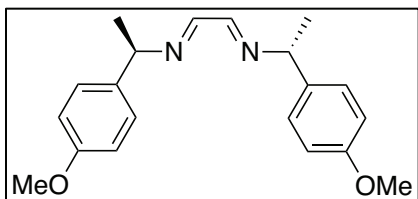
(R)-p-Methoxy-phenylethylamine (2.44 mL, 16.53 mmol, 2 equiv.) was dissolved in DCM (50 mL) under N$_2$ with Na$_2$SO$_4$ and stirred. To the solution glyoxal solution (0.95 mL, 8.27 mmol, 1 equiv.) and formic acid (0.03 mL, 0.827 mmol, 0.1 equiv.) were added and stirred for 16 h. The mixture was filtered over celite, and the solvent was removed *in vacuo* to afford the product[93] (2.1 g, 78%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 8.04 (s, 2H), 7.29-7.27 (m, 4H), 6.91-6.89 (m, 4H), 4.50 (q, *J* = 6.7 Hz, 2H), 3.82 (s, 6H), 1.59 (d, *J* = 6.8 Hz, 6H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 160.5, 158.8, 135.7, 127.8, 114.0, 69.0, 55.3, 23.8.

N,N'-Bis-((R)-1-naphthyethyl)ethane-1,2-diimine (3.11):
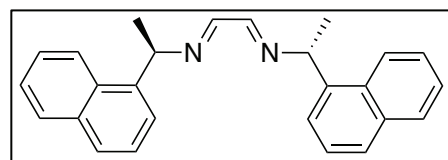
(R)-1-Naphthylethylamine (4.69 mL, 29.2 mmol, 2 equiv.) was dissolved in DCM (50 mL) under N$_2$ and stirred with Na$_2$SO$_4$. To the solution glyoxal solution (1.67 mL, 14.6 mmol, 1 equiv.) and formic acid (0.053 mL, 1.46 mmol, 0.1 equiv.) were added and stirred for 16 h. The mixture was filtered over celite, and the solvent was removed *in vacuo*. The solid obtained was washed with EtOH (25 mL) and product[92] was collected by suction filtration as a yellow/white solid (3.8 g, 72%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 8.18 (s, 2H) 7.85-7.80 (m, 7H), 7.53-7.46 (m, 7H), 4.73 (q, *J* = 6.7 Hz, 2H), 1.71 (d, *J* = 6.7 Hz, 6H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 133.5, 132.8, 128.4, 127.9, 127.6, 126.1, 125.7, 125.2, 125.0, 69.8, 24.1.

HRMS (ESI): 365.2000, [C$_{26}$H$_{25}$N$_2$]$^+$ requires 365.2012.

N,N'-Bis((S)-1-(naphthyl-2,2-dimethylpropyl)ethane-1,2-diimine (3.12):
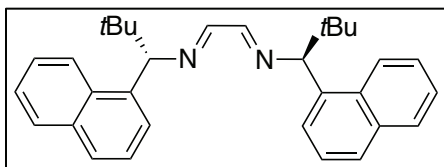
(S)-1-(1-Naphthyl)-(2,2-dimethyl)propylamine **1** (1.0g, 4.96 mmol, 2 equiv.) was dissolved in DCM (15 mL) under N$_2$ with Na$_2$SO$_4$. To the solution glyoxal solution (0.268 mL, 2.35 mmol, 1 equiv.) and formic acid (0.01 mL, 0.165 mmol, 0.07 equiv.) were added and stirred for 5 h. The mixture was filtered over celite, and the resulting solutions solvent was removed *in vacuo*. The crude was recrystallized from MeOH to afford the product[81] as a white solid (0.89 g, 85%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 8.23-8.21 (m, 2H), 8.13 (s, 2H), 7.84-7.82 (m, 2H), 7.71-7.70 (m, 4H), 7.53-7.39 (m, 6H), 5.01 (s, 2H), 1.03 (s, 18H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 137.6, 133.6, 133.6, 133.6, 132.0, 129.0, 128.9, 127.5, 127.3, 127.2, 125.5, 123.5, 123.5, 123.4, 110.0, 36.9, 27.3.

HRMS (ESI): 449.2935, [C$_{32}$H$_{37}$N$_2$]$^+$ requires 449.2951.

N,N'-Bis-((S)-1-napthyethyl)ethane-1,2-diimine (3.13):
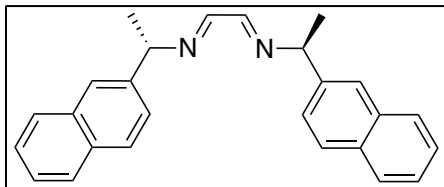
(S)-1-(2-Naphthyl)ethylamine **2** (1.29 g, 7.53 mmol, 2 equiv.) was dissolved in DCM (30 mL) under N$_2$ with Na$_2$SO$_4$ and stirred. To the mixture glyoxal solution (0.43 mL, 3.77 mmol, 1 equiv.) and formic acid (0.015 mL, 0.377 mmol, 0.1 equiv.) were added and stirred for 16 h. The mixture was filtered over celite, and the

resulting solutions solvent was removed *in vacuo* to afford the product as an orange solid (1.14 g, 83%).

¹H NMR (500 MHz, CDCl₃): δ 8.18 (s, 2H), 7.85-7.80 (m, 6H), 7.53-7.46 (m, 8H), 4.73 (q, *J*= 6.7 Hz, 2H), 1.71 (d, *J*= 6.7 Hz, 6H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 160.9, 141.1, 133.5, 132.8, 128.4, 127.9, 127.6, 126.1, 125.7, 125.2, 125.0, 69.8, 24.1.

***N,N'-Bis*-((*S*)-1-naphthypropyl)ethane-1,2-diimine (3.14):**
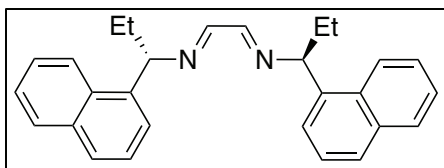
(*S*)-1-(1-Naphthyl)propylamine **3** (0.32g, 0.815 mmol, 2 equiv.) was dissolved in DCM (20 mL) under N₂ with Na₂SO₄ and stirred. To the mixture glyoxal solution (0.047 mL, 0.408 mmol, 1 equiv.) and formic acid (0.002 mL, 0.041 mmol, 0.1 equiv.) were added and stirred for 16 h. The mixture was filtered over celite, and the resulting solutions solvent was removed *in vacuo*. The crude was recrystallized from EtOH to afford the product as a beige solid (0.30, 94%).

¹H NMR (500 MHz, CDCl₃): δ 8.18 (s, 2H), 7.88-7.86 (m, 2H), 7.77-7.75 (m, 2H), 7.68-7.66 (m, 2H), 7.53-7.44 (m, 8H), 5.03-5.00 (m, 2H), 2.21-2.07 (m, 4H), 0.99 (t, *J*= 7.4 Hz, 6H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 161.4, 138.9, 134.0, 130.8, 129.0, 127.6, 125.9, 125.5, 125.4, 124.6, 123.3, 72.6, 30.7, 11.4.

***N,N'-Bis*-((*R*)-3,5-*bis*(trifluoromethyl)-1-phenylethyl)ethane-1,2-diimine (3.15):**
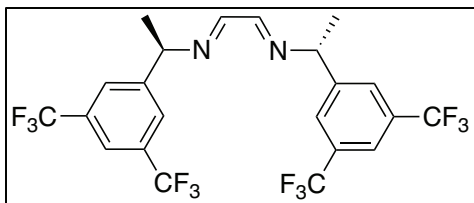
(*R*)-1-(3,5-*Bis*(trifluoromethylphenyl)ethylamine) **3.4** (0.39 g, 1.52 mmol, 2 equiv.) was dissolved in DCM (30 mL) under N₂ with Na₂SO₄ and stirred.

To the mixture glyoxal solution (0.09 mL, 0.760 mmol, 1 equiv.) and formic acid (2 drops) were added and stirred for 16 h. The mixture was filtered over celite, and the solutions solvent was removed *in vacuo* to afford the product as a brown solid (0.40 g, 82%).

¹H NMR (500 MHz, CDCl₃): δ 8.16 (s, 2H), 7.88 (s, 4H), 7.81 (s, 2H), 4.67 (q, *J*= 6.6 Hz, 2H), 1.63 (d, *J*= 6.6 Hz, 6H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 161.3, 146.5, 132.0, 131.7, 126.9, 126.8, 121.3, 68.9, 25.0.

HRMS (ESI): 559.1016, $[C_{22}H_{16}F_{12}N_2Na_1]^+$ requires 559.1014.

N,N'-Bis-((S)-1-pyridylethyl)ethane-1,2-diimine (3.16):
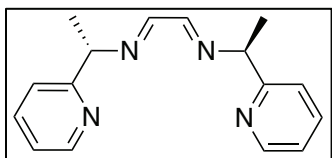
(S)-2-(Pyridyl)ethylamine **3.5** (0.30 g, 2.43 mmol, 2 equiv.) was dissolved in DCM (50 mL) under N_2 in Na_2SO_4 and stirred. To the mixture glyoxal solution (0.14 mL, 1.22 mmol, 1 equiv.) and formic acid (0.05 mL, 0.122 mmol, 0.1 equiv.) were added and stirred for 16 h. The mixture turned black during the reaction, the mixture was filtered over celite and the solvent was removed *in vacuo*. The reaction did not yield the product.

N,N'-Bis-((S)-1-naphthy-trifluoromethyl)ethane-1,2-diimine (3.17):
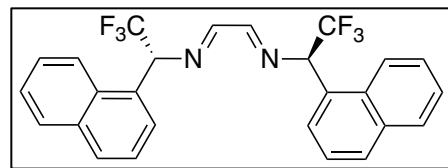
(S)-1-(1-Naphthyl)-(trifluoromethyl)methylamine **3.-6** (0.14g, 0.622 mmol, 2 equiv.) was dissolved in DCM (35 mL) under N_2 with Na_2SO_4 and stirred. To the solution glyoxal solution (0.04 mL, 0.311 mmol, 1 equiv.) and formic acid (2 drops) were added and stirred for 16 h. The mixture was filtered over celite and the resulting

solutions solvent was removed *in vacuo*. The crude product was washed with pentane to afford the product as a white solid (0.11 g, 79%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 8.23 (s, 2H), 8.14 (d, *J*= 8.5 Hz, 2H), 7.92 (t, *J*= 9.2 Hz, 4H), 7.80 (d, *J*= 7.2 Hz, 2H), 7.64-7.56 (m, 4H), 7.50 (t, *J*= 7.7 Hz, 2H), 5.80 (q, *J*= 7.2 Hz, 2H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 165.8, 133.9, 131.3, 130.0, 129.6, 129.2, 128.0, 127.0, 126.0, 125.3, 123.6, 122.7, 69.8 (q, *J*= 30.2 Hz, 2 C).

HRMS (ESI): 459.1262, [C$_{26}$H$_{18}$F$_6$N$_2$Na$_1$]$^+$ requires 255.1985.

2-Bromo-1,3-*bis*{(*R*)2-(3,3-dimethyl)butyl}-1,3,2-diazaphosphole (3.18):
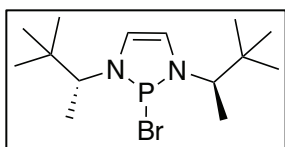
N,N'-Bis-((*R*)-2-(3,3-dimethyl)butyl)ethane-1,2-diimine **3.8** (1.11g, 4.95 mmol, 1 equiv.) was dissolved in DCM (15 mL) in a Schlenk flask under N$_2$ and stirred. To the solution was added cyclohexene (1.50 mL, 14.84 mmol, 3 equiv.) and PBr$_3$ (0.47 mL, 4.95 mmol, 1 equiv.) and the mixture was left to stir for 36 h. The solvent was removed *in vacuo* and the Schlenk flask was brought into the glovebox. The sticky residue was triturated with ether, filtered, and washed with additional ether to afford the product as a yellow solid (1.40 g, 84%). The nitrogen substituents and backbone protons were observed to be equivalent by NMR spectroscopy.

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.03 (s, 2H), 4.11-4.05 (m, 2H), 1.72 (d, *J*= 7.0 Hz, 3H), 0.99 (s, 18H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 124.9 (d, *J*= 6.6 Hz), 65.8 (d, *J*= 9.8 Hz), 34.9 (d, *J*= 5.0 Hz), 26.6 (s), 15.9 (d, *J*= 9.9 Hz).

^{31}P NMR (201 MHz, CDCl$_3$): δ 197.2(s).

HRMS (APCI): 255.1982, $[C_{14}H_{28}N_2P]^+$ requires 255.1985.

2-Bromo-1,3-*bis*{(*R*)1-phenylethyl}-1,3,2-diazaphosphole (3.19):
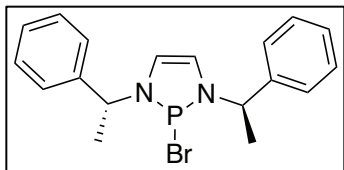
N,N'-Bis-((*R*)-1-phenylethyl)ethane-1,2-diimine **3.9** (5.13 g, 19.4 mmol, 1 equiv.) was dissolved in DCM (75 mL) in a Schlenk flask under N_2 and stirred. To the solution was added PBr$_3$ (1.84 mL, 19.4 mmol, 1 equiv.), and cyclohexene (5.89 mL, 58.2 mmol, 3 equiv.) and the resulting mixture was stirred for 24 h. The solvent was removed *in vacuo*, and the Schlenk flask was brought into the glovebox. The sticky residue was triturated with pentane, then the resulting brown solid was collected by suction filtration to afford the product (4.62 g, 64%). The phenylethyl groups and backbone protons were observed to be equivalent by NMR spectroscopy. Conditions could not be found to increase the purity of the material that was obtained by this step, as a result, material < 90% pure was carried on to the next step.

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.48-7.47 (m, 3H), 7.45-7.42 (m, 3H), 7.40-7.36 (m, 4H), 6.75 (s, 2H), 5.28-5.22 (m, 2H), 2.06 (d, *J*= 6.8 Hz, 6H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 140.3 (d, *J*= 5.1 Hz), 129.2, 128.8, 127.4, 124.6 (d, *J*= 7.4 Hz), 59.3 (d, *J*= 11.8 Hz), 22.1 (d, *J*= 12.1 Hz).

^{31}P NMR (201 MHz, CDCl$_3$): δ 187.3 (s).

HRMS(APCI): 295.1360, $[C_{18}H_{20}N_2P]^+$ requires 295.1359.

2-Bromo-1,3-*bis*{(*R*)1-(*p*-methoxyphenyl)ethyl}-1,3,2-diazaphosphole (3.20):
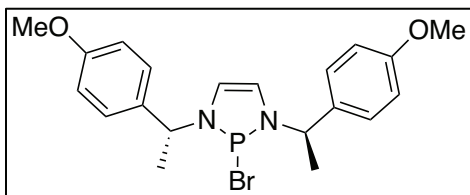
N,N'-Bis-((*R*)-1-*p*-methoxyphenylethyl)ethane-1,2-diimine **3.10** (0.500 g, 1.54 mmol, 1 equiv.) was dissolved in DCM (5 mL) in a Schlenk flask under

N$_2$. To the solution was added cyclohexene (0.38 mL, 4.62 mmol, 3 equiv.) and PBr$_3$ (0.146 mL, 1.54 mmol, 1 equiv.) and then solution was allowed to stir for 36 h. The solvent was removed *in vacuo* and the Schlenk flask was brought into the glove box. Ether was added to the dark residue and stirred, the suspension was filtered and the product was collected by filtration as a grey solid (0.460 g, 72%). The nitrogen substituents and backbone protons were observed to be equivalent by NMR spectroscopy.

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.45-7.43 (m, 4H), 6.96-6.95 (m, 4H), 6.91 (s, 2H), 5.29-5.23 (m, 2H), 3.85 (s, 6H), 2.03 (d, *J*= 6.7 Hz, 6H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 160.0, 132.0 (d, *J*= 5.3 Hz), 128.9, 125.3 (d, *J*= 7.2 Hz), 114.5, 59.0 (d, *J*= 11.7 Hz), 53.4, 22.1 (d, *J*= 22.1 Hz).

^{31}P NMR (201 MHz, CDCl$_3$): δ 189.8 (s).

*Upon attempts with APCI and ESI MS, no HRMS was acquired.

2-Bromo-1,3-*bis*{(*R*)1-(naphthalen-1-yl)ethyl}-1,3,2-diazaphosphole (3.21):
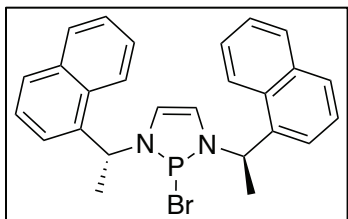
N,*N*'-*Bis*-((*R*)-1-napthyethyl)ethane-1,2-diimine **3.11** (12.6 g, 34.4 mmol, 1 equiv.) was dissolved in DCM (100 mL) under N$_2$ in a Schlenk flask. To this mixture was added cyclohexene (10.4 mL, 103 mmol, 3 equiv.), and PBr$_3$ (3.26 mL, 34.4 mmol, 1 equiv.). An ivory precipate rapidly formed, and the mixture was stirred for 24 h. The flask was brought into the glovebox where it was filtered. The solid was washed with ether, and then washed with minimal acetonitrile to remove unreacted diimine, yielding the product as a colorless powder (11.6 g, 71 %). The nitrogen substituents and backbone protons were observed to be equivalent by NMR spectroscopy.

1H NMR (500 MHz, CDCl₃): δ 8.06-8.04 (m, 2H), 7.95-7.94 (m, 2H), 7.90-7.89 (m, 2H), 7.72-7.70 (m, 2H), 7.57-7.52 (m, 6H), 6.75 (s, 2H), 6.10-6.07 (m, 2H), 2.25 (d, J= 6.8 Hz, 6H).

13C{1H} NMR (125 MHz, CDCl₃): δ 135.8 (d, J= 5.9 Hz), 134.0, 130.5, 129.5, 129.3, 127.0, 126.1, 125.6, 125.3, 124.2 (d, J= 7.7 Hz), 122.2, 55.3 (d, J= 11.8 Hz), 21.6 (d, J= 11.8 Hz).

31P NMR (201 MHz, CDCl₃): δ 188.2 (s).

HRMS (APCI): 395.1684, $[C_{26}H_{24}N_2P]^+$ requires 395.1672.

2-Bromo-1,3-*bis*{(S)1-(naphthalen-1-yl)-(2,2-dimethl)propyl}-1,3,2-diazaphosphole (3.22):
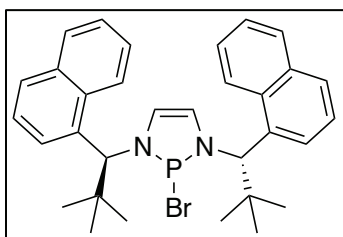
N,N'-Bis((S)-1-(naphthyl-2,2-dimethylpropyl)ethane-1,2-dii-mine **3.12** (0.10 g, 0.223 mmol, 1 equiv.) was dissolved in DCM (10 mL) under N_2 in a Schlenk flask and stirred. To the solution cyclohexene (0.07 mL, 0.669 mmol, 3 equiv.) and PBr₃ (0.02 mL, 0.223 mmol, 1 equiv.) were added and stirred for 20 h. The solvent was removed *in vacuo* to afford a light green powder. No product was observed by NMR.

2-Bromo-1,3-*bis*{(S)1-(naphthalen-1-yl)ethyl}-1,3,2-diazaphosphole (3.23):
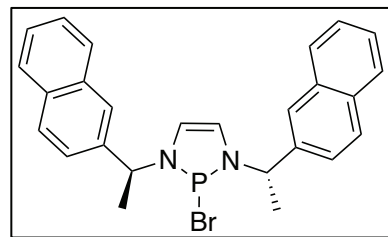
N,N'-Bis-((S)-1-napthyethyl)ethane-1,2-diimine **3.13** (1.0 g, 2.74 mmol, 1 equiv.) was dissolved in DCM (20 mL) under N_2 in a Schlenk flask and stirred. To the solution cyclohexene (0.83 mL, 8.22 mmol, 3 equiv.) and PBr₃ (0.26 mL, 2.74 mmol, 1 equiv.) were added and stirred for 16 h. The solvent was removed *in vacuo* and the Schlenk was brought into the glovebox where the brown solid

was washed with ether and collected by suction filtration to afford the product (1.05g, 81%). Upon attempts to purify with toluene, pentane, benzene, and acetonitrile recrystalizations, the purity was not increased by these methods.

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.95-7.86 (m, 7H), 7.59-7.54 (m, 7H), 6.79 (s, 2H), 5.44-5.41 (m, 2H), 2.15 (d, J= 6.3 Hz, 6H).

^{31}P NMR (201 MHz, CDCl$_3$): δ 187.4.

2-Bromo-1,3-*bis*{(*S*)1-(naphthalen-1-yl)propyl}-1,3,2-diazaphosphole (3.24):
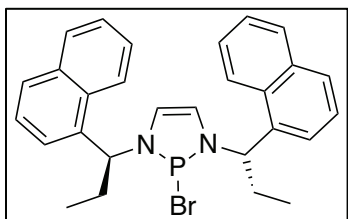
N,N'-Bis-((*R*)-1-naphthypropyl)ethane-1,2-diimine **3.14** (0.-24 g, 0.611 mmol, 1 equiv.) was dissolved in DCM (15 mL) under N$_2$ in a Schlenk and stirred. To the solution cyclohexene (0.19 mL, 1.83 mmol, 3 equiv.) and PBr$_3$ (0.1 mL, 0.611 mmol, 1 equiv.) were added and stirred for 16 h. The solvent was removed *in vacuo* and the flask was brought into the glovebox where the brown residue was washed with ether, and the brown powder was collected by suction filtration to afford the product (0.14 g, 46%).

The product was not isolated in 100% purity, but was continued to the next step.

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.94-7.86 (m, 6H), 7.56-7.54 (m, 8H), 6.78 (s, 2H), 5.86-5.84 (m, 2H), 2.89-2.83 (m, 4H), 0.98-0.95 (m, 6H).

^{31}P NMR (201 MHz, CDCl$_3$): δ 191.3.

2-Bromo-1,3-*bis*{(*R*)-3,5-bistrifluoromethyl-1-phenylethyl}-1,3,2-diazaphosphole (3.25):
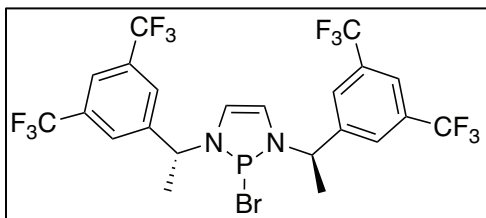
N,N'-Bis-((*R*)-3,5-bis(trifluoromethyl)-1-phenyle-thyl)ethane-1,2-diimine **3.15** (0.10g, 0.186 mmol,

1 equiv.) was dissolved in DCM (5 mL) under N_2 in a Schlenk flask and stirred. To the solution cyclohexene (0.06 mL, 0.558 mmol, 3 equiv.) and PBr_3 (0.02 mL, 0.186 mmol, 1 equiv.) were added and stirred for 16 h. The solvent was removed *in vacuo*, and the brown solid was washed with ether and collected by suction filtration. No conversion to the product was observed by NMR.

2-Bromo-1,3-*bis*{(*S*)1-(naphthalen-1-yl)trifluoromethylethyl}-1,3,2-diazaphosphole (3.26):
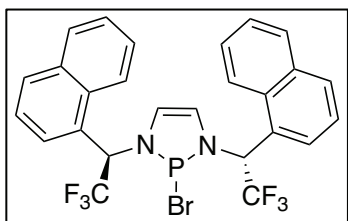
N,N'-Bis-((*S*)-1-naphthy-trifluoromethyl)ethane-1,2-diimine **3.17** (0.11g, 0.232 mmol, 1 equiv.) was dissolved in DCM (5 mL) under N_2 in a Schlenk flask and stirred. To the solution cyclohexene (0.071 mL, 0.696 mmol, 3 equiv.) and PBr_3 (0.022 mL, 0.232 mmol, 1 equiv.) were added and stirred for 16 h. The solvent was removed *in vacuo*, and the Schlenk flask was brought into the glovebox. The green crude was washed with ether and collected by suction filtration to afford a green powder. No product was observed by NMR.

1,3-*Bis*{(*S*)1-(naphthalen-1-yl)-(2,2-dimethl)propyl}-1,3,2-diazaphosphole (3.27):
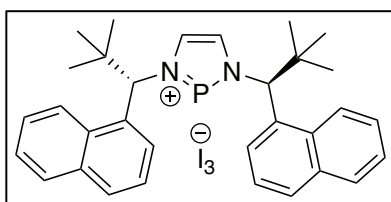
N,N'-Bis((*S*)-1-(naphthyl-2,2-dimethylpropyl)ethane- 1- ,2-diimine **3.12** (0.533 g, 1.19 mmol, 1 equiv.), was dissolved in DCM (5 mL) in the glovebox. Phosphorus triiodide (0.489 g, 1.19 mmol, 1 equiv.) was added to the solution and the resulting mixture was left to stir for 16 h. The solvent was removed *in vacuo*, and the residue was triturated with pentane to afford the product as a brown solid (0.92 g, 90%).

¹H NMR (500 MHz, CD₃CN): δ 8.44 (s, 2H), 8.37 (m, 2H), 7.96-7.88 (m, 6H), 7.73 (m, 2H), 7.62-7.58 (m, 4H), 6.53 (d, J= 10.3 Hz, 2H), 1.29 (s, 18H).

¹³C{¹H} NMR (125 MHz, CD₃CN): δ 136.0, 134.2, 132.53, 132.50, 131.5, 130.7, 129.5, 128.3, 126.8, 124.8, 122.6, 37.2, 28.3.

³¹P NMR (201 MHz, CD₃CN): δ 211.0 (s).

HRMS (APCI): 479.2598, $[C_{32}H_{36}N_2P]^+$ requires 479.2611.

2-Iodo-1,3-*bis*{(*S*)1-(naphthalen-1-yl)-(2,2-dimethl)propyl}-1,3,2-diazaphosphole (3.28):
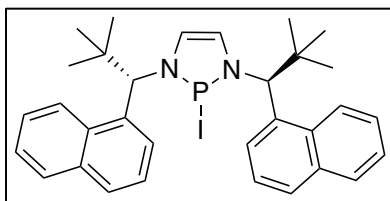
1,3-Di-1(1'-napthyl)ethyl-*t*-butyl-diazaphospholidene tr-iiodide **3.27** (0.500 g, 0.58 mmol, 1 equiv.) was dissolved in ether (4 mL) and stirred in the glovebox. LiH (0.023g, 2.91 mmol, 5 equiv.) was added to the solution and the resulting suspention was allowed to stir for 16 h. The mixture was filtered over celite, and then the solvent was removed *in vacuo* to afford the product as a brown solid (0.150 g, 57%). The nitrogen substituents and backbone protons were observed to be equivalent by NMR spectroscopy. An inseparable adduct of LiI and diethyl ether is observed in the product NMR, which is not detrimental to the following step.

¹H NMR (500 MHz, CD₃CN): δ 8.52-8.50 (m, 2H), 8.19 (s, 2H), 8.01-7.98 (m, 5H), 7.65-7.59 (m, 5H), 6.53 (d, J= 10.9 Hz, 2H), 5.48 (s, 2H), 1.18 (s, 18H).

¹³C{¹H} NMR (125 MHz, CD₃CN): δ 134.0, 133.9 (d, J= 3.7 Hz), 133.4 (d, J= 3.6 Hz), 131.8, 129.9, 129.2, 127.1, 126.3, 124.9, 123.2, 65.3, 36.8, 27.0 (d, J= 3.7 Hz), 14.6.

³¹P NMR (201 MHz, CD₃CN): δ 211.5 (s).

HRMS (APCI): 479.2611, $[C_{32}H_{36}N_2P]^+$ requires 479.2611.

2-Neopentoxy-1,3-*bis*{(*R*)2-(3,3-dimethyl)butyl}-1,3,2-diazaphosphole (3.29):
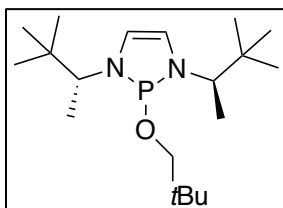
1,3-Di-1(1'-*t*-butyl)ethyl-2-bromo-diazaphospholene **3.18** (0.100 g, 0.30 mmol, 1 equiv.) was dissolved in DCM (5 mL) in a Schlenk flask under N_2. NEt_3 (0.042 mL, 0.30 mmol, 1 equiv.) and neopentyl alochol (0.026 g, 0.30 mmol, 1 equiv.) were added to the solution and the mixture was stirred for 36 h. The solvent was removed *in vacuo*, then the Schlenk flask was brought into the glovebox. The residue was taken up in toluene, and filtered over Celite. The solvent was removed *in vacuo* to afford the product as a brown solid (0.090 g, 88%). The nitrogen substituents and backbone protons were observed to be inequivalent by NMR spectroscopy.

¹H NMR (500 MHz, CDCl₃): δ 5.87-5.86 (m, 1H), 5.75 (s, 1H), 3.48-3.42 (m, 1H), 3.28-3.22 (m, 1H), 2.94-2.91 (m, 1H), 2.85-2.82 (m, 1H), 1.34 (d, *J*= 7.1 Hz, 3H), 1.32 (d, *J*= 7.0 Hz, 3H), 0.96 (s, 9H), 0.93 (s, 9H), 0.87 (s, 9H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 117.0 (d, *J*= 8.9 Hz), 111.0 (d, *J*= 9.4 Hz), 72.0 (d, *J*= 4.0 Hz), 63.5 (d, *J*= 19.7 Hz), 59.9 (d, *J*= 23.5 Hz), 36.8, 36.1 (d, *J*= 6.0 Hz), 31.8 (d, *J*= 1.9 Hz), 27.3 (d, *J*= 2.2 Hz), 27.2 (d, *J*= 4.2 Hz), 26.7, 17.2 (d, *J*= 14.1 Hz), 16.2.

³¹P NMR (201 MHz, CDCl₃): δ 103.0 (s).

$[\alpha]^{21}_{D}$= -46.7° (c= 1.5, CH_2Cl_2).

2-Neopentoxy-1,3-*bis*{(*R*)1-phenylethyl}-1,3,2-diazaphosphole (3.30):
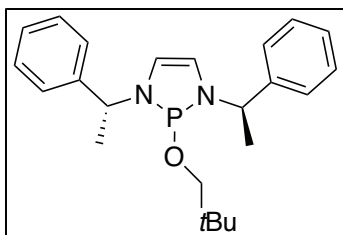
2-Bromo-1,3-*bis*{(*R*)1-phenylethyl}-1,3,2-diazaphosphole **3-.19** (0.500 g, 1.33 mmol, 1 equiv.), was dissolved in DCM (5 mL) in a Schlenk flask under N_2 and stirred. To the solution was added neopentyl alcohol (0.117 g, 1.33 mmol, 1 equiv.),

and NEt$_3$ (0.19 mL, 1.33 mmol, 1 equiv.), then the resulting mixture was left to stir for 3 h. The solvent was removed *in vacuo*, then the flask was brought into the glovebox. The crude solid was suspended in toluene and filtered over celite. The filtrate was concentrated then triturated with pentane. Removal of residual pentane *in vacuo* afforded the product as a dark brown solid (0.385 g, 76%). The phenylethyl groups and backbone protons were observed to be inequivalent by NMR spectroscopy.

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.34-7.25 (m, 10H), 5.86-5.85 (m, 1H), 5.75-5.74 (m, 1H), 4.85 (ap. p, *J*= 7.0 Hz, 1H), 4.76 (ap p, 1H, *J*= 6.8 Hz), 2.89-2.83 (m, 2H), 1.76 (d, *J*= 5.7 Hz, 6H), 0.87 (s, 9H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 129.3, 128.7 (d, *J*= 4.2 Hz), 128.2, 127.6 (d, *J*= 22.5 Hz), 127.0 (d, *J*= 12.4 Hz), 126.6 (d, *J*= 13.4 Hz), 119.0, 58.1, 26.0, 21.4.

^{31}P NMR (201 MHz, CDCl$_3$): δ 97.9 (s).

HRMS (APCI): 295.1364, [C$_{18}$H$_{20}$N$_2$P]$^+$ requires 295.1359.

$[\alpha]^{21}_D$= -120.1° (c= 2.3, CH$_2$Cl$_2$).

2-Neopentoxy-1,3-*bis*{(*R*)1-(*p*-methoxyphenyl)ethyl}-1,3,2-diazaphosphole (3.31):
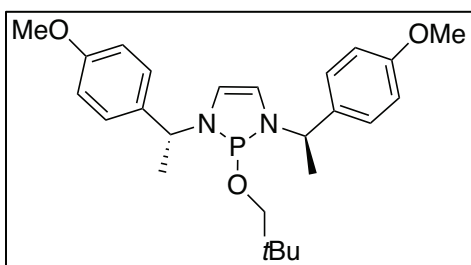
2-Bromo-1,3-*bis*{(*R*)1-(*p*-methoxyphenyl)ethyl}-1,3,2-diazaphosphole **3.20** (0.100g, 0.23 mmol, 1 equiv.) was dissolved in DCM (5 mL) in a Schlenk flask under N$_2$. NEt$_3$ (0.032 mL, 0.23 mmol, 1 equiv.) and neopentyl alcohol (0.020 g, 0.23 mmol, 1 equiv.) were added to the solution, and the mixture was stirred for 24 h. The solvent was removed, and the resulting residue was suspended in toluene. The mixture was filtered over a pad of celite and the filtrate was concentrated to afford the product as a brown oil (0.083 g, 82%). The nitrogen

substituents and backbone protons were observed to be inequivalent by NMR spectroscopy. Observation of parent or derivative ions of this compound with APCI and ESI MS was not possible.

^{1}H NMR (500 MHz, CD$_3$CN): δ 7.19-7.17 (m, 3H), 7.14-7.13 (m, 1H), 6.80-6.77 (m, 4H), 5.84-5.83 (m, 1H), 5.74-5.73 (m, 1H), 4.72 (ap. p, J= 3.0 Hz, 1H), 4.62 (ap. p, J= 3.0 Hz, 1H), 3.31 (s, 6H), 3.09-3.07 (m, 1H), 3.04-3.01 (m, 1H), 1.70 (d, J= 6.9 Hz, 3H), 1.63 (d, J= 6.9 Hz, 3H), 0.98 (s, 9H).

^{13}C{^{1}H} NMR (125 MHz, CD$_3$CN): δ 159.3, 159.2, 158.9, 115.2 (d, J= 9.1 Hz), 113.9 (d, J= 12.4 Hz), 113.8 (d, J= 12.3 Hz), 113.4 (d, J= 9.2 Hz), 112.2 (d, J= 10.5 Hz), 72.8, 72.4 (d, J= 4.9 Hz) 56.7, 55.4 (d, J= 27.0 Hz), 54.4, 31.7 , 26.6, 25.8, 23.4, 22.1 (d, J= 8.4 Hz), 21.6 (d, J= 4.8 Hz).

^{31}P NMR (201 MHz, CD$_3$CN): δ 97.8 (s).

$[\alpha]^{21}_D$= -70.8° (c= 1.3, CH$_2$Cl$_2$).

2-Neopentoxy-1,3-*bis*{(*R*)1-(naphthalen-1-yl)ethyl}-1,3,2-diazaphosphole (3.32):
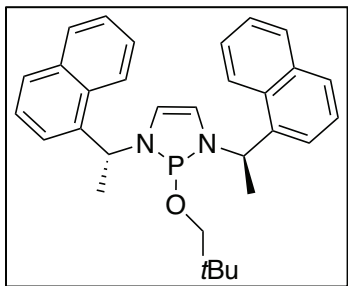
2-Bromo-1,3-*bis*{(*R*)1-(naphthalen-1-yl)ethyl}-1,3,2-diazap-hosphole **3.21** (1.40 g, 2.95 mmol, 1 equiv.) was dissolved in DCM (25 mL) under N$_2$ in a Schlenk flask. Neopentyl alcohol (0.26 g, 2.95 mmol, 1 equiv.) and NEt$_3$ (0.41 mL, 2.95 mmol, 1 equiv.) were added and the resulting mixture was stirred for 4 h. The solvent was removed *in vacuo*, then the flask was brought into the glove box. The resulting brown solid was suspended in toluene, and filtered over celite, then the filtrate concentrated. The resulting residue was triturated with pentane to

afford a brown solid (1.30 g, 92%). The nitrogen substituents and backbone protons were observed to be inequivalent by NMR spectroscopy.

^{1}H NMR (500 MHz, CDCl3): δ 8.31-8.28 (m, 1H), 8.11-8.07 (m, 1H), 7.93-7.81 (m, 3H), 7.72-7.46 (m, 8H), 7.28-7.19 (m, 1H), 7.10-7.07 (m, 1H), 5.86 (t, *J*= 2.5 Hz, 1H), 5.69 (p, *J*= 6.9 Hz, 1H), 5.57-5.52 (m, 2H), 2.98-2.95 (m, 2H), 1.91 (ap. t, *J*= 6.8 Hz, 6 H), 0.88 (s, 9H).

^{13}C{^{1}H} NMR (125 MHz, CDCl3): δ 140.0 (d, *J*= 4.0 Hz), 139.6 (d, *J*= 7.6 Hz), 133.9 (d, *J*= 8.9 Hz), 131.3, 130.8 (d, *J*= 1.7 Hz), 128.9 (d, *J*= 2.9 Hz), 128.1, 127.5, 126.1 (d, *J*= 10.6 Hz), 125.5 (d, *J*= 1.6 Hz), 125.3 (d, *J*= 8.5 Hz), 123.7 (d, *J*= 6.6 Hz), 123.5 (d, *J*= 1.8 Hz), 123.4 (d, *J*= 3.0 Hz), 122.8, 115.5 (d, *J*= 9.0 Hz), 113.5 (d, *J*= 9.4 Hz), 72.6 (d, *J*= 4.6 Hz), 53.8 (d, *J*= 20.0 Hz), 51.5 (d, *J*= 28.2 Hz), 31.8 (d, *J*= 2.2 Hz), 26.7, 22.9 (d, *J*= 17.0 Hz), 22.2 (d, *J*= 4.6 Hz).

^{31}P NMR (201 MHz, CDCl3): δ 97.7 (s).

HRMS (APCI): 483.2571, $[C_{31}H_{36}N_2OP]^+$ requires 483.2560.

$[\alpha]^{21}_D$= -10.2° (c= 2.3, CH_2Cl_2).

Elemental analysis: Calculated for $[C_{31}H_{35}N_2OP]$ C: 77.15, H: 7.31, N: 5.80. Found C: 76.85, H: 7.04, N: 5.88.

2-Hydro-1,3-*bis*{(*R*)1-(naphthalen-1-yl)ethyl}-1,3,2-diazaphosphole (3.32'):
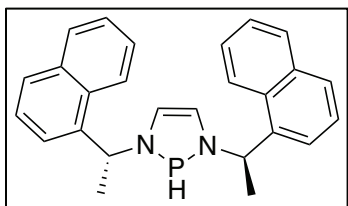
2-Neopentoxy-1,3-*bis*{(*R*)1-(naphthalen-1-yl)ethyl}-1,3,2-d-iazaphosphole **3.32** (0.02 g, 0.0414 mmol, 1 equiv.) was dissolved in THF (1 mL) and shaken in a 1-dram vial in the

glovebox. To the solution HB(pin) (0.006 mL, 0.0414 mmol, 1 equiv.) was added and shaken. The mixture was then placed in an oven dried NMR tube, capped, and sealed with teflon tape. Acquired ^{31}P NMRs after 5 minutes, 2 hours, and 5 hours are shown.

^{31}P NMR (201 MHz, THF, C$_6$D$_6$ capillary): δ 67.3 (d, J= 165.8 Hz).

2-Neopentoxy-1,3-*bis*{(*S*)1-(naphthalen-1-yl)-(2,2-dimethl)propyl}-1,3,2-
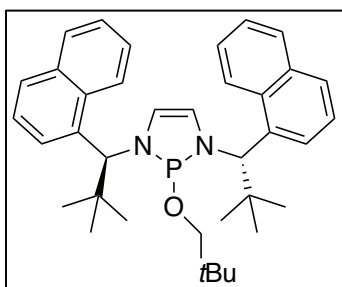
diazaphosphole (3.33):

2-Iodo-1,3-*bis*{(*S*)1-(naphthalen-1-yl)-(2,2-dimethl)propyl}-1-,3,2-diazaphosphole **3.28** (0.100 g, 0.17 mmol, 1 equiv.) was dissolved in DCM (5 mL) under N$_2$ in a Schlenk flask and stirred. Neopentyl alcohol (0.015 g, 0.17 mmol, 1 equiv.) and

NEt$_3$ (0.023 mL, 0.17 mmol, 1 equiv.) were added to the solution and the resulting mixture was stirred for 4 h. The solvent was removed *in vacuo*, and then the flask was brought into the glovebox. The resulting colorless solid was suspended in toluene (10 mL) then filtered over celite. The solvent was removed *in vacuo* to afford the product as a colorless solid (0.071g, 76%). The nitrogen substituents and backbone protons were observed to be inequivalent by NMR spectroscopy.

^{1}H NMR (500 MHz, CDCl$_3$): δ 8.29-8.25 (m, 2H), 7.98-7.96 (m, 1H), 7.84-7.77 (m, 2H), 7.73-7.65 (m, 3H), 7.51-7.40 (m, 5H), 7.30-7.28 (m, 1H), 6.31 (s, 1H), 6.06 (s, 1H), 5.46 (d, J= 9.9 Hz, 1H), 5.27 (d, J= 10.5 Hz, 1H), 2.12-1.17 (m, 2H), 1.15 (s, 9H), 1.02 (s, 9H), 0.10 (s, 9H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 138.3, 137.1 (d, J= 2.9 Hz), 133.9 (d, J= 1.8 Hz), 132.2 (d, J= 1.8 Hz), 128.9 (d, J= 15.4 Hz), 127.3 (d, J= 13.1 Hz), 126.8 (d, J= 7.8 Hz), 125.8 (d, J= 3.0 Hz), 124.9 (d, J= 6.4 Hz), 124.6 (d, J= 19.6 Hz), 123.6, 123.4 (d, J= 1.9

Hz), 118.8 (d, $J = 8.5$ Hz), 113.4 (d, $J = 8.2$ Hz), 71.7 (d, $J = 7.5$ Hz), 65.6 (d, $J = 19.1$ Hz), 62.8 (d, $J = 2.4$ Hz), 62.5 (d, $J = 1.7$ Hz), 46.3, 37.9, 37.7 (d, $J = 6.6$ Hz), 30.5 (d, $J = 1.8$ Hz), 28.7 (d, $J = 4.5$ Hz), 28.5 (d, $J = 2.5$ Hz), 26.0, 25.6, 8.6.

^{31}P NMR (201 MHz, CDCl$_3$): δ 103.2 (s).

HRMS (APCI): 479.2624, $[C_{32}H_{36}N_2P]^+$ requires 479.2611.

$[\alpha]^{21}_D = -9.7°$ (c = 1.5, CH$_2$Cl$_2$).

2-Neopentoxy-1,3-*bis*{(*S*)1-(naphthalen-2-yl)ethyl}-1,3,2-diazaphosphole (3.34):
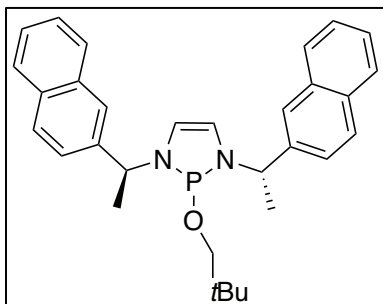
2-Bromo-1,3-*bis*{(*S*)1-(naphthalen-1-yl)ethyl}-1,3,2-diazaphosphole **3.23** (0.50g, 1.05 mmol, 1 equiv.) was dissolved in DCM (20 mL) in a Schlenk flask under N$_2$ and stirred. To the solution NEt$_3$ (0.15 mL, 1.05 mmol, 1 equiv.) and neopentylalcohol (0.093 g, 1.05 mmol, 1 equiv.) were added and stirred for 16 h. The solvent was removed *in vacuo* and the Schlenk flask was brought into the glovebox. The brown crude was dissolved in toluene, and filtered over a pad of celite. The solution was concentrated *in vacuo*, and triturated with pentane to afford the product (0.25 g, 50%). The formation of product was determined by ^{31}P NMR, the ^{1}H NMR was broad and incomparable. Attempts at recrystallizations were attempted but did not further purify the compound, and therefore was used without further purification.

^{31}P NMR (201 MHz, CDCl$_3$): δ 97.9.

2-Neopentoxy-1,3-*bis*{(*S*)1-(naphthalen-1-yl)propyl}-1,3,2-diazaphosphole (3.35):
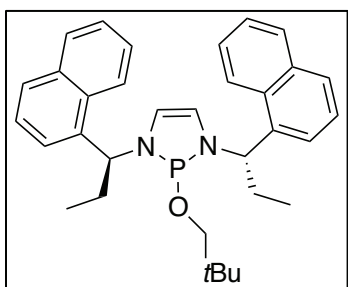
2-Bromo-1,3-*bis*{(*S*)1-(naphthalen-1-yl)propyl}-1,3,2-diazaphosphole **3.24** (0.10 g, 0.199 mmol, 1 equiv.) was dissolved

in DCM (5 mL) in a Schlenk flask under N$_2$ and stirred. To the solution NEt$_3$ (0.03 mL,

0.199 mmol, 1 equiv.) and neopentylalcohol (0.018 g, 0.199 mmol, 1 equiv.) were added

and stirred for 6 h. The solvent was removed *in vacuo* and the crude was brought into the

glovebox. The crude was take up in toluene, filtered over a pad of celite, and

concentrated *in vacuo* to afford the product (0.6g, 60%). This product was very broad in

the proton NMR, and had small ^{31}P signals. This was further used in catalysis and

showed to induce enenatiomeric induction.

1,3-[4,5-Dihydro-2-(4,5-dihydro-4,4-di-(*R*)-benzyloxazol-2-yl)-4,4-

dimethyloxazole]2-halo-diazaphosphole (3.36):
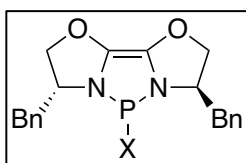
(a) 4,5-Dihydro-2-(4,5-dihydro-4,4-di-(*R*)-benzyloxazol-2-yl)-4,4-

dimethyloxazole (0.50 g, 1.56 mmol, 1 equiv.) was dissolved in

DCM (10 mL) in a Schlenk flask under N$_2$ and stirred. To the

solution cyclohexene (0.47 mL, 4.68 mmol, 3 equiv.) and PBr$_3$ (0.15 mL, 1.56 mmol, 1

equiv.) and stirred for 16 h. The solvent was removed *in vacuo* and the crude was brought

into the glovebox. The crude was washed with ether and collected by suction filtration as

a white solid. No product was observed by NMR.

(b) 4,5-Dihydro-2-(4,5-dihydro-4,4-di-(*R*)-benzyloxazol-2-yl)-4,4-dimethyloxazole (0.10

g, 0.312 mmol, 1 equiv.) was dissolved in toluene (3 mL) and stirred in the glovebox. To

the solution was added PI$_3$ (0.13 g, 0.312 mmol, 1 equiv.) and stirred for 16 h. The

solvent was removed *in vacuo*. No product was observed by NMR.

(c) 4,5-Dihydro-2-(4,5-dihydro-4,4-di-(*R*)-benzyloxazol-2-yl)-4,4-dimethyloxazole (0.05

g, 0.156 mmol, 1 equiv.) was dissolved in THF (1 mL) in the glovebox and stirred. To the

solution SnCl$_2$ (0.03 g, 0.156 mmol, 1 equiv.) was added and stirred for 15 min, followed

by the addition of PCl₃ (0.014 mL, 0.156 mmol, 1 equiv.) for 4 h. The solvent was removed *in vacuo*, and no product was observed by NMR.

N,N'-Bis-((R)-1-naphthyethyl)3-methylcyclopropanethane-1,2-diimine (3.37):
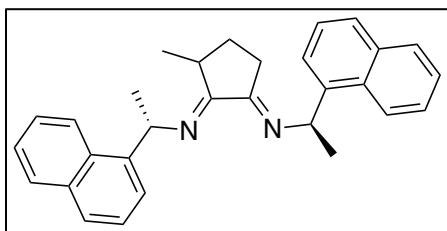
3-Methyl-1,2-cyclopentanone (2.5 g, 22.30 mmol, 1 equiv.) was dissolved in DCM (20 mL) with sieves and stirred under N₂. To the solution (*R*)-1-naphthylethylamine (7.6 mL, 22.30 mmol, 2 equiv.) and formic acid (5 drops) were added and stirred for 7 d at reflux. The product was observed 20% as an inseperable mixture.

2-Halo-1,3-*bis*{(R)1-(naphthalen-1-yl)ethyl}-1,3,2-diazaphosphole (3.38):
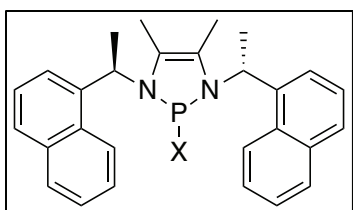
(a) (*R*)-1-(Naphthalen-1-yl)ethyl-2,3-dimethyldiimine (0.0-5g, 0.127 mmol, 1 equiv.) was dissolved in THF (1 mL) in the glovebox and stirred. To the solution SnCl₂ (0.024 g, 0.127 mmol, 1 equiv.) was added and stirred for 15 min, followed by the addition of PCl₃ (0.011 mL, 0.127 mmol, 1 equiv.) stirred for 4 h. The solvent was removed *in vacuo*, and no conversion to the product was observed.

(b) (*R*)-1-(Naphthalen-1-yl)ethyl-2,3-dimethyldiimine (0.66 g, 1.68 mmol, 1 equiv.) was dissolved in DCM (15 mL) in a Schlenk flask under N₂. To the solution cyclohexene (0.51 mL, 5.04 mmol, 3 equiv.) and PBr₃ (0.16 mL, 1.68 mmol, 1 equiv.) were stirred for 16 h. The solvent was removed *in vacuo*, and the brown crude was brought into the glovebox where it was washed with ether and collected as a brown solid by suction filtration. No product was observed by NMR.

2,3-Butanedione-(2,6-diisopropylphenyl)imine (3.39):
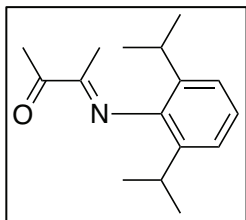
2,3-Methylbutadione (5 mL, 56.98 mmol, 1 equiv.) was dissolved in benzene (15 mL) with Na_2SO_4 under N_2 and stirred. To the mixture 2,6-diisopropylphenylamine (10.8 mL, 56.98 mmol, 1 equiv.) and p-toluenesulfonic acid (0.11 g, 0.570 mmol, 0.01 equiv.) were added and stirred for 4 d. The Na_2SO_4 was removed by suction filtration and the filtrate was concentrated *in vacuo* to afford the product as a dark oil (13.0 g, 93%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.21-7.13 (m, 3H), 2.62 (s, 3H), 2.61-2.58 (m, 2H), 1.85 (s, 3H), 1.19-1.16 (m, 12H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 200.1, 166.7, 134.6, 124.4, 123.1, 28.4, 24.9, 23.1, 22.7, 15.0.

N-(2,6-Diisopropylphenyl)-N'-((R)-1-naphthyethyl)ethane)-1,2-diimine (3.40):
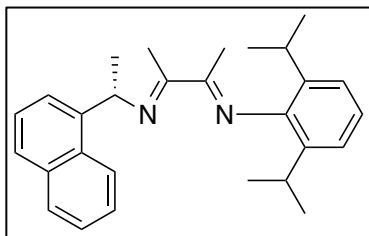
2,3-Butanedione-(2,6-diisopropylphenyl)imine **3.39** (3.5 g, 14.26 mmol, 1 equiv.) was dissolved in DCM (20 mL) and stirred under N_2 with sieves. To the solution *(R)*-1-naphthethylamine (2.29 mL, 14.26 mmol, 1 equiv.) and formic acid (5 drops) were added and stirred for 8 d. The solvent was removed *in vacuo*, and the crude was taken up in MeOH and stored in the freezer for 2 d. The MeOH solution was decanted from the oil at the bottom of the flask, which was then further washed and decanted with pentane to afford the product as a yellow oil (4.0 g, 70%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 8.40 (d, J= 8.5 Hz, 1H), 7.92 (dd, J= 8.1, 14.2 Hz, 2H), 7.84-7.83 (m, 1H), 7.63-7.54 (m, 3H), 7.23-7.12 (m, 3H), 5.69 (q, J= 6.6 Hz, 1H), 2.81-2.75 (m, 1H), 2.66-2.61 (m, 1H), 2.39 (s, 3H), 2.10 (s, 3H), 1.76 (d, J= 6.6 Hz, 3H), 1.27-1.13 (m, 12H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 146.5, 141.9, 135.2, 135.1, 134.1, 130.7, 129.1, 127.2, 125.8, 125.4, 124.3, 123.7, 123.5, 122.9, 57.6, 28.3, 28.2, 24.4, 23.2, 23.1, 22.9, 22.7, 16.5, 13.0.

HRMS (ESI): 399.2807, $[C_{28}H_{35}N_2]^+$ requires 399.2795.

2-Halo-1-{(*R*)1-(naphthalen-1-yl)ethyl},3-(2,6-diisopropyl)-2,3-dimethyl-1,3,2-diazaphosphole (3.41):
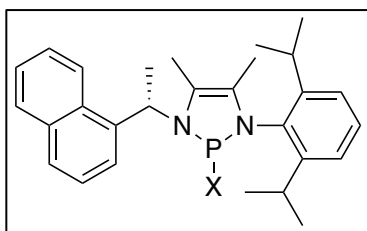
(a) *N*-(2,6-Diisopropylphenyl)-*N'*-((*R*)-1- naphthye-thyl)-ethane)-1,2-diimine **3.40** (0.10 g, 0.251 mmol, 1 equiv.) was dissolved in DCM (5 mL) in a Schlenk flask under N$_2$ and stirred. To the solution cyclohexene (0.076 mL, 0.702 mmol, 3 equiv.) and PBr$_3$ (0.024 mL, 0.251 mmol, 1 equiv.) were added and stirred for 16 h. The solvent was removed *in vacuo* and the red solid was washed with ether and collected by suction filtration in the glovebox. No conversion to the product was observed by NMR.

(b) *N*-(2,6-Diisopropylphenyl)-*N'*-((*R*)-1-naphthyethyl)ethane)-1,2-diimine **3.40** (0.50 g, 1.25 mmol, 1 equiv.) was dissolved in THF (5 mL) in a 4 dram vial in the glovebox and stirred. To the solution was added Li metal (0.03 g, 4.26 mmol, 3.4 equiv.) and stirred for 16 h. The excess Li metal was removed by filtration, and the red/purple solution was placed in the freezer at -35°C, followed by the addition of NEt$_3$HCl (0.363g, 2.63 mmol, 2.1 equiv.), and then warmed to room temperature and stirred for 4 h. The solution was again cooled to -35°C in the freezer, and cold PCl$_3$ (0.109 mL, 1.25 mmol, 1 equiv.) was added and stirred at room temperature for 16 h. The solvent was removed *in vacuo*, but no product was observed by NMR.

N-(1-((*R*)1-Naphthalenyl)ethyl)-benzamide (3.42):
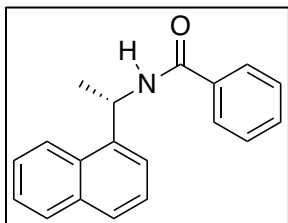
(R)-Naphthethylamine (3.36 mL, 29.19 mmol, 1 equiv.) was dissolved in DCM (80 mL) and stirred under N_2. To the solution benzylchloride (4.68 mL, 29.19 mmol, 1 equiv.) and NEt_3 (4.06 mL, 29.19 mmol, 1 equiv.) were added and stirred for 48 h. The solvent was removed *in vacuo*, DCM (50 mL) was added to the residue, then washed with water and the resulting organic solution was concentrated *in vacuo* to afford the product[94] as a white solid (7.3 g, 91%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 8.22 (d, *J*= 8.47 Hz, 1H), 7.93-7.92 (m, 1H), 7.87 (d, *J*= 8.23 Hz, 1H), 7.78-7.76 (m, 2H), 7.65-7.63 (m, 1H), 7.58-7.49 (m, 4H), 7.44-7.49 (m, 2H), 6.37-6.36 (m, 1H), 6.17 (p, *J*= 6.9 Hz, 1H), 1.83 (d, *J*= 6.8 Hz, 3H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 138.2, 134.5, 134.0, 131.5, 131.3, 128.8, 128.6, 126.9, 126.7, 125.9, 125.2, 123.5, 122.7, 45.3, 20.7.

N-((*R*)-1-Naphthethyl)phenyl-imidoyl chloride (3.43):
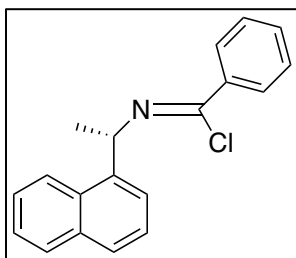
N-(1-((*R*)1-Naphthalenyl)ethyl)-benzamide **3.42** (0.50 g, 1.82 mmol, 1 equiv.) was dissolved in DCM (20 mL) and stirred under N_2. To the solution oxalylchloride (0.16 mL, 1.82 mmol, 1 equiv.) and 2,6-lutidine (0.21 mL, 1.82 mmol, 1 equiv.) were added and stirred for 24 h. The solvent was removed *in vacuo*, and the crude was used without any further purification (0.52 g, 97%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 8.13-8.11 (m, 2H), 7.92-7.90 (m, 1H), 7.85 (7.83 (m, 1H), 7.80-7.76 (m, 1H), 7.59-7.50 (m, 3H), 7.40-7.33 (m, 3H), 7.26-7.24 (m, 2H), 5.95 (m, 1H), 1.75 (d, *J*= 7.7 Hz, 3H).

N-((*R*)-1-Naphthethyl)phenyl-imidoyl diphenylmethanamine (3.44):
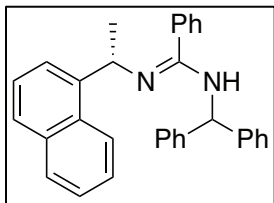
N-((*R*)-1-Naphthethyl)phenyl-imidoyl chloride **3.43** (0.53 g, 1.81 mmol, 1 equiv.) was dissolved in toluene (20 mL) under N_2. To the solution diphenylmethanamine (0.31 mL, 1.81 mmol, 1 equiv.) was added and stirred at reflux for 16 h. The solvent was removed *in vacuo*, and the crude was dissolved in DCM (15 mL) and stirred with a saturated solution of $NaHCO_3$ (15 mL) for 1 h. The organic layer was dried over Na_2SO_4 and the solvent was removed *in vacuo* to afford the crude which was crystalized in EtOH, and collected by suction filtration as a white solid (0.1g, 13%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 8.23-8.22 (m, 1H), 7.93-7.91 (m, 1H), 7.87-7.86 (m, 1H), 7.78-7.76 (m, 2H), 7.65-7.63 (m, 1H), 7.58-7.48 (m, 6H), 7.44-7.35 (m, 7H), 7.28-7.25 (m, 3H), 6.38-6.37 (m, 1H), 6.21-6.16 (m, 1H), 1.84-1.81 (overlap, 4H).

2-Chloro-1-{(*R*)1-(naphthalen-1-yl)ethyl},3-(diphenylmethane)-4-nitro-5-phenyl 1,4,2-diazaphosphole (3.45):
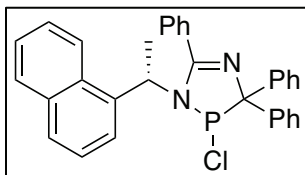
N-((R)-1-Naphthethyl)phenyl-imidoyl diphenylmethanamine **3.44** (0.08 g, 0.170 mmol, 1 equiv.) was dissolved in THF (5 mL) under N_2 and stirred in a Schlenk flask. The solution was cooled to 0 °C, followed by the addition of 1 M LiHMDS (0.17 mL, 0.170 mmol, 1 equiv.), which was stirred for 15 min. To the solution PCl_3 (0.015 mL, 0.170 mmol, 1 equiv.) was added and stirred for 16 h. The solvent was removed *in vacuo* and the crude was dissolved in toluene in the glovebox, filtered over celite and concentrated *in vacuo*. No product was observed by NMR.

(*S*)-*N*-(Prop-2-ynyl)-2,3-dihydro-1*H*-inden-1-amine (Rasagiline) (3.46):
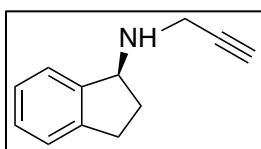
132

N-(2,3-Dihydroinden-1-ylidene)prop-2-yn-1-amine (200 mg, 1.18 mmol, 1 equiv.) was dissolved in THF (1 mL) and stirred. Pre-catalyst **3.32** (11 mg, 0.023 mmol, 0.02 equiv.) and HB(pin) (0.17 mL, 1.18 mmol, 1 equiv.) were added and the mixture was stirred for 16 h. The solvent was removed *in vacuo* and the work up from the general procedure was performed to afford the product[28] (170 mg, 84%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.39-7.38 (m, 1H), 7.30-23 (m, 3H), 4.46 (t, *J*= 5.8 Hz, 1H), 3.61-3.52 (m, 2H), 3.11-3.05 (m, 1H), 2.90-2.84 (m, 1H), 2.47-2.41 (m, 1H), 2.30 (t, *J*= 2.4 Hz, 1H), 1.93-1.88 (m, 1H), 1.57 (br.s, 1H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 144.5, 143.8, 127.7, 126.3, 124.9, 124.2, 82.5, 71.4, 61.9, 36.2, 33.4, 30.5.

The enantiomeric excess was determined by HPLC on an Astec Cellulose DMP column, t_{major}= 19.479 min, t_{min}= 20.556 min. Enantiomeric ratio= 85:15.

$[\alpha]^{21}_D$= -11.25° (c=1.3, CHCl$_3$)

HRMS (ESI): 172.1116, $[C_{12}H_{14}N]^+$ requires 172.1121.

Elemental analysis: Calculated for $[C_{12}H_{13}N]$ C: 84.17, H: 7.65, N: 8.18. Calculated C: 83.47, H: 7.35, N: 7.86.

(*S*)-*N*-Benzyl-*N'*-(*tert*-butyloxycarbonyl)-2,3-dihydro-1*H*-inden-1-amine (3.47):
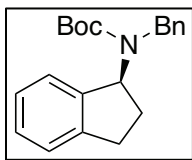
N-(2,3-Dihydroinden-1-ylidene)(phenyl)methanamine (400 mg, 1.81 mmol, 1 equiv.) was dissolved in THF (2 mL) and stirred. Pre-catalyst **3.32** (17.0 mg, 0.036 mmol, 0.02 equiv.) and HB(pin) (0.26 mL, 1.81 mmol, 1 equiv.) were added and the mixture was stirred for 16 h. The solvent was removed *in vacuo*, and the workup from the general procedure was performed to afford the free amine product[28] (302 mg, 75%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.44-7.23 (m, 9H), 4.33 (t, J= 6.4 Hz, 1H), 3.98-3.88 (m, 2H), 3.11-3.01 (m, 1H), 2.89-2.81 (m, 1H), 2.48-2.42 (m, 1H), 1.97-1.90 (m, 1H), 1.69 (br. s, 1H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 145.3, 143.7, 140.7, 128.4, 128.2, 127.4, 126.9, 126.3, 124.8, 124.1, 62.8, 51.4, 33.7, 30.4.

HRMS (ESI): 224.1438, $[C_{16}H_{18}N]^+$ requires 224.1434.

The amine (100 mg, 0.45 mmol, 1 equiv.) was dissolved in DCM (5 mL) and stirred. NEt$_3$ (0.062 mL, 0.45 mmol, 1 equiv.) and di-*tert*-butyl dicarbonate (0.103 mL, 0.45 mmol, 1 equiv.) were added and the mixture was stirred for 48 h. The solvent was removed *in vacuo* and the product was passed through a basic aluminum column with 10% EtOAc in hexanes. The product fractions were collected and concentrated to afford the product[95] (130 mg, 90%).

^{1}H NMR (500 MHz, 338K, CD$_3$CN): δ 7.34-7.12 (m, 9H), 5.59-5.58 (m, 1H), 4.55-4.16 (m, 2H), 2.95-2.89 (m, 1H), 2.84-2.79 (m, 1H), 2.35-2.32 (m, 1H), 2.05-1.97 (m, 1H), 1.40 (s, 9H).

^{13}C{^{1}H} NMR (125 MHz, 338K, CD$_3$CN): δ 155.9, 143.4, 142.7, 140.3, 128.1, 127.4, 127.0, 126.6, 126.2, 124.7, 123.8, 79.3, 62.5, 48.6, 30.3, 29.9, 27.6.

The enantiomeric excess was determined by HPLC on an Astec Cellulose DMP column, t$_{major}$=12.658 min, t$_{min}$= 10.449 min.

Enantiomeric ratio= 83:17.

$[\alpha]^{21}_D$= -19.43° (c= 1.47, EtOH).

HRMS (ESI): 346.1769, $[C_{21}H_{25}NNaO_2]^+$ requires 346.1778.

(*S*)-*N*-(4-Methoxybenzyl)-1-phenylethanamine (3.48):
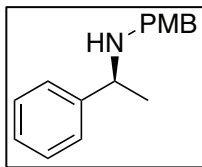
(4-Methoxyphenyl)-*N*-(1-phenylethylidene)methanamine (200 mg, 0.836 mmol, 1 equiv.) was dissolved in THF (1 mL) and stirred. Pre-catalyst **3.32** (8.1 mg, 0.017 mmol, 0.02 equiv.) and HB(pin) (0.121 mL, 0.836 mmol, 1 equiv.) were added and the mixture was stirred for 16h. The solvent was removed *in vacuo* and the work up from the general procedure was performed to afford the product[28] (181 mg, 90%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.39-7.21 (m, 7H), 6.89-6.86 (m, 2H), 3.84 (q, *J*= 6.6 Hz, 1H), 3.82 (s, 3H), 3.62 (ABq, *J*= 13.1 Hz, 1H), 3.60 (ABq, *J*= 12.8 Hz, 1H), 1.39 (d, *J*= 6.6 Hz, 3H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 158.6, 145.5, 132.6, 129.3, 128.5, 126.9, 126.8, 113.8, 57.4, 55.3, 51.0, 24.4.

The enantiomeric excess was determined by HPLC on an Astec Cellulose DMP column, t$_{major}$= 15.751 min, t$_{min}$= 16.455 min. Enantiomeric ratio= 85:15.

$[\alpha]^{21}_{D}$= -26.30° (c= 3.67, CHCl$_3$).

HRMS (ESI): 242.1544, $[C_{16}H_{20}NO]^{+}$ requires 242.1539.

(*S*)-*N*-Benzyl-1-(4'-cyanophenyl)ethylamine (3.49):
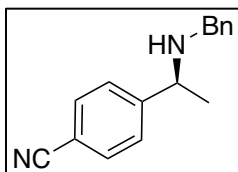
Phenyl-*N*-(4'-cyano-1-phenylethylidene)methanamine (200 mg, 0.85 mmol, 1 equiv.) was dissolved in THF (1 mL) and stirred. Pre-catalyst **3.32** (8.2 mg, 0.017 mmol, 0.02 equiv.) and HB(pin) (0.124 mL, 0.85 mmol, 1 equiv.) were added and the mixture was stirred for 16 h. The solvent was removed *in vacuo*, and the work up in the general procedure was performed to afford the product[30] (133 mg, 66%).

¹H NMR (500 MHz, CDCl₃): δ 7.68-7.66 (m, 2H), 7.54-7.52 (m, 2H), 7.35-7.34 (m, 1H), 7.30-7.29 (m, 4H), 3.91 (q, J= 6.6 Hz, 1H), 3.67 (ABq, J= 13.2 Hz, 1H), 3.61 (ABq, J= 13.2 Hz, 1H) 1.39 (d, J= 6.6 Hz, 3H), 1.31 (br. s, 1H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 151.4, 140.1, 132.4, 128.5, 128.0, 127.6, 127.1, 119.0, 110.8, 57.4, 51.8, 24.5.

The enantiomeric excess was determined by HPLC on an Astec Cellulose DMP column, t_{major}= 27.546 min, t_{min}= 25.459 min. Enantiomeric ratio= 81:19.

$[\alpha]^{21}_D$= +27.0° (c= 0.67, CHCl₃).

HRMS (ESI): 237.1377, $[C_{16}H_{17}N_2]^+$ requires 237.1386.

(*S*)- *N*-Benzyl-1-(4'-methoxy)phenylethylamine (3.50):
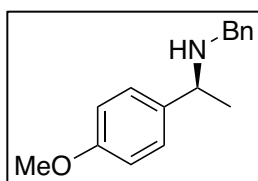
Phenyl-*N*-(4'-methoxy-1-phenylethylidene)methanamine (200 mg, 0.836 mmol, 1 equiv.) was dissolved in THF (1 mL) and stirred. Pre-catalyst **3.32** (8.1 mg, 0.017 mmol, 0.02 equiv.) and HB(pin) (0.121 mL, 0.836 mmol, 1 equiv.) were added and the mixture was stirred for 12 h. The solvent was removed *in vacuo* and the work up from the general procedure was performed to afford the product[30] (155 mg, 77%).

¹H NMR (500 MHz, CDCl₃): δ 7.36-7.27 (m, 7H), 6.94-6.92 (m, 2H), 3.85 (s, 3H), 3.81 (q, J= 6.6, 1H), 3.69 (ABq, J= 13.2 Hz, 1H), 3.63 (ABq, J= 13.2 Hz, 1H), 1.61 (br. s, 1H), 1.38 (d, J= 6.6 Hz, 3H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 158.6, 140.7, 137.6, 128.4, 128.2, 127.7, 126.8, 113.8, 56.8, 55.3, 51.6, 24.5.

The enantiomeric excess was determined by HPLC on an Astec Cellulose DMP column, t_{major}= 15.776 min, t_{min}= 17.609 min. Enantiomeric ratio= 87:13.

$[\alpha]^{21}{}_D$= -32.86° (c= 3.67, CHCl$_3$)

HRMS (ESI): 242.1540, [C$_{16}$H$_{20}$NO]$^+$ requires 242.1539.

(*S*)-*N*-(4-Methoxybenzyl)-1-4-methoxyphenylethanamine (3.51):
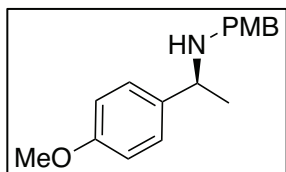
(4-Methoxyphenyl)-*N*-(4'-methoxy-1-phenylethylidene)methan-amine (200 mg, 0.74 mmol, 1 equiv.) was dissolved in THF (1 mL) and stirred. Pre-catalyst **3.32** (7.2 mg, 0.015 mmol, 0.02 equiv.) and HB(pin) (0.108 mL, 0.74 mmol, 1 equiv.) were added and the mixture was stirred for 16 h. The solvent was removed *in vacuo*, and the work up in the general procedure was performed to afford the product[22] (175 mg, 87%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.33-7.30 (m, 2H), 7.24-7.22 (m, 2H), 6.93-6.92 (m, 2H), 6.89-6.87 (m, 2H), 3.85 (s, 3H), 3.82 (s, 3H), 3.81-3.80 (overlapped, 1H), 3.64 (ABq, *J*= 13.0 Hz, 1H), 3.57 (ABq, *J*= 12.9 Hz, 1H), 1.38 (d, *J*= 6.6 Hz, 3H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 158.6, 129.4, 127.8, 113.9, 113.8, 56.7, 55.3, 50.8, 24.3.

The enantiomeric excess was determined by HPLC on an Astec Cellulose DMP column, t$_{major}$= 24.493 min, t$_{min}$= 23.649 min. Enantiomeric ratio= 88:12.

$[\alpha]^{21}{}_D$= -21.90° (c= 1.33, MeOH).

HRMS (ESI): 272.1637, [C$_{17}$H$_{22}$NO$_2$]$^+$ requires 272.1645.

(*S*)-*N*-Benzyl-*N*'(*tert*-butyloxycarbonyl)-1-(2-napthyl)ethylamine (3.52):
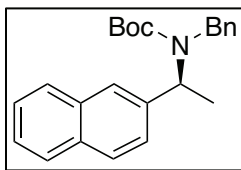
Phenyl-*N*-(2-napthylethylidene)methanamine (400 mg, 1.54 mmol, 1 equiv.) was dissolved in THF (2 mL) and stirred. Pre-catalyst **3.32** (14.9 mg, 0.028 mmol, 0.02 equiv.) and HB(pin) (0.15 mL, 1.54 mmol, 1 equiv.) were added and the mixture was stirred for 16 h. The solvent was

removed *in vacuo* and the workup from the general procedure was performed to afford the free amine product[30] (275 mg, 68%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.89-7.86 (m, 2H), 7.81 (s, 1H), 7.58-7.56 (m, 1H), 7.51-7.48 (m, 2H), 7.37-7.28 (m, 6H), 4.03 (q, *J*= 6.5 Hz, 1H), 3.73 (ABq, *J*= 13.1 Hz, 1H), 3.67 (ABq, *J*= 13.3 Hz, 1H), 1.58 (br. s, 1H), 1.48 (d, *J*= 6.6 Hz, 3H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 143.0, 140.7, 133.5, 132.9, 128.4, 128.3, 128.1, 127.8, 127.7, 126.9, 125.9, 125.5, 125.4, 124.9, 57.6, 51.7, 24.5.

HRMS (ESI): 262.1581, [C$_{19}$H$_{20}$N]$^+$ requires 262.1590.

The amine (275 mg, 1.05 mmol, 1 equiv.) was dissolved in DCM (5 mL) and stirred. Triethylamine (0.15 mL, 1.05 mmol, 1 equiv.) and di-*tert*-butyl dicarbonate (0.24 mL, 1.05 mmol, 1 equiv.) were added to the solution and stirred for 24 h. The solvent was removed *in vacuo* and the product was passed through a basic aluminum column with 10% EtOAc in hexanes. The product fractions were collected and the solvent was removed *in vacuo* to afford the product[96] (290 mg, 88%).

^{1}H NMR (500 MHz, 338K, CD$_3$CN): δ 7.89-7.80 (m, 4H), 7.53-7.47 (m, 3H), 7.28-7.22 (m, 5H), 5.55-5.54 (m, 1H), 4.54-4.26 (m, 2H), 1.62 (d, *J*= 7.1 Hz, 3H), 1.42 (s, 9H).

^{13}C{^{1}H} NMR (125 MHz, 338K, CD$_3$CN): δ 155.9, 140.3, 140.1, 133.3, 132.6, 128.0, 127.8, 127.7, 127.4, 127.1, 126.4, 126.1, 126.0, 125.8, 125.3, 79.5, 54.7, 47.7, 27.6, 17.4.

The enantiomeric excess was determined by HPLC on an Astec Cellulose DMP column, t_{major}= 17.409 min, t_{min}= 14.797 min.

Enantiomeric ratio= 84:16.

$[\alpha]^{21}_D$= -66.38° (c= 1.33, CHCl$_3$).

HRMS (ESI): 384.1919, [C$_{24}$H$_{27}$NNaO$_2$]$^+$ requires 384.1934.

(S)-N-Benzyl-1-(1-napthyl)ethylamine (3.53):

BnHN
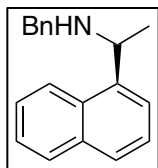
Phenyl-N-(1-napthylethylidene)methanamine (200 mg, 0.77 mmol, 1 equiv.), was dissolved in THF (1 mL) and stirred. Pre-catalyst **3.32** (7.4 mg, 0.015 mmol, 0.02 equiv.) and HB(pin) (0.112 mL, 0.77 mmol, 1 equiv.) were added and the mixture was stirred for 16 h. The solvent was removed *in vacuo*, and the work up in the general procedure was performed to afford the product[30] (145 mg, 72%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 8.22-8.21 (m, 1H), 7.94-7.92 (m, 1H), 7.80 (d, J= 7.6 Hz, 2H), 7.57-7.52 (m, 3H), 7.37-7.36 (m, 3H), 7.31-7.29 (m, 2H), 4.74 (q, J= 6.6 Hz, 1H), 3.81 (ABq, J= 13.1, 1H), 3.74 (ABq, J= 13.1 Hz, 1H) 1.71 (br. s, 1H), 1.57 (d, J= 6.6 Hz, 3H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 141.1, 140.7, 134.1, 131.4, 128.9, 128.4, 128.2, 127.3, 126.9, 125.8, 125.7, 125.3 123.1, 122.9, 53.1, 51.9, 23.7.

The enantiomeric excess was determined by HPLC on an Astec Cellulose DMP column, t_{major}= 19.040 min, t_{min}= 20.851 min. Enantiomeric ratio= 73:27.

$[\alpha]^{21}_D$= +21.2° (c= 0.73, CHCl$_3$).

HRMS (ESI): 262.1540, $[C_{19}H_{20}N]^+$ requires 262.1590.

(S)-N-(4-Methoxybenxyl)-N'(*tert*-butyloxycarbonyl) -1-(2'-chlorophenyl)ethylamine (3.54):

Boc—N—PMB
Cl
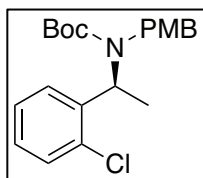
(4-Methoxyphenyl)-N-(2'-chloro-1-phenylethylidene)methanamine (-500 mg, 1.83 mmol, 1 equiv.) was dissolved in THF (4 mL) and stirred. Pre-catalyst **3.32** (17.6 mg, 0.037 mmol, 0.02 equiv.) and HB(pin) (0.27 mL, 1.83 mmol, 1 equiv.) were added and the mixture was stirred for 16 h. The

solvent was removed *in vacuo* and the workup from the general procedure was performed to afford the free amine product[30] (350 mg, 70%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.65-7.63 (m, 1H), 7.39-7.30 (m, 3H), 7.26-7.20 (m, 3H), 6.90-6.88 (m, 2H), 4.37 (q, *J*= 6.7 Hz, 1H), 3.83 (s, 3H), 3.63-3.57 (m, 2H), 1.38 (d, *J*= 6.6 Hz, 3H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 158.6, 142.6, 133.3, 132.7, 129.6, 129.3, 127.8, 127.5, 127.2, 113.9, 113.8, 55.3, 53.8, 51.2, 22.8.

HRMS (ESI): 276.1137, [C$_{16}$H$_{19}$ClNO]$^+$ requires 276.1150.

The amine (350 mg, 1.27 mmol, 1 equiv.) was dissolved in DCM (5 mL) and stirred. Triethylamine (0.18 mL, 1.27 mmol, 1 equiv.) and di-*tert*-butyl dicarbonate (0.29 mL, 1.27 mmol, 1 equiv.) were added to the solution and stirred for 24 h. The solvent was removed *in vacuo* and the product was passed through a basic aluminum column with 10% EtOAc in hexanes. The product fractions were collected and the solvent was removed *in vacuo* to afford the product (280 mg, 80%).

^{1}H NMR (500 MHz, 338K, CD$_3$CN): δ 7.49-7.25 (m, 4H), 7.05-6.79 (m, 4H), 5.61-5.58 (m, 1H), 4.37-4.24 (m, 2H), 3.78 (s, 3H), 1.48 (d, *J*= 7.1 Hz, 3H), 1.44 (s, 9H).

^{13}C{^{1}H} NMR (125 MHz, 338K, CD$_3$CN): δ 158.6, 139.8, 134.0, 132.1, 129.5, 128.7, 128.4, 128.2, 126.9, 113.5, 79.3, 54.9, 52.5, 46.4, 27.6, 17.2.

The enantiomeric excess was determined by HPLC on a Chiralpak ADH column, t$_{major}$= 13.731 min, t$_{min}$= 14.721 min.

Enantiomeric ratio= 80:20

[α]$^{21}_D$= -4.6° (c= 1.1, CHCl$_3$).

HRMS (ESI): 398.1487, [C$_{21}$H$_{26}$ClNNaO$_3$]$^+$ requires 398.1493.

Elemental analysis: Calculated for [$C_{21}H_{26}ClNO_3$] C: 67.10, H: 6.99, N: 3.73. Found C: 66.49, H: 6.59, N: 3.65.

(*S*)-*N*-(4'-Methoxybenzyl)-1-propargylphenylethanamine (3.55):
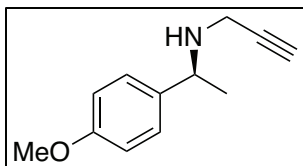
Propargyl-*N*-(4'-methoxy-1-phenylethylidene)methanamine (2-00 mg, 1.07 mmol, 1 equiv.) was dissolved in THF (1 mL) and stirred. Pre-catalyst **3.32** (10.0 mg, 0.021 mmol, 0.02 equiv.) and HB(pin) (0.155 mL, 1.07 mmol, 1 equiv.) were added to the and the mixture was stirred for 16 h. The solvent was removed *in vacuo*, and the workup from the general procedure was performed to afford the product (0.170, 84%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.29-7.26 (m, 2H), 6.90-6.87 (m, 2H), 3.99 (q, *J*= 6.6 Hz, 1H), 3.82 (s, 3H), 3.39-3.13 (m, 2H), 2.23 (t, *J*= 2.4 Hz, 1H), 1.56 (br. s, 1H), 1.36 (d, *J*= 6.6 Hz, 3H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 158.7, 136.4, 127.9, 113.8, 82.3, 71.2, 55.6, 55.3, 35.8, 23.9.

The enantiomeric excess was determined by HPLC on an Astec Cellulose DMP column, t_{major}= 17.396 min, t_{min}= 16.446 min.

Enantiomeric ratio= 84:16.

$[\alpha]^{21}_D$= -53.93° (c= 1.53, CHCl$_3$).

HRMS (ESI): 212.1048, [$C_{12}H_{15}NNaO$]$^+$ requires 212.1046.

(*S*)-*N*-Propargyl-1-(4'-cyanophenyl)ethylamine (3.56):
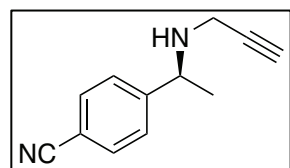
Propargyl-*N*-(4'-cyano-1-phenylethylidene)methanamine (200 mg, 1.10 mmol, 1 equiv.) was dissolved in THF (2 mL) and stirred. Pre-catalyst **3.32** (10.6 mg, 0.022 mmol, 0.02 equiv.) and

HB(pin) (0.160 mL, 1.10 mmol, 1 equiv.) were added and the mixture was stirred for 16 h. The solvent was removed *in vacuo* and the workup from the general procedure was performed to afford the product (180 mg, 89%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.66-7.503 (m, 4H), 4.14 (q, *J*= 6.6 Hz, 1H), 3.43-3.12 (m, 2H), 2.26 (t, *J*= 2.4 Hz, 1H), 1.60 (s, 1H), 1.38 (d, *J*= 6.6 Hz, 3H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 150.3, 132.4, 132.4, 127.7, 118.9, 111.1, 81.7, 71.7, 56.1, 35.9, 24.0.

The enantiomeric excess was determined by HPLC on an Astec Cellulose DMP column, t_{major}= 34.982 min, t_{min}= 33.513min.

Enantiomeric ratio= 71:29

$[\alpha]^{21}_D$= -26.63° (c= 1.33, CHCl$_3$).

HRMS (ESI): 207.0891, $[C_{12}H_{12}N_2Na]^+$ requires 207.0893.

(*S*)-*N*-Benzyl-*N'*-(*tert*-butyloxycarbonyl)-2-methyl-1-phenylpropylamine (3.57):
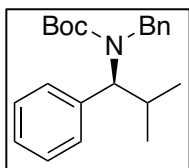
Phenyl-*N*-(1-phenylpropylidene)methanamine (400 mg, 1.69 mmol, 1 equiv.) was dissolved in THF (2 mL) and stirred. Pre-catalyst **3.32** (16.0 mg, 0.034 mmol, 0.02 equiv.) and HB(pin) (0.25 mL, 1.69, 1 equiv.) were added and the mixture was stirred for 16 h. The solvent was removed *in vacuo* and the workup from the general procedure was performed to afford the free amine product[97] (225 mg, 56%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.39-7.27 (m, 10H), 3.64 (ABq, *J*= 13.5 Hz, 1H), 3.50 (ABq, *J*= 13.5 Hz, 1H), 3.39 (d, *J*= 6.9 Hz, 1H), 1.97-1.87 (m, 1H), 1.02 (d, *J*= 6.9 Hz, 3H), 0.80 (d, *J*= 6.8 Hz, 3H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 142.9, 141.0, 128.3, 128.1, 128.0, 126.8, 126.7, 68.8, 51.8, 34.5, 19.7, 19.5.

HRMS (ESI): 240.1742, $[C_{17}H_{22}N]^+$ requires 240.1747.

The amine (160 mg, 0.67 mmol, 1 equiv.) was dissolved in DCM (5 mL) and stirred. Triethylamine (0.093 mL, 0.67 mmol, 1 equiv.) and di-*tert*-butyl dicarbonate (0.15 mL, 0.67 mmol, 1 equiv.) were added to the solution and stirred for 48 h. The solvent was removed *in vacuo* and the product was passed through a basic aluminum column with 10% EtOAc in hexanes. The product fractions were collected and the solvent was removed *in vacuo* to afford the product (200 mg, 88%).

¹H NMR (500 MHz, 338K, CD₃CN): δ 7.43-6.92 (m, 10H), 4.80-4.77 (m, 1H), 4.44-4.28 (m, 2H), 2.63-2.58 (m, 1H), 1.41 (s, 9H), 1.02 (d, *J*= 6.5 Hz, 3H), 0.83 (d, *J*= 6.5 Hz, 3H).

¹³C{¹H} NMR (125 MHz, 338K, CDCl₃): δ 129.0, 128.2, 127.6, 127.3, 127.1, 126.1, 47.4, 28.4, 27.6, 25.0, 20.0, 19.3.

The enantiomeric excess was determined by HPLC on an Astec Cellulose DMP column, t_{major}= 9.628min, t_{min}= 10.410min.

Enantiomeric ratio= 55:45.

$[\alpha]^{21}_D$= +14.58° (c= 2.4, CHCl₃).

HRMS (ESI): 362.2077, $[C_{22}H_{29}NO_2Na]^+$ requires 362.2091.

(*S*)-*N*-Cyclohexyl-*N*'(*tert*-butyloxycarbonyl)-1-(4'-methoxyphenyl)ethylamine (3.58):
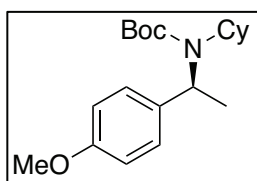
Cyclohexyl-*N*-(4'-methoxy-1-phenylethylidene)methanamine (500 mg, 2.16 mmol, 1 equiv.) was dissolved in THF (4 mL) and stirred. Pre-catalyst **3.32** (20.9 mg, 0.043 mmol, 0.02 equiv.) and HB(pin)

(0.314 mL, 2.16 mmol, 1 equiv.) were added and the mixture was stirred for 16 h. The solvent was removed *in vacuo* and the workup from the general procedure was performed to afford the free amine product[98] (420 mg, 83%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.25-7.24 (m, 2H), 6.90-6.89 (m, 2H), 3.95 (q, J= 6.6 Hz, 1H), 3.84 (s, 3H), 2.32-2.25 (m, 1H), 2.01-1.99 (m, 1H), 1.74-1.67 (m, 3H), 1.59 (s, 1H), 1.32 (d, J= 6.6 Hz, 3H), 1.22-1.01 (m, 6H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 158.4, 138.5, 127.4, 113.7, 55.2, 53.8, 53.5, 34.6, 33.3, 26.2, 25.3, 25.1, 25.0.

HRMS (ESI): 232.1687, [C$_{15}$H$_{22}$NO]$^+$ requires 232.1696.

The amine (290 mg, 1.24 mmol, 1 equiv.) was dissolved in DCM (5 mL) and stirred. Triethylamine (0.17 mL, 1.24 mmol, 1 equiv.) and di-*tert*-butyl dicarbonate (0.29 mL, 1.024 mmol, 1 equiv.) were added to the solution and stirred for 24 h. The solvent was removed *in vacuo* and the product was passed through a basic aluminum column with 10% EtOAc in hexanes. The product fractions were collected and the solvent was removed *in vacuo* to afford the product[98] (200 mg, 48%).

^{1}H NMR (500 MHz, 338K, CD$_3$CN): δ 7.32-7.30 (m, 2H), 6.91-6.90 (m, 2H), 5.15-5.14 (m, 1H), 3.82 (s, 3H), 3.21-3.20 (m, 1H), 1.81-1.67 (m, 5H), 1.56 (d, J= 7.0 Hz, 3H), 1.43-1.41 (m, 9H), 1.12-1.07 (m, 5H).

^{13}C{^{1}H} NMR (125 MHz, 338K, CD$_3$CN): δ 158.6, 135.1, 128.2, 113.3, 79.7, 55.0, 54.9, 52.2, 31.7, 30.9, 27.8, 26.2, 25.4, 17.4.

The enantiomeric excess was determined by HPLC on a Chiralpak ADH column, t_{major}= 11.029 min, t_{min}= 9.396 min.

Enantiomeric ratio= 67:33

$[\alpha]^{21}_D= -6.8°$ (c= 0.87, CHCl$_3$).

HRMS (ESI): 356.2199, $[C_{20}H_{31}NNaO_3]^+$ requires 356.2196.

(*S*)-*N*-Cyclopropyl-1-(4-methoxyphenyl)ethylamine (3.59):
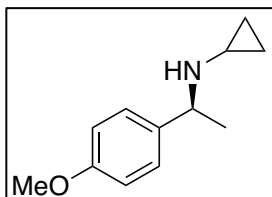
Cyclopropyl-*N*-(4'-methoxy-1-phenylethylidene)methanamine (-500 mg, 2.64 mmol, 1 equiv.) was dissolved in THF (3 mL) and stirred. Pre-catalyst **3.32** (25 mg, 0.053 mmol, 0.02 equiv.) and HB(pin) (0.38 mL, 2.64 mmol, 1 equiv.) were added and the mixture was stirred for 16 h. The solvent was removed *in vacuo* and the workup from the general procedure was performed to afford the product (450 mg, 89%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.35-7.32 (m, 2H), 6.92-6.89 (m, 2H), 3.93 (q, *J*= 6.7 Hz, 1H), 3.82 (s, 3H), 2.06-1.98 (m, 1H), 1.49 (d, *J*= 6.7 Hz, 3H), 1.27 (s, 1H), 0.55-0.42 (m, 4H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 158.8, 128.1, 113.9, 58.2, 55.3, 28.8, 22.7, 5.9, 5.5.

The enantiomeric excess was determined by HPLC on a Chiralpak ADH column, t_{major}= 13.539 min, t_{min}= 12.968 min.

Enantiomeric ratio= 69:31.

$[\alpha]^{21}_D= -15.5°$ (c= 1.3, CHCl$_3$).

HRMS (ESI): 192.1377, $[C_{12}H_{18}NO]^+$ requires 192.1383.

(*S*)-*N*-Benzyl-1-(pyridin-2-yl)ethanamine (3.60):
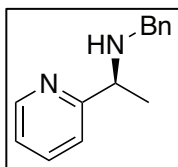
Phenyl-*N*-(1-(pyridine-2-yl)ethylidene)methanamine (200 mg, 0.95 mmol, 1 equiv.) was dissolved in THF (1 mL) and stirred. Pre-catalyst **3.32** (9.2 mg, 0.019 mmol, 0.02 equiv.) and HB(pin) (0.138 mL, 0.95 mmol, 1 equiv.) were added and the mixture was stirred for 16 h. The solvent was

removed *in vacuo*, and the work up in the general procedure was performed to afford the product[30] (173 mg, 86%).

¹H NMR (500 MHz, CDCl₃): δ 8.60 (dq, J = 1.79, 0.92 Hz, 1H), 7.67 (td, J = 7.65, 1.82 Hz, 1H), 7.38-7.16 (m, 7H), 3.95 (q, J = 6.7, 1H), 3.67-3.66 (m, 2H), 1.99 (s, 1H), 1.44 (d, J= 6.7 Hz, 3H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 164.6, 149.4, 140.5, 136.5, 128.3, 128.2, 126.8, 121.9, 121.2, 58.7, 51.8, 22.9.

The enantiomeric excess was determined by HPLC on an Astec Cellulose DMP column, t_{major}= 27.778 min, t_{min}= 26.054 min. Enantiomeric ratio= 73:27.

$[\alpha]^{21}_{D}$= -21.26° (c= 3.8, CHCl₃)

HRMS (ESI): 213.1390, $[C_{14}H_{17}N_2]^+$ requires 213.1386.

(*S*)-*N*-Furfuryl-*N'*(*tert*-butyloxycarbonyl)-1-(phenyl)ethylamine (3.61):
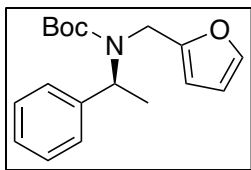
Furyl-*N*-(1-phenylethylidene)methanamine (300 mg, 1.51 mmol, 1 equiv.) was dissolved in THF (3 mL) and stirred. Pre-catalyst **3.32** (14 mg, 0.030 mmol, 0.02 equiv.) and HB(pin) (0.22 mL, 1.51 mmol, 1 equiv.) were added to the solution and stirred for 16 h. The solvent was removed *in vacuo* and the workup from the general procedure was performed to afford the free amine product[99] (230 mg, 76%).

¹H NMR (500 MHz, CDCl₃): δ 7.39-7.36 (m, 5H), 7.31-7.28 (m, 1H), 6.34-6.33 (m, 1H), 6.14-6.13 (m, 1H), 3.82 (q, J= 6.6 Hz, 1H), 3.70 (ABq, J= 14.5 Hz, 1H), 3.62 (ABq, J= 14.5 Hz, 1H), 1.69 (s, 1H), 1.40 (d, J= 6.6 Hz, 3H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 154.1, 145.1, 141.7, 128.5, 127.0, 126.8, 110.1, 106.8, 57.1, 44.0, 24.3.

HRMS (ESI): 202.1225, $[C_{13}H_{16}NO]^+$ requires 202.1226.

The amine product (230 mg, 1.14 mmol, 1 equiv.) was dissolved in DCM (3 mL) and stirred. NEt$_3$ (0.16 mL, 1.14 mmol, 1 equiv.) and di-*tert*-butyloxycarbonylanhydride (0.26 mL, 1.14 mmol, 1 equiv.) were added to the solution and stirred for 24 h. The solvent was removed *in vacuo* and the product was passed through a basic aluminum column with 10% EtOAc: hexanes. The product was collected and solvent was removed *in vacuo* to afford the product (250 mg, 70%).

^{1}H NMR (500 MHz, 338K, CD$_3$CN): δ 7.38-7.28 (m, 5H), 6.35-6.34 (m, 1H), 6.14-6.13 (m, 1H), 4.45-4.15 (m, 2H), 2.03 (s, 1H), 1.55 (d, *J*= 7.2 Hz, 3H), 1.43 (s, 9H).

^{13}C{^{1}H} NMR (125 MHz, 338K, CD$_3$CN): δ 155.3, 153.4, 142.4, 141.3, 128.2, 126.9, 126.8, 116.9, 116.7, 107.3, 107.0, 79.5, 54.3, 40.8, 27.6, 17.0.

The enantiomeric excess was determined by HPLC on a Chiralpak ADH column, t$_{major}$= 10.729 min, t$_{min}$= 9.490 min.

Enantiomeric ratio= 84:16.

$[\alpha]^{21}_D$= -34.3° (c= 1.1, CHCl$_3$).

HRMS (ESI): 324.1562, $[C_{18}H_{23}NNaO_3]^+$ requires 324.1570.

(*S*)-*N*-Benzyl-*N'*-(*tert*-butyloxycarbonyl)-1-(ferrocene)ethylamine (3.62):
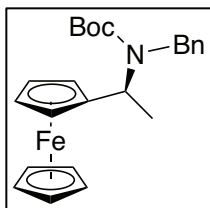
Phenyl-*N*-(1-ferroceneethylidene)methanamine (500 mg, 1.58 mmol, 1 equiv.) was dissolved in THF (3 mL) and stirred. Pre-catalyst **3.32** (15 mg, 0.032 mmol, 0.02 equiv.) and HB(pin) (0.23 mL, 1.58 mmol, 1 equiv.) were added to the solution and stirred for 16 h. The solvent was removed *in vacuo* and the workup from the general procedure was performed to afford the free amine product (350 mg, 70%).

¹H NMR (500 MHz, CDCl₃): δ 7.37-7.36 (m, 4H), 7.30-7.29 (m, 1H), 4.22-4.21 (m, 2H), 4.16-4.14 (m, 7H), 3.88-3.80 (m, 2H), 3.61 (q, J= 6.5 Hz, 1H), 1.59 (s, 1H), 1.46 (d, J= 6.5 Hz, 3H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 140.8, 128.4, 128.1, 126.9, 93.7, 68.4, 67.4, 67.3, 67.2, 65.9, 51.4, 51.4, 21.6.

HRMS (ESI): 319.1016, $[C_{19}H_{21}FeN]^+$ requires 319.1018.

The amine (350 mg, 1.10 mmol, 1 equiv.) was dissolved in DCM (5 mL) and stirred. Triethylamine (0.15 mL, 1.10 mmol, 1 equiv.) and di-*tert*-butyl dicarbonate (0.25 mL, 1.10 mmol, 1 equiv.) were added to the solution and stirred for 24 h. The solvent was removed *in vacuo* and the product was passed through a basic aluminum column with 10% EtOAc in hexanes. The product fractions were collected and the solvent was removed *in vacuo* to afford the product (335 mg, 73%).

¹H NMR (500 MHz, 338K, CD₃CN): δ 7.28-7.16 (m, 5H), 5.34-5.33 (m, 1H), 4.34-4.07 (m, 11H), 2.03 (s, 1H), 1.47 (d, J= 7.1 Hz, 3H), 1.42 (s, 9H).

¹³C{¹H} NMR (125 MHz, 338K, CD₃CN): δ 155.4, 140.6, 127.8, 127.0, 126.2, 89.6, 79.1, 68.7, 68.4, 68.0, 67.0, 66.8, 27.6, 17.3.

The enantiomeric excess was determined by HPLC on a Chiralpak ADH column, t_{major}= 10.656 min, t_{min}= 9.791 min.

Enantiomeric ratio= 75:25

$[\alpha]^{21}_D$= 63.9° (c= 1.3, CHCl₃).

HRMS (ESI): 419.1526, $[C_{24}H_{29}FeNO_2]^+$ requires 419.1542.

Elemental analysis: Calculated for $[C_{24}H_{29}FeNO_2]$ C: 68.74, H: 6.97, N: 3.34. Found C: 68.64, H: 6.79, N: 3.32.

(*S*)-*N*-Benzyl-*N'*(*tert*-butyloxycarbonyl)-1-(3,4,5-trimethoxyphenyl)ethylamine (3.63):
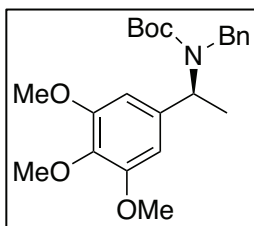
Phenyl-*N*-(3,4,5-trimethoxy-1-phenylethylidene)methanamine (500 mg, 1.67 mmol, 1 equiv.) was dissolved in THF (3 mL) and stirred. Pre-catalyst **3.32** (16 mg, 0.033 mmol, 0.02 equiv.) and HB(pin) (0.24 mL, 1.67 mmol, 1 equiv.) were added and the mixture was stirred for 16 h. The solvent was removed *in vacuo* and the workup from the general procedure was performed to afford the free amine product (300 mg, 60%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.37-7.27 (m, 5H), 6.64 (s, 2H), 3.91 (s, 6H), 3.89 (s, 3H), 3.79 (q, *J*= 6.4 Hz, 1H), 3.72(ABq, *J*= 13.2 Hz, 1H), 3.66 (ABq, *J*= 13.2 Hz, 1H), 1.61 (s, 1H), 1.39 (d, *J*= 6.6 Hz, 3H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 153.3, 141.5, 140.7, 136.8, 128.4, 128.1, 126.9, 103.5, 60.8, 57.9, 56.1, 51.8, 24.7.

HRMS (ESI): 302.1743, [C$_{18}$H$_{24}$NO$_3$]$^+$ requires 302.1751.

The amine (300 mg, 0.995 mmol, 1 equiv.) was dissolved in DCM (3 mL) and stirred. Triethylamine (0.14 mL, 0.995 mmol, 1 equiv.) and di-*tert*-butyl dicarbonate (0.23 mL, 0.995 mmol, 1 equiv.) were added to the solution and stirred for 48 h. The solvent was removed *in vacuo* and the product was passed through a basic aluminum column with 10% EtOAc in hexanes. The product fractions were collected and the solvent was removed *in vacuo* to afford the product (280 mg, 73%).

^{1}H NMR (500 MHz, 338K, CD$_3$CN): δ 7.30-7.21 (m, 5H), 6.57 (s, 2H), 5.30-5.29 (m, 1H), 4.47-4.27 (m, 2H), 3.78 (s, 6H), 3.74 (s, 3H), 1.51 (d, *J*= 7.1 Hz, 3H), 1.44 (s, 9H).

¹³C{¹H} NMR (125 MHz, 338K, CD₃CN): δ 155.8, 153.2, 140.3, 138.0, 137.7, 128.0, 127.2, 126.4, 105.4, 79.4, 59.8, 55.9, 54.6, 47.5, 27.7, 17.2.

The enantiomeric excess was determined by HPLC on an Astec cellulose-DMP column eluted with 98:2 hexanes/isopropanol, at 0.7 mL/min, t_{major}= 21.609 min, t_{min}= 19.966 min.

Enantiomeric ratio= 87:13.

$[\alpha]^{21}_D$= -22.4° (c= 0.87, CHCl₃).

HRMS (ESI): 424.2103, $[C_{23}H_{31}NNaO_5]^+$ requires 424.2094.

Elemental analysis: Calculated for $[C_{23}H_{31}NO_5]$ C: 68.80, H: 7.80, N: 3.49. Found C: 67.90, H: 7.34, N: 3.42.

(*S*)-*N*-Paramethoxybenzyl-*N*'(*tert*-butyloxycarbonyl)-1-(3,4,5-trimethoxyphenyl)ethylamine (3.64):
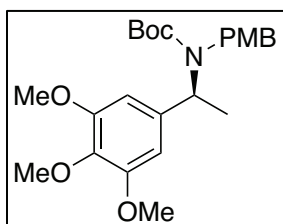
(4-Methoxyphenyl)-*N*-(3,4,5-trimethoxy-1-phenylethylidene)-m-ethanamine (500 mg, 1.52 mmol, 1 equiv.) was dissolved in THF (3 mL) and stirred. Pre-catalyst **3.32** (14.7 mg, 0.030 mmol, 0.02 equiv.) and HB(pin) (0.22 mL, 1.52 mmol, 1 equiv.) were added and the mixture was stirred for 16 h. The solvent was removed *in vacuo* and the workup from the general procedure was performed to afford the free amine product (350 mg, 70%).

¹H NMR (500 MHz, CDCl₃): δ 7.24-7.23 (m, 2H), 6.90-6.88 (m, 2H), 6.63 (s, 2H), 3.91 (s, 6H), 3.89 (s, 3H), 3.84 (s, 3H), 3.77 (q, *J*= 6.5 Hz, 1H), 3.65 (ABq, *J*= 13.0 Hz, 1H), 3.58 (ABq, *J*= 3.58 Hz, 1H), 1.54 (s, 1H), 1.38 (d, *J*= 5.9 Hz, 3H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 158.6, 153.3, 141.5, 136.8, 132.8, 129.3, 113.8, 103.5, 60.8, 57.8, 56.1, 55.3, 51.1, 24.6.

HRMS (ESI): 332.1847, [C$_{19}$H$_{26}$NO$_4$]$^+$ requires 332.1856.

The amine (350 mg, 1.06 mmol, 1 equiv.) was dissolved in DCM (3 mL) and stirred. Triethylamine (0.15 mL, 1.06 mmol, 1 equiv.) and di-*tert*-butyl dicarbonate (0.24 mL, 1.06 mmol, 1 equiv.) were added to the solution and stirred for 48 h. The solvent was removed *in vacuo* and the product was passed through a basic aluminum column with 10% EtOAc in hexanes. The product fractions were collected and the solvent was removed *in vacuo* to afford the product (315 mg, 87%).

^{1}H NMR (500 MHz, 338K, CD$_3$CN): δ 7.15-7.13 (m, 4H), 6.54 (s, 2H), 5.23 (m, 1H), 4.42-4.21 (m, 2H), 3.79-3.78 (m, 9H), 3.74 (s, 3H), 1.51 (d, *J*= 7.1 Hz, 3H), 1.44 (s, 9H).

^{13}C{^{1}H} NMR (125 MHz, 338K, CD$_3$CN): δ 158.7, 155.8, 153.1, 138.2, 137.6, 116.9, 113.4, 105.4, 79.3, 59.8, 55.9, 54.9, 54.6, 47.1, 27.7, 17.2.

The enantiomeric excess was determined by HPLC on an Astec cellulose-DMP column eluted with 98:2 hexanes/isopropanol, at 0.7 mL/min, t_{major}= 35.639 min, t_{min}= 31.333 min.

Enantiomeric ratio= 84:16.

[α]$^{21}_D$= -41.6° (c= 1.3, CHCl$_3$).

HRMS (ESI): 454.2197, [C$_{24}$H$_{33}$NNaO$_6$]$^+$ requires 454.2200.

(*S*)-*N*-2,2-Diphenylpropyl-1-(phenyl)ethylamine (3.65):
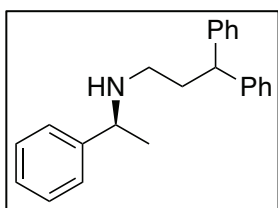
(2,2-Diphenyl)-*N*-(1-phenylethylidene)propanamine (500 mg, 1.59 mmol, 1 equiv.) was dissolved in THF (3 mL) and stirred. Pre-catalyst **3.32** (15.4 mg, 0.032 mmol, 0.02 equiv.) and

HB(pin) (0.23 mL, 1.59 mmol, 1 equiv.) were added and the mixture was stirred for 16 h. The solvent was removed *in vacuo* and the workup from the general procedure was performed to afford the product[30] (480 mg, 95%).

¹H NMR (500 MHz, CDCl₃): δ 7.33-7.17 (m, 15H), 4.02 (t, *J*= 7.7 Hz, 1H), 3.72 (q, *J*= 6.5 Hz, 1H), 2.54-2.44 (m, 2H), 2.29-2.21 (m, 2H), 1.42 (m, 1H), 1.33 (d, *J*= 6.6 Hz, 3H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 145.8, 145.0, 144.7, 128.4, 128.3, 127.9, 127.8, 126.8, 126.5, 126.1, 58.2, 49.1, 46.0, 36.1, 24.3.

The enantiomeric excess was determined by HPLC on a Chiralpak ADH column, t_{major}= 11.466 min, t_{min}= 12.898 min.

Enantiomeric ratio= 86:14

$[\alpha]^{21}_{D}$= -27.3° (c= 1.1, CHCl₃).

HRMS (ESI): 316.2065, $[C_{23}H_{26}N]^{+}$ requires 316.2060.

Elemental analysis: Calculated for $[C_{23}H_{25}N]$ C: 87.57, H: 7.99, N: 4.44. Found C: 86.61, H: 7.79, N: 4.40.

(*S*)-*N*-Phenyl-1-(phenyl)ethylamine (3.66):
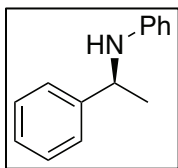
Phenyl-*N*-(1-phenylethylidene)methanamine (100 mg, 0.512 mmol, 1 equiv.) was dissolved in THF (1.5 mL) and stirred. Pre-catalyst **3.32** (25.0 mg, 0.051 mmol, 0.1 equiv.) and HB(pin) (0.074 mL, 0.512 mmol, 1 equiv.) were added and the mixture was stirred for 16 h. The solvent was removed *in vacuo* and the workup from the general procedure was performed to afford the product[30] (25 mg, 25%).

¹H NMR (500 MHz, CDCl₃): δ 7.36 (m, 2H), 7.31 (m, 2H), 7.22 (m, 1H), 7.08 (m, 2H) 6.63 (m, 1H), 6.51 (m, 2H), 4.48 (br. q, *J*= 6.5 Hz, 1H), 4.00, (br. s, 1H), 1.51 (d, 3H, *J*= 6.5 Hz).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 158.6, 147.5, 137.4, 129.2, 127.0, 117.3, 114.2, 113.5, 55.4, 53.0, 25.1

The enantiomeric excess was determined by HPLC on an Astec Cellulose DMP column, t_{major}= 18.110 min, t_{min}= 21.373 min.

Enantiomeric ratio= 62:38.

$[\alpha]^{21}_D$= -10.13° (c= 0.53, CH₂Cl₂).

(*S*)-*N*-Phenyl-1-(4-methoxyphenyl)ethylamine (3.67):
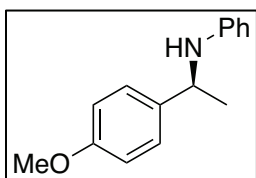
N-[1-(4-Methoxyphenyl)ethylidene]aniline (100 mg, 0.444 mmol, 1 equiv.) was dissolved in THF (1.5 mL) and stirred. Pre-catalyst **3.32** (21.0 mg, 0.044 mmol, 0.1 equiv.) and HB(pin) (0.064 mL, 0.512 mmol, 1 equiv.) were added and the mixture was stirred for 16 h. The solvent was removed *in vacuo* and the workup from the general procedure was performed to afford the product[30] (10 mg, 10%).

¹H NMR (500 MHz, CDCl₃): δ 7.28 (m, 2H), 7.09 (m, 2H), 6.85 (m, 2H), 6.63 (tt, *J*= 7.0, 1.0 Hz, 1H), 6.51 (m, 2H), 4.44 (q, *J*= 6.5 Hz, 1H), 3.98 (br. s, 1H), 3.78 (s, 3H), 1.49 (d, *J*= 6.5 Hz, 3H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 158.6, 147.5, 137.4, 129.2, 127.0, 117.3, 114.2, 113.5, 55.4, 53.0, 25.1.

The enantiomeric excess was determined by HPLC on an Astec Cellulose DMP column, t_{major}= 43.834 min, t_{min}= 45.717 min.

Enantiomeric ratio= 56:44.

$[\alpha]^{21}_D$= -5.75° (c= 0.80, CHCl$_3$).

(S)-N-Benzyl-1-(furfuryl)ethylamine (3.68):
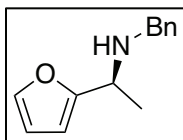
N-[1-(Furan-2-yl)ethylidene]benzylamine (200 mg, 1.00 mmol, 1 equiv.) was dissolved in THF (3 mL) and stirred. Pre-catalyst **3.32** (9.7 mg, 0.02 mmol, 0.02 equiv.) and HB(pin) (0.146 mL, 1.00 mmol, 1 equiv.) were added to the solution and stirred for 16 h. The solvent was removed *in vacuo* and the work-up from the general procedure was performed to afford the product[30] (142 mg, 71%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.31-7.22 (m, 6H), 6.32 (dd, *J* = 3.3, 1.8 Hz, 1H), 6.16 (d, *J*= 3.0 Hz, 1H), 3.89 (q, *J*= 7.0 Hz, 1H), 3.70 (ABq, 2H), 1.43 (d, *J*= 7.0, 3H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 158.0, 141.5, 140.5, 128.5, 128.3, 127.0, 110.0, 105.6, 51.3, 50.7, 20.6.

The enantiomeric excess was determined by HPLC on an Astec Cellulose DMP column, t_{major}= 13.421 min, t_{min}=14.268 min.

Enantiomeric ratio= 69:31.

(S)-N-Benzyl-1-(2'-chlorophenyl)ethylamine (3.69):
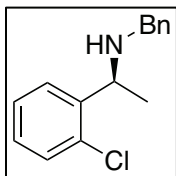
Phenyl-N-(2'-chloro-1-phenylethylidene)methanamine (200 mg, 0.821 mmol, 1 equiv.) was dissolved in THF (1 mL) and stirred. Pre-catalyst **3.32** (7.9 mg, 0.016 mmol, 0.02 equiv.) and HB(pin) (0.12 mL, 0.821 mmol, 1 equiv.) were added and the mixture was stirred for 16 h. The solvent was removed *in vacuo* and the work up from the general procedure was performed to afford the product[30] (161 mg, 80%).

¹H NMR (500 MHz, CDCl₃): δ 7.61 (dd, *J* = 7.5, 1.5 Hz, 1H), 7.35-7.22 (m, 7H), 7.17 (td, *J* = 8.0, 1.5 Hz, 1H), 4.34 (q, *J* = 6.5 Hz, 1H), 3.62 (ABq, 2H), 1.59 (br. s, 1H), 1.35 (d, *J*= 6.5 Hz, 3H)

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 142.6, 140.7, 133.5, 129.8, 128.5, 128.3, 127.9, 127.6, 127.3, 127.1, 54.0, 51.9, 22.9.

The enantiomeric excess was determined by HPLC on an Astec Cellulose DMP column, t_{major}= 13.868 min, t_{min}= 14.879 min. Enantiomeric ratio= 82:18.

(*S*)-*N*-Methyl-*N*'-(*tert*-butyloxycarbonyl)-1-(4-methoxyphenyl)ethylamine (3.70):
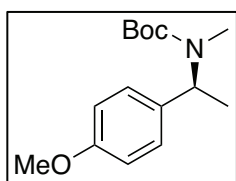
N-(4'-Methoxy-1-phenylethylidene)methanamine (400 mg, 2.45 mmol, 1 equiv.) was dissolved in THF (3 mL) and stirred. Pre-catalyst **3.32** (23.7 mg, 0.049 mmol, 0.02 equiv.) and HB(pin) (0.36 mL, 2.45 mmol, 1 equiv.) were added and the mixture was stirred for 16 h. The solvent was removed *in vacuo* and the workup from the general procedure was performed to afford the free amine product[22] (183 mg, 53%).

¹H NMR (500 MHz, CDCl₃): δ 7.32 (d, *J*= 8.5 Hz, 2H), 6.86 (d, *J*= 9.0 Hz, 2H), 3.80 (s, 3H), 3.59 (q, *J*= 6.5 Hz, 1H), 2.29 (s, 3H), 1.33 (d, *J*= 6.5 Hz, 3H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 158.7, 137.6, 127.7, 113.9, 59.7, 55.4, 34.6, 23.9.

The amine (122 mg, 0.74 mmol, 1 equiv.) was dissolved in DCM (5 mL) and stirred. Triethylamine (0.10 mL, 0.74 mmol, 1 equiv.) and di-*tert*-butyl dicarbonate (0.17 mL, 0.74 mmol, 1 equiv.) were added to the solution and stirred for 24 h. The solvent was removed *in vacuo* and the product was passed through a basic aluminum column with 10% EtOAc in hexanes. The product fractions were collected and the solvent was removed *in vacuo* to afford the product[72] (90 mg, 46%).

¹H NMR (500 MHz, 338K, CD₃CN): δ 7.26-7.24 (m, 2H), 6.94-6.93 (m, 2H), 5.41-5.37 (m, 1H), 3.82 (s, 3H), 2.60 (s, 3H), 1.50 (s, 9H).

¹³C{¹H} NMR (125 MHz, 338K, CD₃CN): δ 158.9, 155.6, 134.1, 128.0, 113.8, 78.9, 55.0, 52.5, 27.7, 16.1.

The enantiomeric excess was determined by HPLC on a Chiralpak ADH column, t_{major}= 17.684 min, t_{min}= 13.112 min.

Enantiomeric ratio= 66:34

$[\alpha]^{21}_D$= -26.4° (c= 1.9, CHCl₃).

(*S*)-*N*-2-Phenylpropyl-1-(4-methoxyphenyl)ethylamine (3.71):
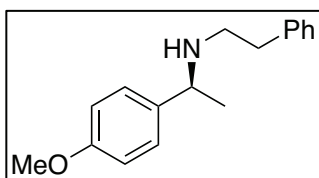
(2-Phenyl)-*N*-(4'-methoxy-1-phenylethylidene)ethanamine (-300 mg, 1.18 mmol, 1 equiv.) was dissolved in THF (2 mL) and stirred. Pre-catalyst **3.32** (11.4 mg, 0.024 mmol, 0.02 equiv.) and HB(pin) (0.17 mL, 1.18 mmol, 1 equiv.) were added and the mixture was stirred for 16 h. The solvent was removed *in vacuo* and the work-up from the general procedure was performed to afford the product[100] (190 mg, 76 %)

¹H NMR (500 MHz, CDCl₃): δ 7.32-7.19 (m, 7H), 6.89-6.88 (m, 2H), 3.83 (s, 3H), 3.77 (q, *J*= 6.5 Hz, 1H), 2.75 (m, 4H), 1.34 (d, *J*= 6.6 Hz, 3H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 158.5, 140.2, 137.8, 128.7, 128.4, 127.5, 126.1, 113.8, 57.5, 55.3, 48.9, 36.5, 24.3.

The enantiomeric excess was determined by HPLC on an Astec cellulose-DMP column, t_{major}= 21.064 min, t_{min}= 22.096 min.

Enantiomeric ratio= 81:19.

$[\alpha]^{21}_D$= -41.4° (c= 0.87, CHCl₃).

(*S*)-*N*-2,2-Diphenylpropyl-1-(4-methoxyphenyl)ethylamine (Fendiline) (3.72):
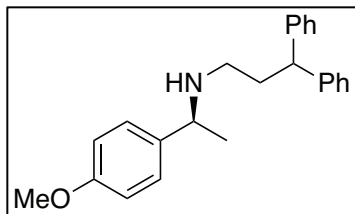
(2,2-Diphenyl)-*N*-(4'-methoxy-1-phenylethylidene)-propa-namine (500 mg, 1.46 mmol, 1 equiv.) was dissolved in THF (3 mL) and stirred. Pre-catalyst **3.32** (14.1 mg, 0.0292 mmol, 0.02 equiv.) and HB(pin) (0.211 mL, 1.46 mmol, 1 equiv.) were added, and the mixture was stirred for 16 h. The solvent was removed *in vacuo* and the workup from the general procedure was performed to afford the product[30] (401 mg, 80%).

¹H NMR (500 MHz, CDCl₃): δ 7.28-7.14 (m, 12H), 6.85-6.83 (m, 2H), 3.98 (t, *J*= 7.7 Hz, 1H), 3.81 (s, 3H), 3.65 (q, *J*= 7.3 Hz, 1H) 2.49-2.38 (m, 2H), 2.27-2.17 (m, 2H), 1.35 (br. s, 1H), 1.28 (d, *J*= 6.6 Hz, 3H).

¹³C{¹H} NMR (125 MHz, CDCl₃): δ 158.4, 145.0, 144.7, 137.8, 128.4, 127.9, 127.7, 127.5, 126.1, 113.7, 57.4, 55.3, 49.0, 46.0, 36.0, 24.3.

The enantiomeric excess was determined by HPLC on a Chiralpak ADH column with 98:2 hexanes/isopropanol at 0.7 mL/min, t_{major}= 10.168 min, t_{min}= 11.515 min.

Enantiomeric ratio= 79:21.

$[\alpha]^{21}_{D}$= -30.7° (c= 0.87, CHCl₃).

Chapter 4 : Cationic Phosphorus Compounds

4.1: Contributions

Mass spectrometric data were acquired by Mr. Xiao Feng (Mass Spectrometry Laboratory, Dalhousie University).

4.2: Introduction

Phosphorus[III] Lewis bases are a widely explored class of compounds. They are well studied and employed in FLP chemistry as a partner to split hydrogen and as ligands in metal chemistry. A lesser-known feature of phosphorus[III] containing molecules is their ability to act as Lewis acids. Although phosphorus acting as a Lewis acid is underexplored, one exception is its role in the Wittig reaction, as a phosphorus[V] ylide.[101]

In 2013 the Stephan group[102] showed an important example of phosphorus[V] acting as a Lewis acid, generated by reacting $P(C_6F_5)_3$ with XeF_2 to afford a phosphorus[V] compound that could then be converted into a Lewis acid by reacting it with $[^+SiEt_3][^-B(C_6F_5)_4]$. This compound was found to be highly Lewis acidic, and was competent in abstracting fluorides from molecules such as trifluorotoluene (Scheme 4.1).
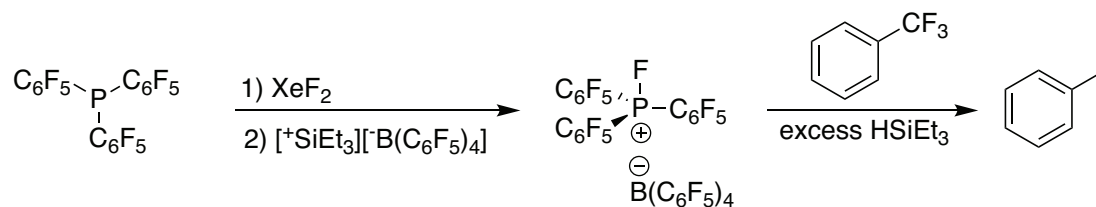
Scheme 4.1: Defluorination mediated *via* a phosphorus Lewis acid

Stephan was able to quantify the Lewis acidity of these phosphorus compounds using the Guttman-Childs measure of Lewis acidity. Upon mixing $^+P(C_6F_5)_3F$ with Et_3PO, a perturbation in the ^{31}P NMR spectrum about 1.5 times that than when mixed with BCF

was observed. This experiment showed that not only are phosphorus compounds able to act as Lewis acids, but they can be more Lewis acidic than BCF, which is well known as a strong Lewis acid.

In 2015 the Stephan group[103] further expanded on the idea of phosphorus acting as a Lewis acid. The development of increasingly Lewis acidic molecules has greatly expanded chemistry in this area. Since the genesis of FLP chemistry, FLPs are traditionally composed of a boron based Lewis acid and a phosphorus or nitrogen Lewis base. In their 2015 report, they were able to synthesize an FLP from only phosphorus-based reagents. This FLP was capable of splitting H_2, demonstrating the dual activity of phosphorus in Lewis acid/base chemistry. Scheme 4.2 represents evidence for the use of phosphorus reagents as Lewis acids, and their abilities in FLP chemistry.
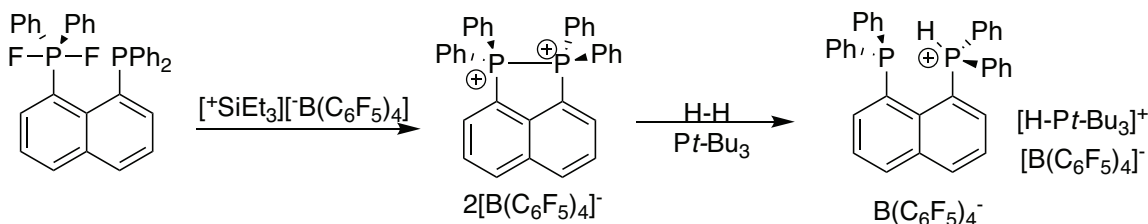
Scheme 4.2: Activation of dihydrogen with a phosphorus Lewis acid

During seminal studies by the Gudat group, the ability of diazaphospholenes to act as potential Lewis acids was disclosed.[2] Through the long phosphorus halogen bond of the diazaphospholene compounds, one can observe the dissociation of the halogen affording a variety of cationic phosphorus species. These compounds are uniquely stable due to the aromaticity of the cationic diazaphospholenes. When reacting a diazaphospholene hydride with $[Ph_3C^+][^-BF_4]$, the hydride is abstracted affording the cationic, Lewis acidic diazaphospholene (Scheme 4.3).
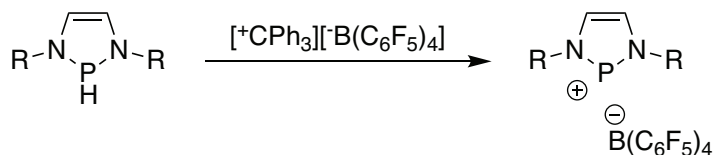
Scheme 4.3: Diazaphospholene cation

This chapter presents the first use of diazaphospholene Lewis acids developed in our laboratory. These catalysts behave as Lewis acids in a variety of Lewis acid catalyzed reactions such as the hydrosilylation of imines and ketones. Continuing efforts towards the activation of dihydrogen, and the hydrogenation of imines will be explained herein.

4.3: Results and Discussion

4.3.1: Synthesis of Cationic Diazaphospholenes

I sought to explore the use of diazaphospholenes as Lewis acids in the activation of dihydrogen, and their application in the reduction of imines. The idea was that using a common counterion such as BArF, would facilitate the synthesis of stable diazaphospholene cations. Upon mixing previously reported diazaphospholene bromides **2.5** and **2.6** with NaBArF in DCM, the generation of new cationic diazaphospholenes occurred, as seen by changes in the ^{31}P NMR spectra, with new shifts at δ 203.2, and 205.9 ppm, respectively, as broad singlets (Scheme 4.4).
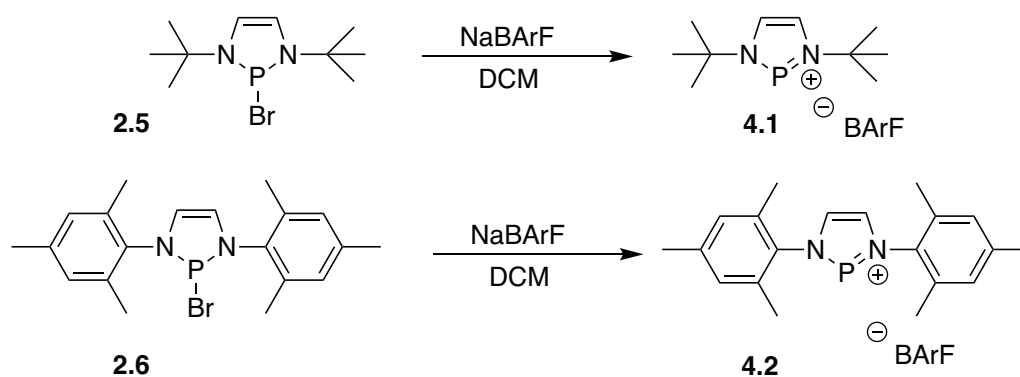
Scheme 4.4: Synthesis of cationic diazaphospholenes

The newly synthesized diazaphospholene cations are interesting due their potential as Lewis acids, affording complementary reactivity to the previously reported diazaphospholene systems. This system could prove useful in expanding the field of diazaphospholene catalysis, as salts of this nature have yet to be explored in any kind of catalytic reactions, and their properties are greatly underexplored with respect to diazaphospholenes in hydride-delivering reactions. The BArF salts of these compounds were chosen, becuase this weakly coordinating anion is well known to be benign in chemistry, and would instead allow for chemistry at the cationic site.

4.3.2: Reactivity of Diazaphospholene Lewis Acids

With phosphorus^{III} cations **4.1** and **4.2** in hand, I explored their reactivity to see if they act as Lewis bases, as many phosphorus compounds do, or if they could be electron poor enough to behave as Lewis acids. A method of probing their ability to act as a Lewis acid would be to use them as catalysts in hydrosilylation reactions with ketones and imines. Substrate **4.3** was used as a test substrate to probe a variety of silane sources. No conversion was observed using triethylsilane or vinyl silane, whereas full conversion to product **4.3** was observed when employing diphenylsilane. Therefore, diphenylsilane was used to evaluate the scope of the reaction (Scheme 4.5). Conversion to the products was

determined by NMR spectroscopy; no further purification of the products was performed, as these are well known products from my previous chapters. This study was helpful in determining that these cations can indeed act as Lewis acids based on their ability to catalyze the hydrosilylation of imines and a ketone.
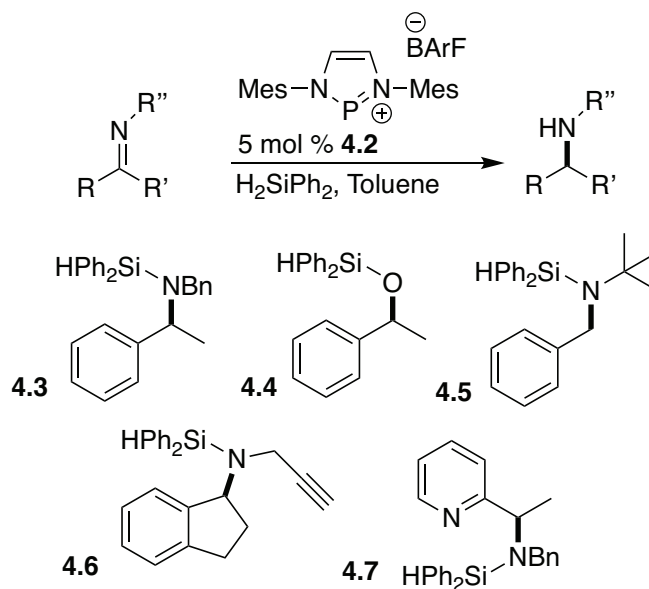
Scheme 4.5: Scope of hydrosilylations

As can be seen from Scheme 4.5, the cationic diazaphospholene **4.2** is competent in catalyzing the hydrosilylation of ketimines, an aldimine, and a ketone to their corresponding products **4.3**, **4.6**, and **4.7**, **4.5**, and **4.4**. In general, conversions for these transformations are high, usually >90% determined by use of NMR spectroscopy, except for product **4.7**, which proceeded with a 50% conversion. One possible mechanism for these reactions is that the catalyst acts as a typical Lewis acid, such as AlCl$_3$, coordinating to the nitrogen or oxygen, increasing the positive charge on the carbon, which can then be attacked by the hydride from the silane source. The product is then obtained as the silyl-protected amine or alcohol. When **4.2** was mixed with H$_2$SiPh$_2$, no P-H formation was observed.

The main purpose for the synthesis of these cationic diazaphospholenes, and investigating their abilities as Lewis acids is for their potential application in the splitting of dihydrogen. The current diazaphospholene systems in Chapters 2 and 3 use HB(pin) as the terminal reductant, but moving to more atom-economical reactions using H_2 as a terminal reductant is attractive. In addition, this would add to knowledge of the fundamental reactivity of main group compounds of this class. Since the discovery that these catalysts are behaving as Lewis acids, their use in dihydrogen splitting would be very important, and so efforts in these transformations were pursued. A variety of conditions towards the splitting of dihydrogen were attempted, and are shown in Table 4.1.

Table 4.1: Hydrogenation conditions
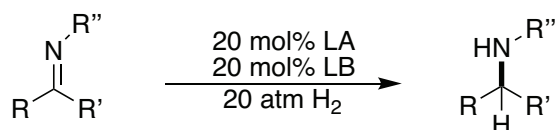
Entry	Lewis acid	Lewis base	Solvent	Substrate	Conversion (%)
1	**4.1**	none	TFT	R=Ph, R'= Me, R''= Bn	0
2	**4.1**	PPh₃	TFT	R=Ph, R'= Me, R''= Bn	0
3	**4.1**	2,6-lutidine	TFT	R=Ph, R'= Me, R''= Bn	0
4	**4.1**	DMAP	TFT	R=Ph, R'= Me, R''= Bn	0
5	**4.1**	DABCO	TFT	R=Ph, R'= Me, R''= Bn	0
6	**4.1**	PPh₃	TFT	R=Ph, R'= H, R''= Bn	0
7	**4.1**	2,6-lutidine	TFT	R=Ph, R'= H, R''= Bn	0
8	**4.1**	DMAP	TFT	R=Ph, R'= H, R''= Bn	0
9	**4.1**	DABCO	TFT	R=Ph, R'= H, R''= Bn	0

Entry	Lewis acid	Lewis base	Solvent	Substrate	Conversion (%)
10	**4.1**	**2.18**	TFT	R=Ph, R'= Me, R''= Bn	20
11	**4.2**	**2.18**	TFT	R=Ph, R'= Me, R''= Bn	65
12	**4.2**	none	TFT	R=Ph, R'= Me, R''= Bn	0
13	**4.2**	**2.18**	TFT	R=Ph, R'= H, R''= Bn	55
14	none	**2.18**	TFT	R=Ph, R'= Me, R''= Bn	0
15	**4.2**	**2.19**	THF	R=Ph, R'= Me, R''= Bn	37
16(**4.8**)	**4.2**	**2.19**	toluene	R=Ph, R'= Me, R''= Bn	90
17	**4.2**	**2.19**	TFT	R=Ph, R'= Me, R''= Bn	58
18	**4.2**	**2.19**	dioxane	R=Ph, R'= Me, R''= Bn	0
19	tBu-DAP-dimer	none	TFT	R=Ph, R'= Me, R''= Bn	0
20	**4.2**	**2.19**	toluene	R=Ph, R'= H, R''= Bn	50
21	**4.2**	**2.19**	toluene	acetophenone	0
22	**4.2**	**2.19**	toluene	R=Ph, R'= Me, R''= Ph	0
23	**4.2**	**2.42**	TFT	R=Ph, R'= Me, R''= Bn	0
24	**4.2**	**2.42**	TFT	R=4-OMeC$_6$H$_4$, R'= Me, R''= Bn	0
25	**4.2**	PCy$_3$	TFT	R=Ph, R'= Me, R''= Bn	0
26	**4.2**	PCy$_3$	TFT	R=4-OMeC$_6$H$_4$, R'= Me, R''= Bn	0
27	BCF	**2.42**	TFT	R=Ph, R'= Me, R''= Bn	0
28	**4.2**	**2.18**	toluene, 100°C	R=Ph, R'= Me, R''= Bn	34
29	**4.2**	**2.18**	toluene, 100°C	R=Ph, R'= H, R''= tBu	0
30	**4.2**	tBu$_3$P	toluene, 100°C	R=Ph, R'= Me, R''= Bn	0

Entry	Lewis acid	Lewis base	Solvent	Substrate	Conversion (%)
31	**4.1**	**2.18**	toluene, 100°C	R=Ph, R'= Me, R''= Bn	0
32	**4.1**	tBu$_3$P	toluene, 100°C	R=Ph, R'= Me, R''= Bn	0

Many Lewis bases were paired with compounds **4.1** and **4.2** with minimal success in splitting and delivering H$_2$. Entries 10 and 11 (Table 4.1) were able to show evidence that the cationic phosphorus compounds could be viable at the splitting of dihydrogen. Compound **4.2** is observed to be a better Lewis acid than **4.1**, which makes sense due to the electron-withdrawing nature of the Mes group, compared to the electron-donating nature of the tBu group. When using a preformed diazaphospholene-hyride as the Lewis base, paired with a diazaphospholene cation as the Lewis acid, hydrogenation of a benzyl imine was observed. A solvent screen in entries 15, 16, and 17 (Table 4.1) showed that using toluene in these hydrogenations provides superior conversions, 90%, when compared to TFT or dioxane, 58% and 0%, respectively. Multiple repetitions of entry 16 (Table 4.1) were conducted, conversions from 50-90% were obtained, but in general the conversion was >75%. A drawback from using the current system is that the only Lewis base screened that can be paired with a cationic phosphorus to split and deliver dihydrogen is a preformed diazaphospholene-hydride. Based on the results from Chapters 2 and 3 it is known that diazaphospholene-hydrides are competent for the reduction of imines by themselves, meaning that there will be a 20% background reduction if 20 mol % of the diazaphospholene-hydride is used. Although it is undesirable to have to use the preformed diazaphospholene-hydride as a Lewis base, this system has shown promise for the hydrogenation of imines with conversions up to 90% in entry 16 (Table 4.1).

Although a consistent, and user-friendly method of hydrogenation has yet to be found using cationic phosphorus cations **4.1** and **4.2**, efforts have been made at assessing their pairings with Lewis bases, and it can be said that using preformed diazaphospholene-hydrides with the cationic phosphorus species can split and deliver dihydrogen, although the mechanism of this catalysis is unclear.

4.4: Conclusions and Future Work

In conclusion, two cationic diazaphospholenes were synthesized through facile routes. These compounds were competent catalysts in the hydrosilylation of imines and ketones, showing their use as phosphorus-based Lewis acids, a class of molecules that are very underdeveloped compared to Lewis bases. Upon observing Lewis acidic properties of these catalysts, they were applied towards the splitting of dihydrogen and further hydrogenation of imines. After screening many Lewis bases, it was observed that pairing a Mes-based cationic diazaphospholene with Mes-DAP-hydride is competent for hydrogenating benzyl imines, although much work is still to be done in this area.

Future work for this project will consist of finding a better Lewis acid/base pair for hydrogenation chemistry, namely moving away from preformed diazaphospholene-hydrides, as they are competent reducing agents on their own, and decompose readily. Investigating different weakly coordinating anions, as well as different side chains of the catalyst are all areas that could enhance the hydrogenation chemistry, and Lewis acidicty of these compounds. Moving to very large, non-coordinating counter ions such as carborane, teflates, or 3,5-*bis*-chloro-tetraphenylborate would all be logical counterions to allow for chemistry at the cation. Switching the sidechains from *t*Bu or Mes to Ph, C_6F_5,

or 3,5-*bis*-trifluoromethylaniline would all be logical modifications to study the effects of Lewis acidity in these molecules.

The use of these cations in defluorination reactions, and the Diels-Alder reaction would both be possible reactions these Lewis acids could catalyze.

4.5: Experimental Section

4.5.1: General Considerations

Synthesis of diazaphospholene derivatives was carried out using diazaphospholene-halogens prepared in Chapter 2. These were further modified to the cationic species in a glovebox using oven dried 4 dram vials. Filtration and crystallization of diazaphospholene derivatives was conducted in a 2001 IT Glovebox (O_2 levels typically 4 ppm, H_2O levels typically 5 ppm). Hydrosilylation reactions were carried out in 1 dram oven dried scintillation vials equipped with magnetic stir bars and green Qorpak® PTFE lined caps. Substrates, reagents and solvents were loaded into vials inside the IT Glovebox. ^{1}H, ^{13}C, and ^{31}P NMR data were collected at 300K on Bruker AV-500 or AV-300 NMR spectrometers. Standard NMR tubes and caps were used. Caps on sensitive samples were overwrapped with PTFE tape. Chemical shifts are reported in parts per million from phosphoric acid (for ^{31}P NMR). ^{1}H NMR spectra are referenced to residual non-deuterated NMR solvent ($CHCl_3$ =7.26 ppm). ^{13}C NMR spectra are referenced to the central $CDCl_3$ peak (77.0 ppm).

Reagents:

3 Å Molecular Sieves were purchased from Aldrich, and dried at 200 °C at 0.5 torr for 36 hours prior to use.

Silanes were purchased from Aldrich and used as received.

NaBArF$_{24}$ was prepared in the lab by Dr. Alex Speed, following standard protocols in the literature.

All other reagents were purchased from Aldrich and used as received.

Solvent:

Acetonitrile, trifluorotoluene, and **dioxane** was purchased from VWR in a 1L EMD Drisolv® bottle. This bottle was taken into the glovebox, and stored over activated 3 Å molecular sieves.

Dichloromethane (ACS grade) was purchased from Fisher and distilled from calcium hydride immediately before use.

Diethyl ether, and tetrahydrofuran were purchased from Fisher and was distilled from a purple solution of benzophenone/sodium ketyl, and stored in the glovebox over activated 3 Å molecular sieves were added.

Toluene and **pentane** were deoxygenated and dried by sparging with dinitrogen gas, followed by passage through a double-column solvent purification system purchased from mBraun Inc. The solvents were stored over activated 3 Å molecular sieves in the glovebox.

Deuterochloroform (Cambridge Isotopes) was stored over activated 3 Å molecular sieves, but otherwise used as received.

Imines:

All ketones, aldehydes and amines employed in amine preparation were purchased from Aldrich, and used as received after purity was verified by ^{1}H NMR.

Imines were prepared by a 1:1 combination of the appropriate ketone/aldehyde and amine in dichloromethane, in the presence of 1 equivalent of titanium ethoxide for 96 hours. The reactions were quenched by addition of aqueous KOH (15 %), filtered onto Na_2SO_4, refiltered and concentrated. Purification of solid imines was accomplished by taking up the obtained solids in warm pentane, and cooling the resulting clear pentane solutions of the imine to -15 °C. The resulting crystals were collected in air by suction filtration and were dried for 12 hours in a vacuum desiccator at approximately 30 torr over P_2O_5 before being brought into the glovebox. Liquid amines were dried by azeotropic distillation with benzene before use. Yields of imines were typically > 60% by this method.

General procedure for hydrosilylation:

Inside the glovebox, the imine or ketone to be reduced was dissolved in CH_3CN in a 1 dram vial equipped with a magnetic stir bar (0.1 M). The silane (1 equiv.) was added as a liquid, and the catalyst (0.05 equiv.) was added as a solid. The resulting mixture was stirred for 16 h. Product amines and alcohols were obtained as crudes, the reaction conversion was determined by NMR spectroscopy. The products were not isolated, as these compounds are known from Chapters 2 and 3 in the thesis. These reactions were primarily used to determine that the catalyst is acting as a Lewis acid.

General procedure for imine hydrogenation:

Inside the glovebox, the imine to be hydrogenated was dissolved in solvent (usually TFT or toluene) in a 1 dram vial equipped with a magnetic stir bar. The Lewis acid (0.2 equiv.) and Lewis base (0.2 equiv.) were added to this solution and stirred. The vials were capped with a B-14 septum, and pierced with a needle, to allow hydrogen to flow into the vessel. The vials were then placed in side of a Parr bomb inside of the glove

box. Upon closure and tightening, the Parr bomb was removed from the glovebox, purged

5 times with dihydrogen gas, and finally filled with 20 atm of dihydrogen gas, and stirred

for 16 h. When heating was required, the Parr Bomb was clamped in the fumehood with a

ring clamp, and lowered into an oil bath. The reactions were removed from the Parr

bomb, the solvent was removed *in vacuo*, and NMR conversions were obtained. Only

crude spectra of reactions that showed conversions will be provided in the appendix.

Only reactions that showed conversion will be elaborated upon in the synthesis and

characterization section, all other reactions that afforded no conversions follow the

general procedure with no deviations, and are not further discussed herein.

4.5.2: Synthesis and Characterization

1,3-Di-*tert*-butyl-1,3,2-diazaphosphole BArF (4.1):
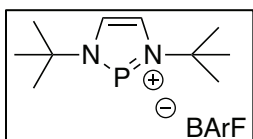
2-Bromo-1,3-di-*tert*-butyl-1,3,2-diazaphosphole **2.5** (0.50 g, 1.79 mmol, 1 equiv.) was dissolved in DCM (7 mL) and stirred in a 4 dram vial in the glovebox. To the solution NaBArF (1.59 g, 1.79 mmol, 1 equiv.) was added and stirred for 14 h. The mixture was filtered over a pad of Celite to remove the NaBr produced during the reaction; the solvent was removed from the filtrate *in vacuo*. The crude was washed with TFT (5 mL), and then pentane, and dried *in vacuo* to afford the product as an orange solid (1.7 g, 89%).

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.82 (s, 2H), 7.72 (s, 8H), 7.57 (s, 4H), 1.69 (m, 18H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 161.7 (q, *J*= 49.9 Hz), 143.4, 134.8, 131.9 (d, *J*= 3.5 Hz), 129.1 (q, *J*= 2.8 Hz), 128.8 (q, *J*= 2.9 Hz), 128.7, 127.8, 125.6, 123.4, 121.3, 118.9, 117.5, 63.7, 31.2 (d, *J*= 9.4 Hz), 30.1, 27.8.

^{31}P NMR (201 MHz, CDCl$_3$): δ 203.2 (s).

1,3-Di-mesityl-1,3,2-diazaphosphole BArF (4.2):
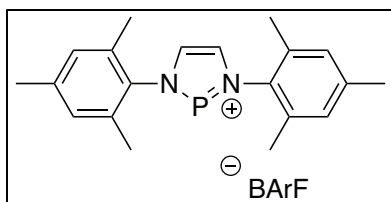
2-Bromo-1,3-di-mesityl-1,3,2-diazaphosphole **2.6** (0.50 g, 1.24 mmol, 1 equiv.) was dissolved in DCM (7 mL) and stirred in a 4 dram vial in the glovebox. To the solution NaBArF (1.09 g, 1.24 mmol, 1 equiv.) was added and stirred for 14 h. The mixture was fitered over a pad of Celite to remove the NaBr produced during the reaction, and the solvent was removed from the filtrate *in vacuo*. The crude was triturated 5 times with pentane (5x5 mL), and dried *in vacuo* after each trituration to afford the product as a green powder (1.1 g, 75%).

*Note: If sufficient trituration is not performed, the product will solidify into a solid black puck overnight, as opposed to a green powder.

^{1}H NMR (500 MHz, CDCl$_3$): δ 7.81 (s, 2H), 7.72 (s, 8H), 7.53 (s, 4H), 7.16 (s, 4H), 2.42 (s, 6H), 2.13 (s, 12H).

^{13}C{^{1}H} NMR (125 MHz, CDCl$_3$): δ 161.7 (q, *J*= 50.1 Hz), 136.9, 134.8, 133.0, 130.7, 129.1-129.0 (m (unresolved q)), 128.8-128.7 (m (unresolved q)), 125.6, 123.4, 117.5, 48.8, 21.0, 17.1.

^{31}P NMR (201 MHz, CDCl$_3$): *δ* 205.9 (s).

N-Benzyl-1-phenylethanamine (4.3):
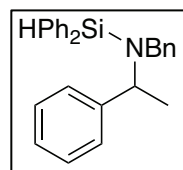
N-Benzyl-1-phenylethanimine (50 mg, 0.239 mmol, 1 equiv.) was dissolved in toluene (1 mL) and stirred. To the solution 1,3-di-mesityl-1,3,2-diazaphosphole BArF **4.2** (14 mg, 0.0119 mmol, 0.05 equiv.) and

diphenylsilane (0.044 mL, 0.239 mmol, 1 equiv.) were added and stirred for 14 h. The solvent was removed *in vacuo*, and a crude NMR (¹H, 500 MHz, CDCl₃) was performed to observe full conversion to the product.[28] No further purification was done.
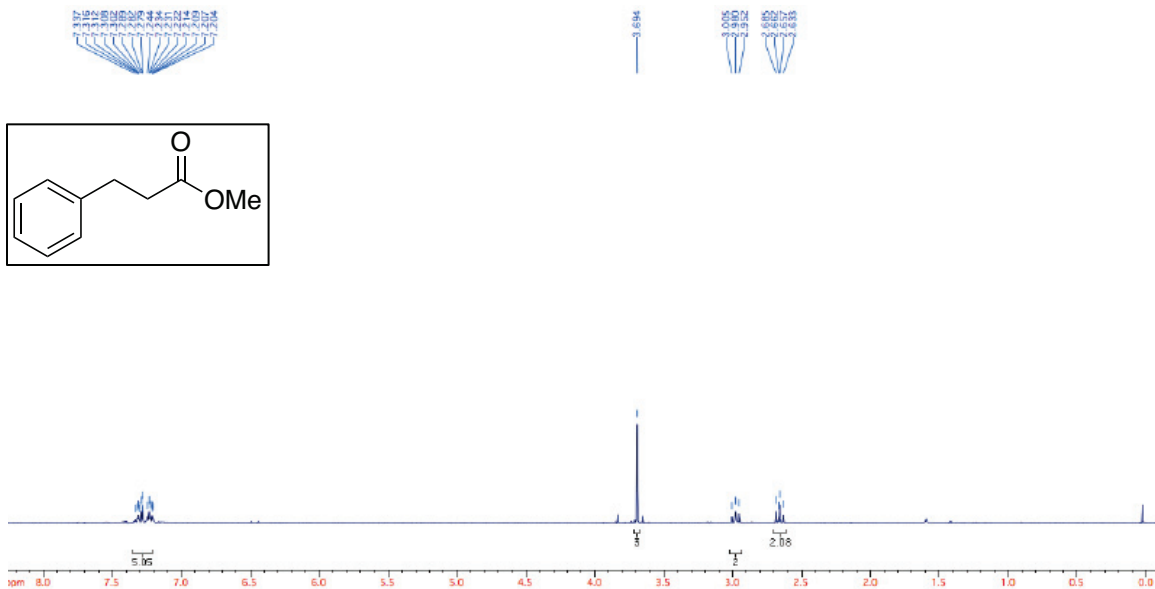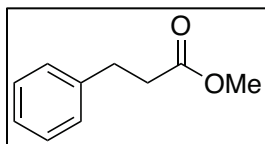
Phenethanol (4.4):
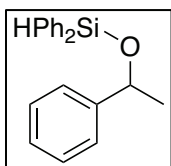
Acetophenone (30 mg, 0.250 mmol, 1 equiv.) was dissolved in toluene (1 mL) and stirred. To the solution 1,3-di-mesityl-1,3,2-diazaphosphole BArF **4.2** (14.8 mg, 0.0124 mmol, 0.05 equiv.) and diphenylsilane (0.046 mL, 0.250 mmol, 1 equiv.) were added and stirred for 14 h. The solvent was removed *in vacuo* and a crude NMR (¹H, 500 MHz, CDCl₃) was performed to observe full conversion to the product.[11] No further purification was performed.

N-Benzyl-2-methylpropan-2-amine(4.5):
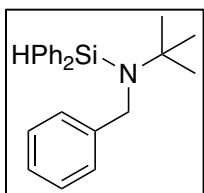
(*E*)-*N*-Benzylidene-2-methylpropan-2-amine (50 mg, 0.310 mmol, 1 equiv.) was dissolved in toluene (1 mL) and stirred. To the solution 1,3-di-mesityl-1,3,2-diazaphosphole BArF **4.2** (18.4 mg, 0.0155 mmol, 0.05 equiv.) and diphenylsilane (0.058 mL, 0.310 mmol, 1 equiv.) were added and stirred for 14 h. The solvent was removed *in vacuo* and a crude NMR spectrum (¹H, 500 MHz, CDCl₃) was aquired to observe full conversion to the product.[28] No further purification was performed.

N-(Prop-2-ynyl)-2,3-dihydro-1*H*-inden-1-amine (4.6):
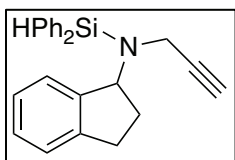
N-(2,3-Dihydroinden-1-ylidene)prop-2-yn-1-amine (50 mg, 0.294 mmol, 1 equiv.) was dissolved in toluene (1 mL) and stirred. To the solution 1,3-di-mesityl-1,3,2-diazaphosphole BArF **4.2** (17.3 mg, 0.0147 mmol, 0.05 equiv.) and diphenylsilane (0.054 mL, 0.294 mmol, 1 equiv.) were

added and stirred for 14 h. The solvent was removed *in vacuo* and a crude NMR spectrum (^{1}H, 500 MHz, CDCl$_3$) was obtained to observe 50%~ conversion to the product.[28] No further purification was performed.

N-Benzyl-1-(pyridin-2-yl)ethanamine (4.7):
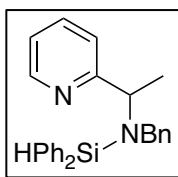
Phenyl-*N*-(1-(pyridin-2-yl)ethylidene)methanamine (50 mg, 0.255 mmol, 1 equiv.) was dissolved in toluene (1 mL) and stirred. To the solution 1,3-di-mesityl-1,3,2-diazaphosphole BArF **4.2** (15.1 mg, 0.0127 mmol, 0.05 equiv.) and diphenylsilane (0.047 mL, 0.255 mmol, 1 equiv.) were added and stirred for 14 h. The solvent was removed *in vacuo* and a crude NMR spectrum (^{1}H, 500 MHz, CDCl$_3$) was aquired to observe 57%~ converstion to the product.[28] No further purification was performed.

N-Benzyl-1-phenylethanamine (4.8):
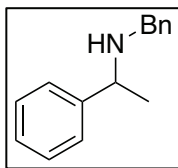
N-Benzyl-1-phenylethanimine (20 mg, 0.0956 mmol, 1 equiv.) was dissolved in toluene (1 mL) and stirred. To the solution 1,3-di-mesityl-1,3,2-diazaphosphole BArF **4.2** (22.7 mg, 0.00478 mmol, 0.2 equiv.) and 2-hydro-1,3-di-mesityl-1,3,2-diazaphosphole (6.2 mg, 0.00478 mmol, 0.2 equiv.) were added and stirred. The reaction was loaded into a Parr Bomb and removed from the glovebox. The vessel was purged five times with H$_2$ gas, and then pressurized to 20 atm with H$_2$. The reaction was stirred for 16 h. The gas was released from the vessel, and the solvent was removed from the reaction *in vacuo* and a crude NMR spectrum (^{1}H, 500 MHz, CDCl$_3$) was obtained to observe 90%~ converstion to the product. No further purification was performed.

*Note: This is a representative example of a hydrogenation performed in Table 4. Crude

NMR data is provided in Appendix 3 to show NMR conversion to the product.[28]

Chapter 5 : Conclusions

In Chapter 2 a more convenient diazaphospholene pre-catalyst was synthesized. This proved useful in that it has increased stability and is easier (more stable) to handle than the previously reported diazaphospholene hydrides. A variety of saturated and unsaturated diazaphospholene pre-catalysts were assessed for their ability as entry points in catalysis, and it was discovered that unsaturation in the pre-catalyst backbone was crucial for catalysis. This system, when paired with HB(pin) as a terminal reductant, was able to hydroborate imines and α,β-unsaturated carbonyl compounds. A mechanistic study was conducted, highlighting potential intermediates in the proposed catalytic cycle using NMR spectroscopy. Major decomposition products were isolated in this study. This work afforded a more convenient pre-catalyst, and highlighted its use in two new modes of reductive catalysis. This project was published in *Angewandte Chemie International Edition*, and was further highlighted as industrially relevant by *Organic Process Research and Development*, and *Synfacts*.

Chapter 3 shows the use of chiral primary amines to synthesize chiral diazaphospholene pre-catalysts. This project focused on the synthesis of pseudo C_2-symmetric diazaphospholene pre-catalysts. During this project an array of chiral pre-catalysts were synthesized and assessed for their ability to induce enantioinduction in imine hydroborations. A predictive model was developed to explain the observed induction for the best diazaphospholene pre-catalyst. With the best catalyst in hand a large number of imine hydroborations were conducted, affording a library of enriched secondary amines with high enantiomeric ratios. This method employed novel pre-catalysts in one of the first chiral imine hydroborations using HB(pin) to afford valuable

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secondary amines, with enantiomeric rations up to 88:12. This work was published in *Angewandte Chemie International Edition*, and a provisional patent has been filed to protect these catalyst architectures.

Chapter 4 presents the synthesis of novel diazaphospholene cation complexes. These cations were used in the hydrosilylation of imines and ketones, and were found to function as competent Lewis acids, which is unusual for phosphorus[III] compounds. Efforts towards the splitting and delivery of dihydrogen have been made, but more work in this field is to be done.

In concluding, this thesis represents work towards more facile routes of synthesizing chiral and achiral diazaphospholene pre-catalysts, and their catalytic abilities in a variety of reactions such as the hydroboration of imines and α,β-unsaturated carbonyl compounds. This new mode of main-group catalysis allows for low catalyst loadings when compared to others in the field. Chiral diazaphospholenes are best in class at affording the chiral hydroboration of imines, with very good e.r.'s, affording desirable enantiomerically enriched secondary amines. It is certain these new pre-catalysts will have a widespread application due to their ease of preparation, low catalyst loadings, and high chemo- and enantio- selectivities.

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Appendix A: NMR spectra for Chapter 2
1,4-Di(*tert*-butyl)-1,4-diazabutadiene (2.1):
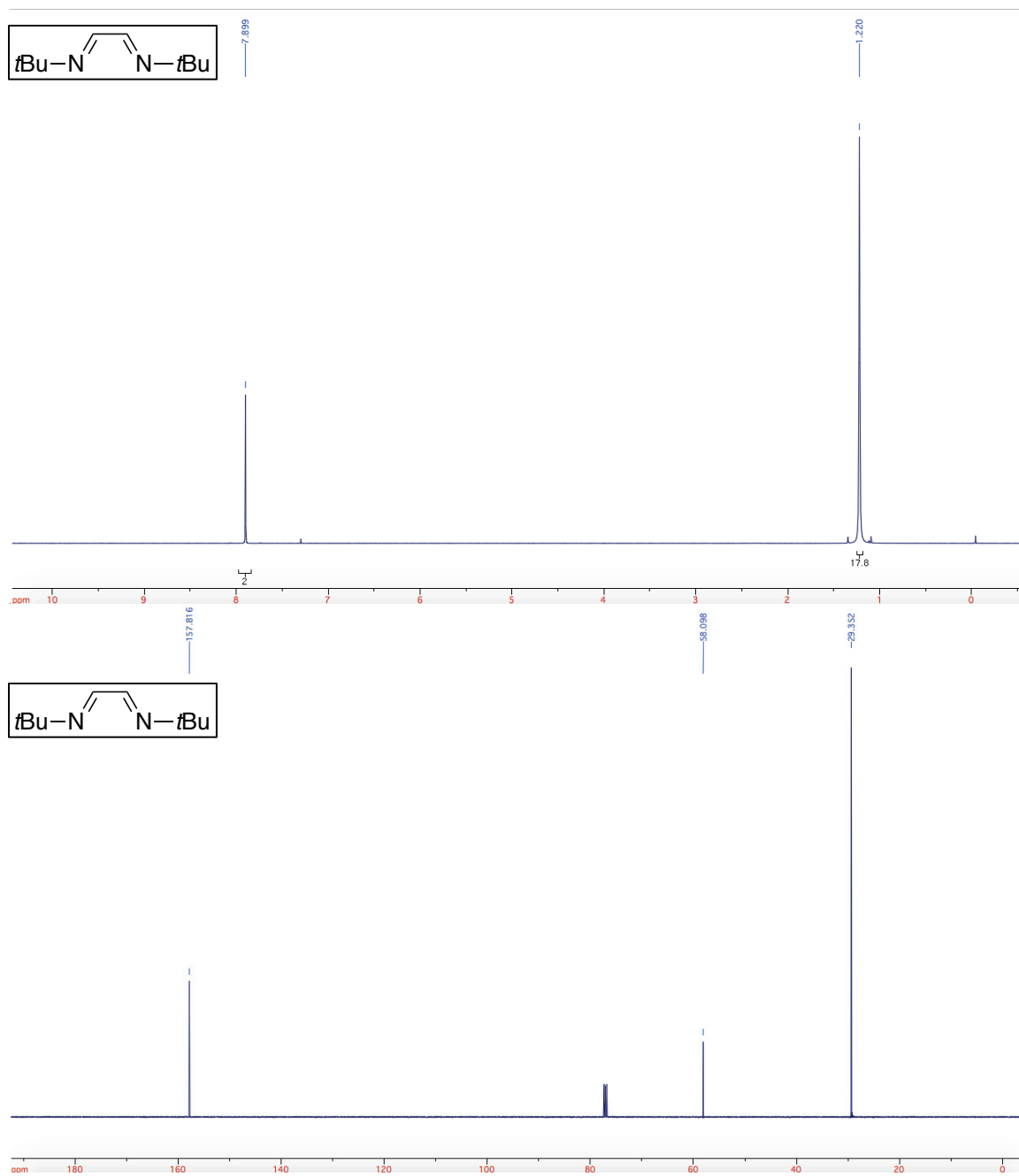
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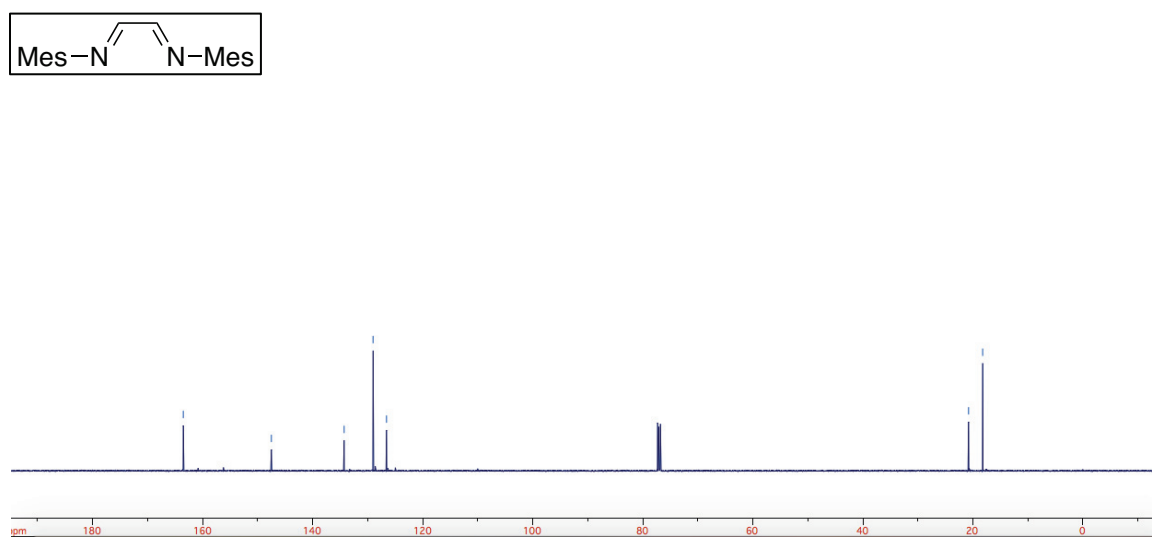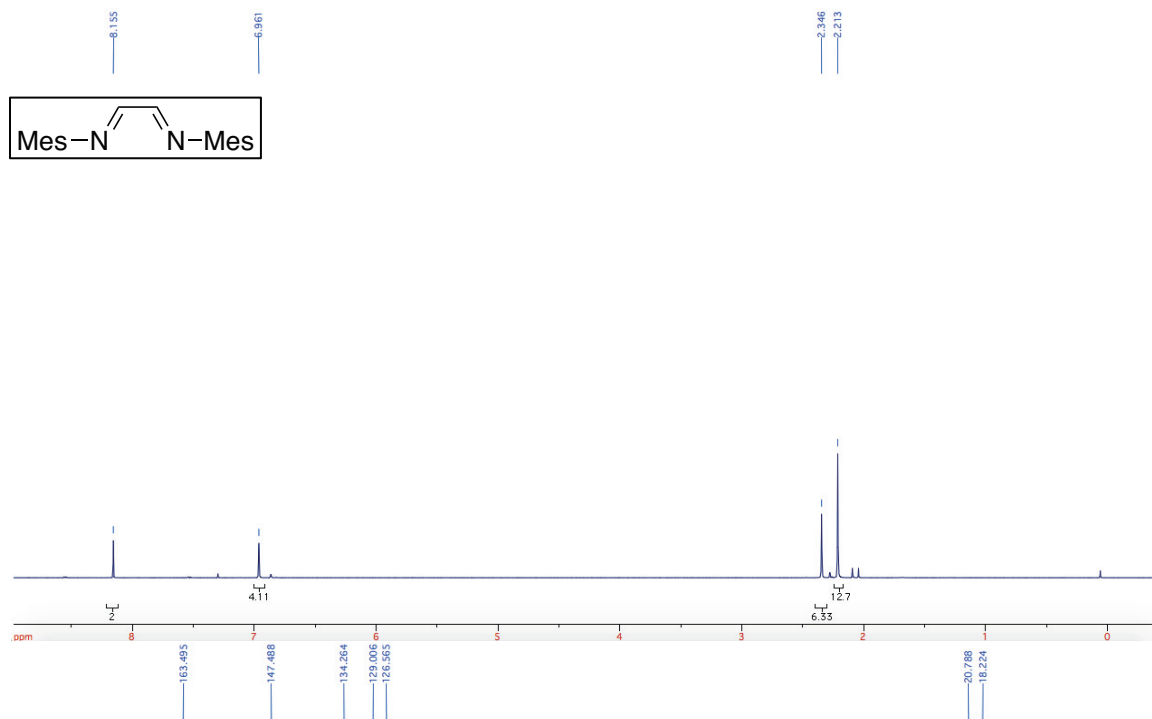
1,4-Di(cyclohexyl)1,4-diazabutadiene (2.3):
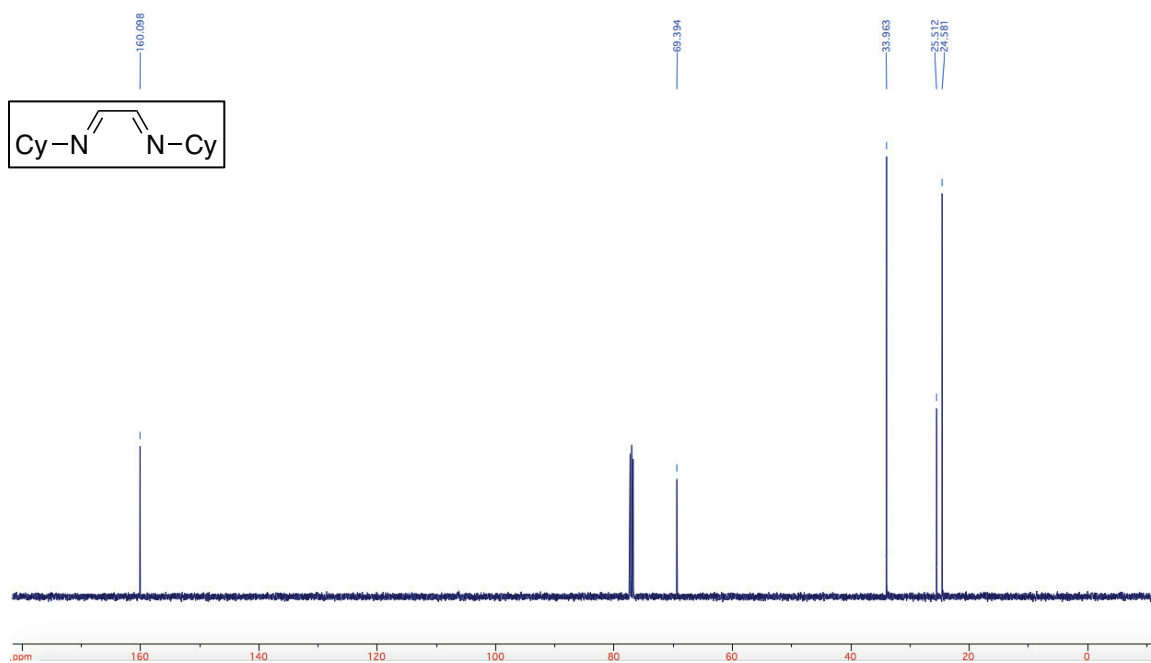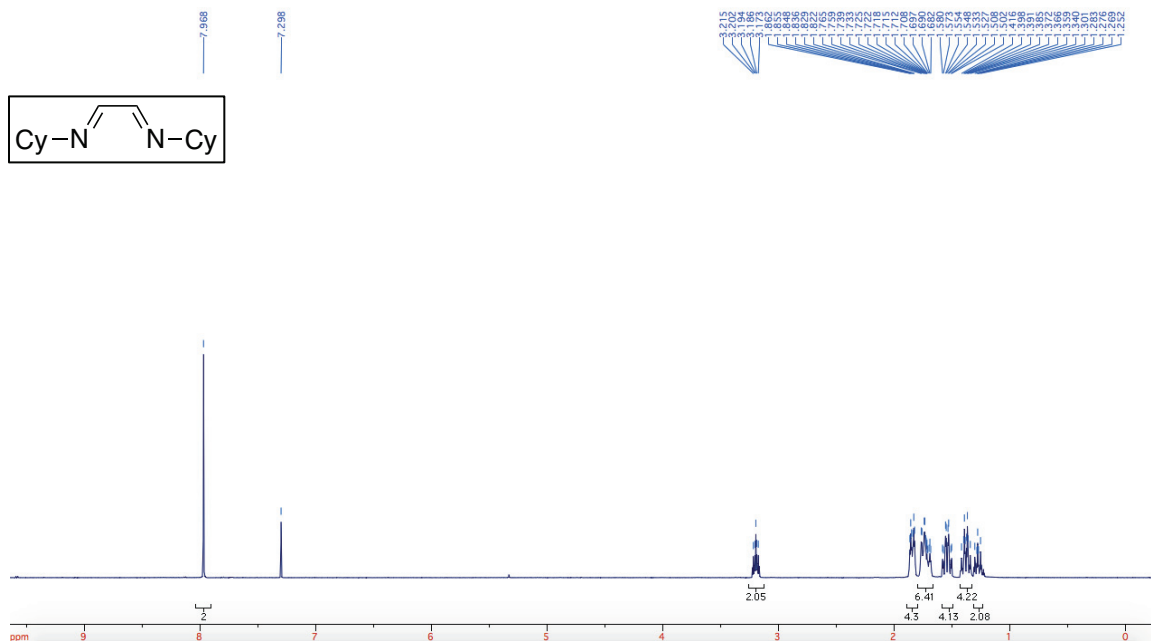
2-Bromo-1,3-di-*tert*-butyl-1,3,2-diazaphosphole (2.5):
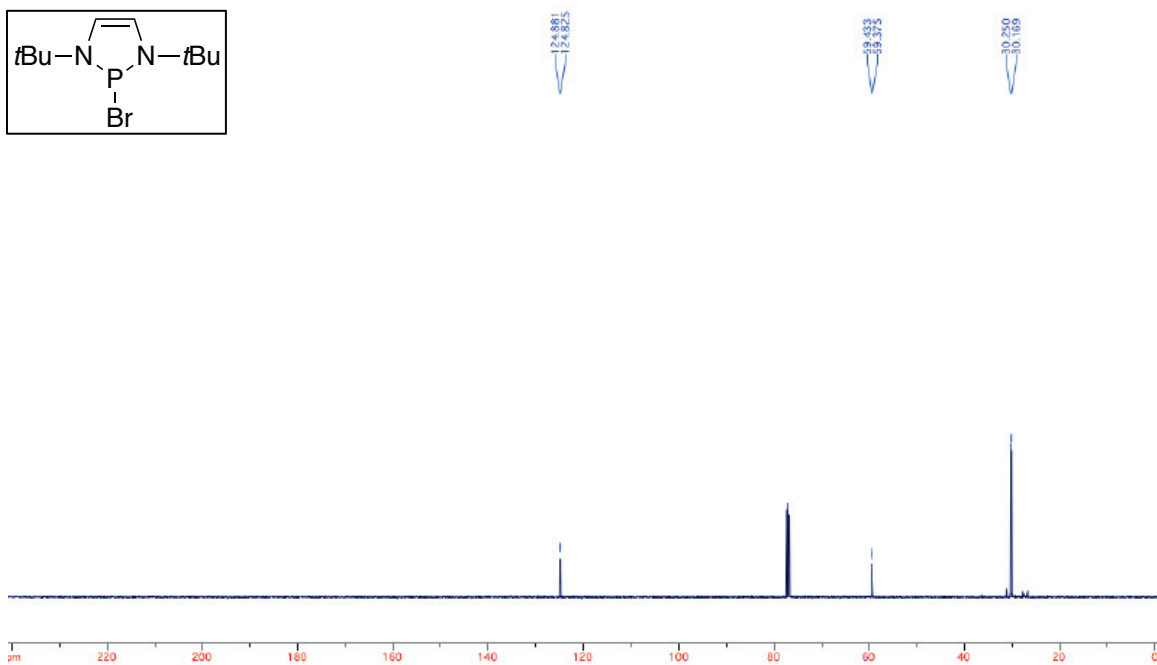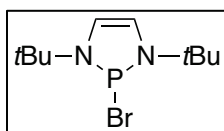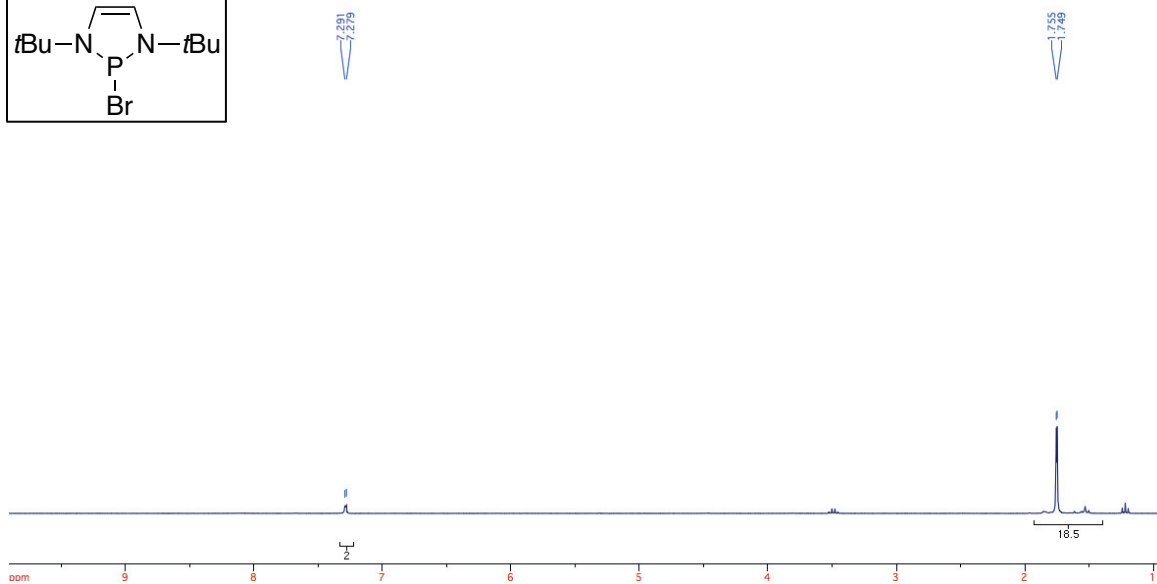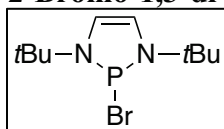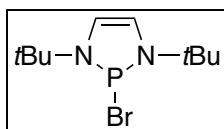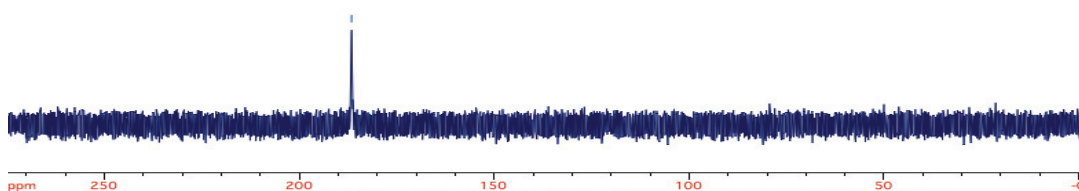
2-Bromo-1,3-di-mesityl-1,3,2-diazaphosphole (2.6):

Mes—N   N—Mes
     \ P /
       Br

Mes—N   N—Mes
     \ P /
       Br

174.313
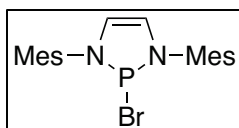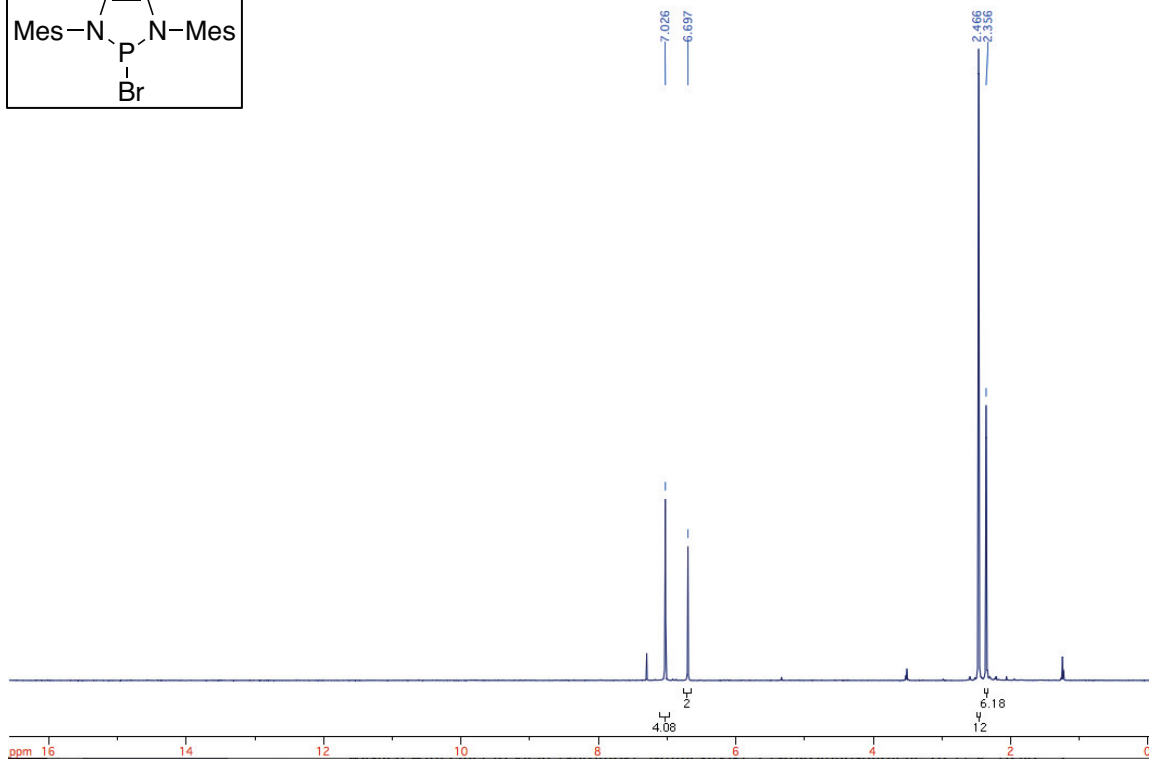
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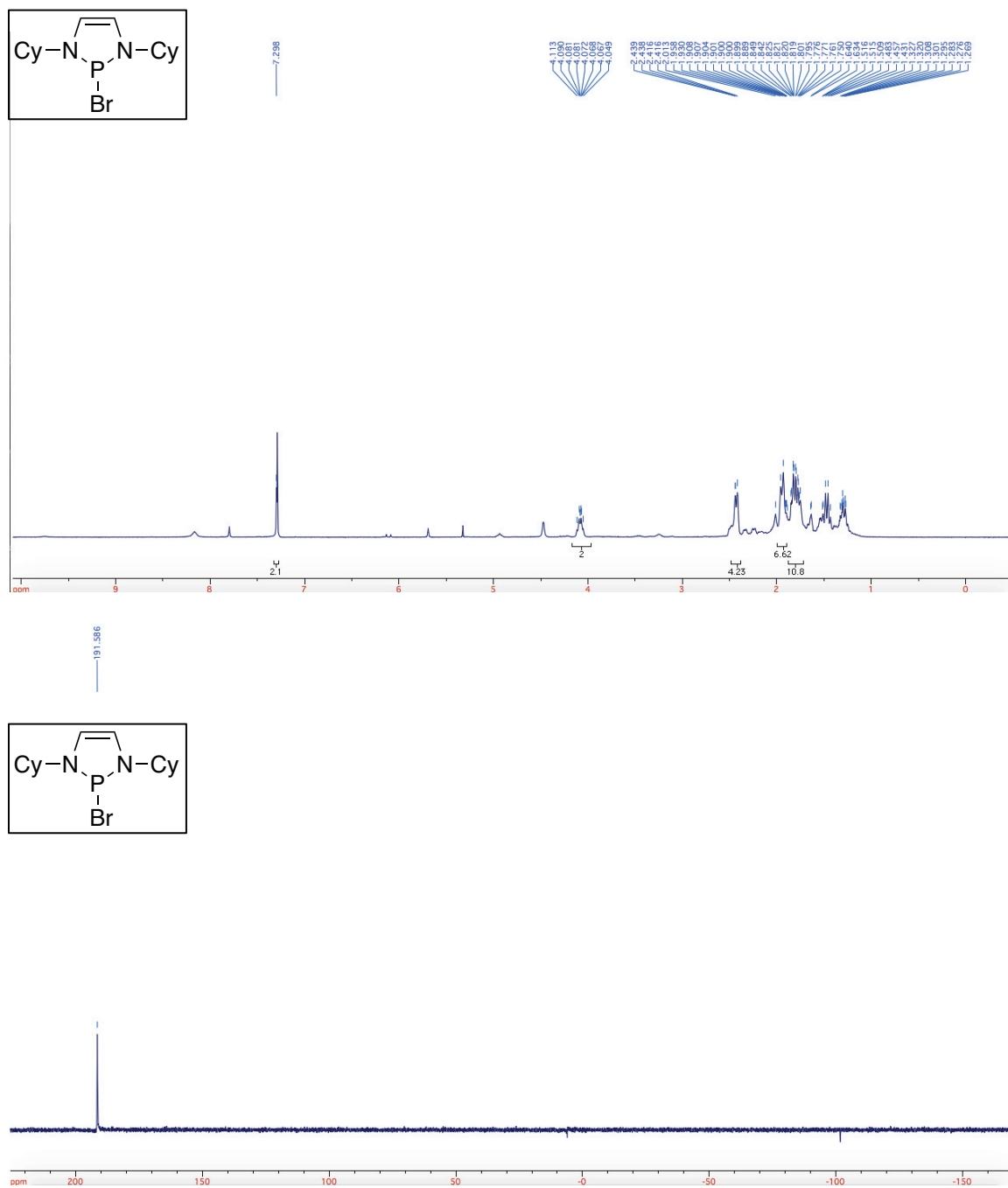
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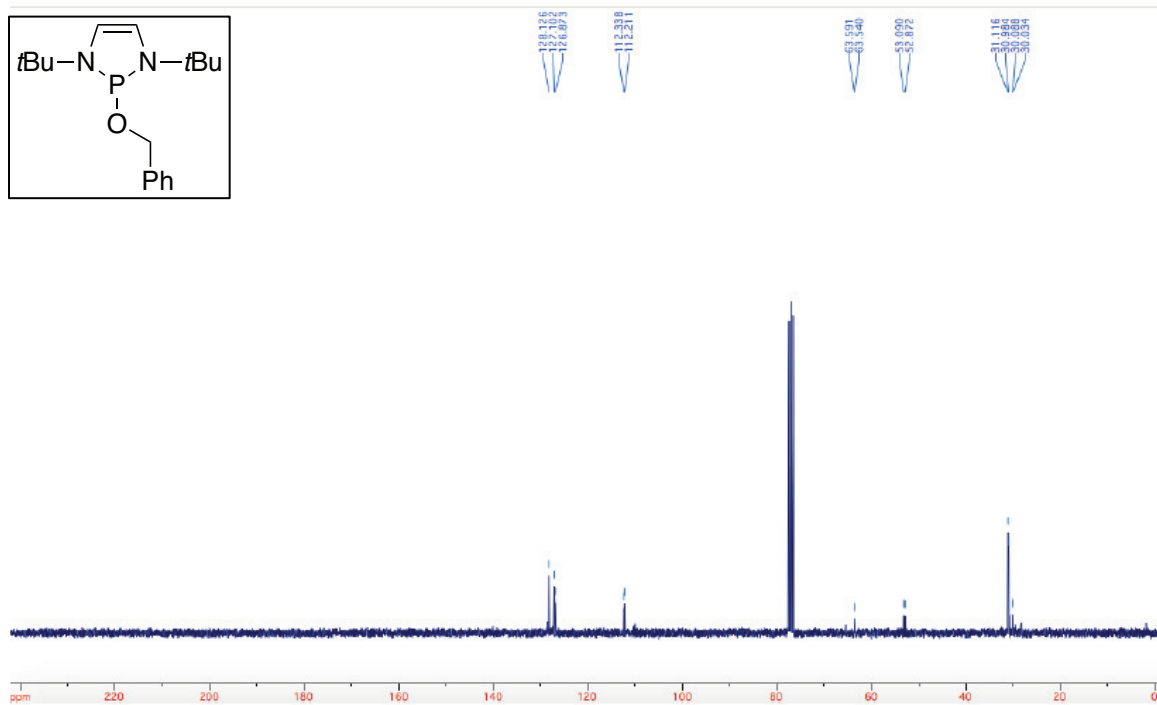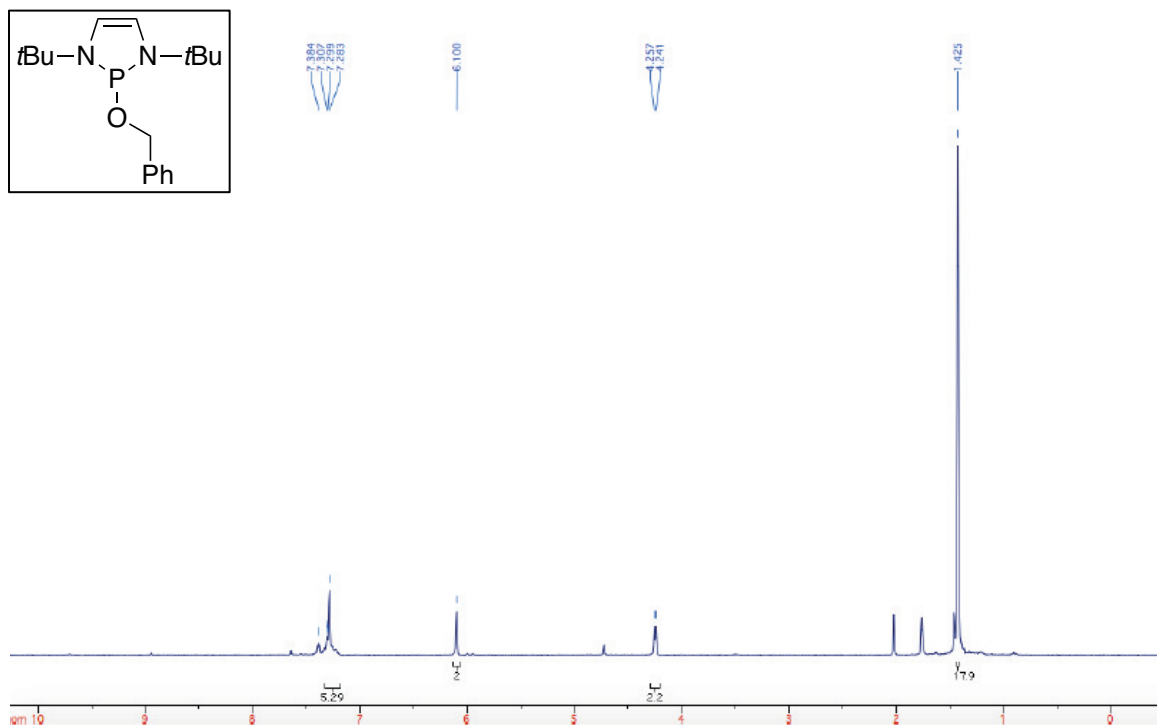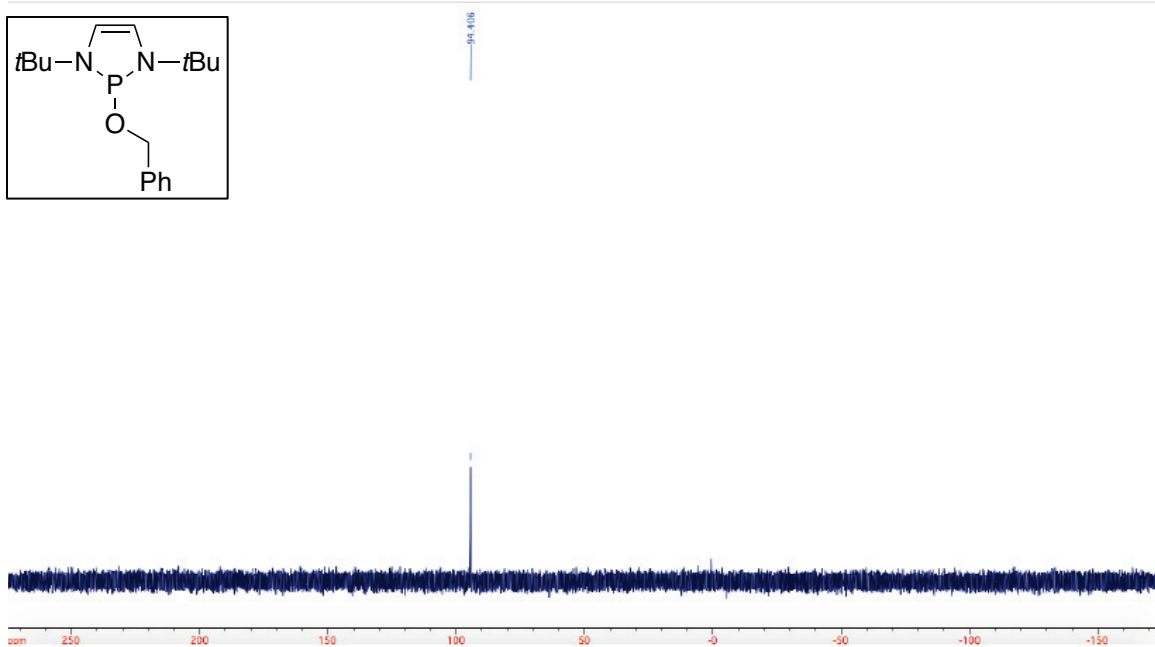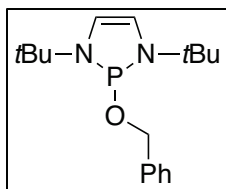
1,3-Di-mesityl-2-(benzyloxy)-1,3,2-diazaphosphole (2.9):
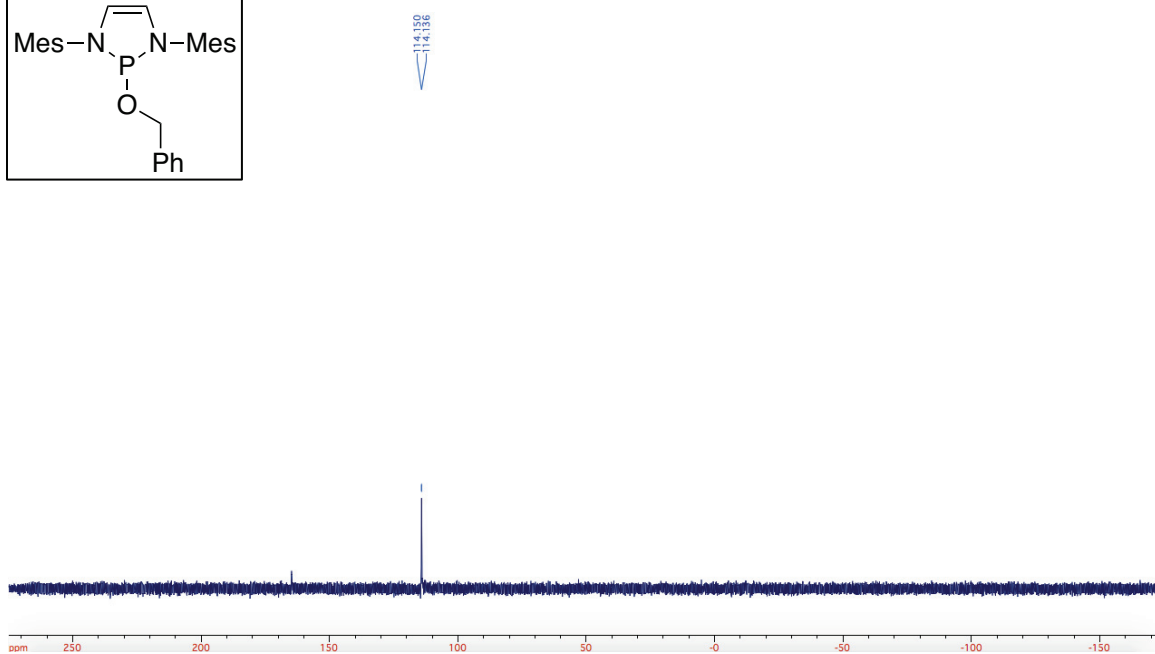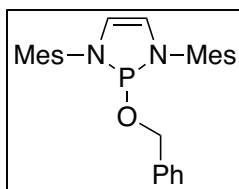
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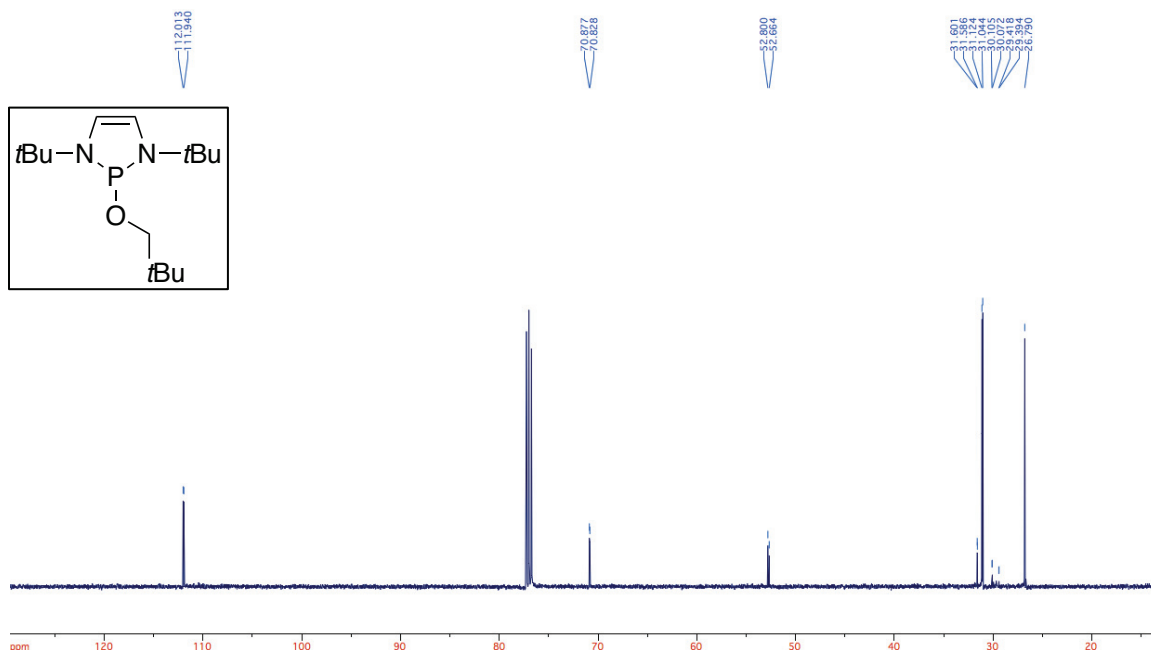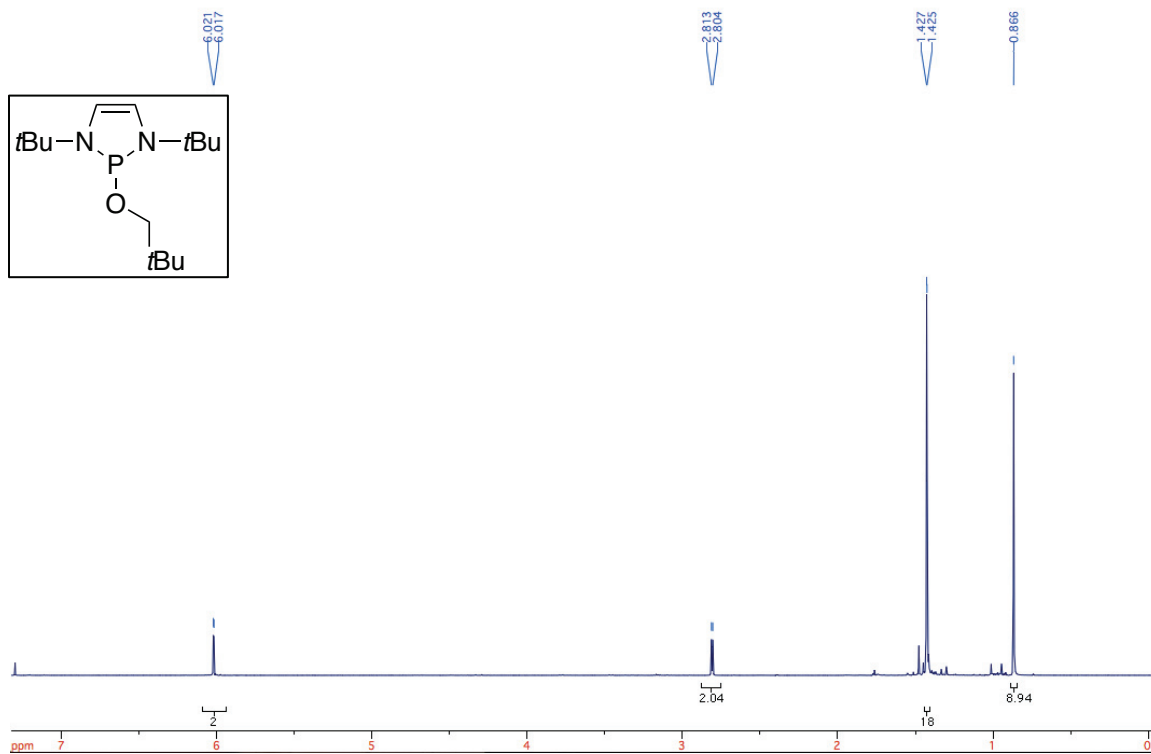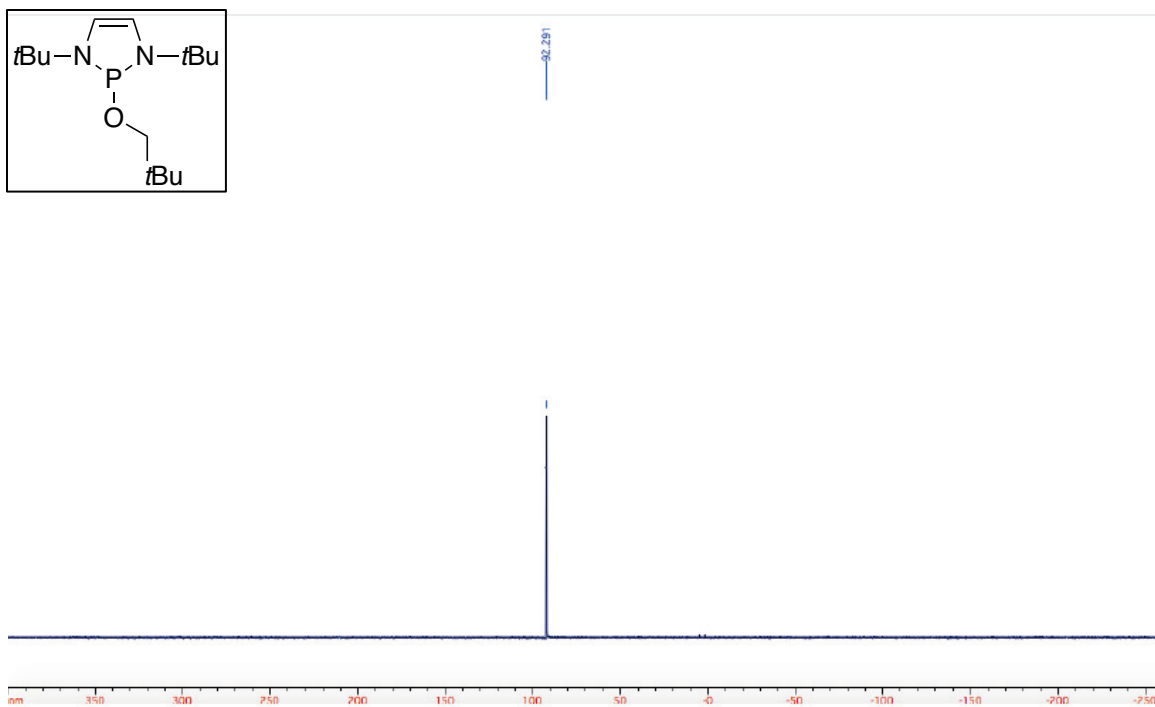
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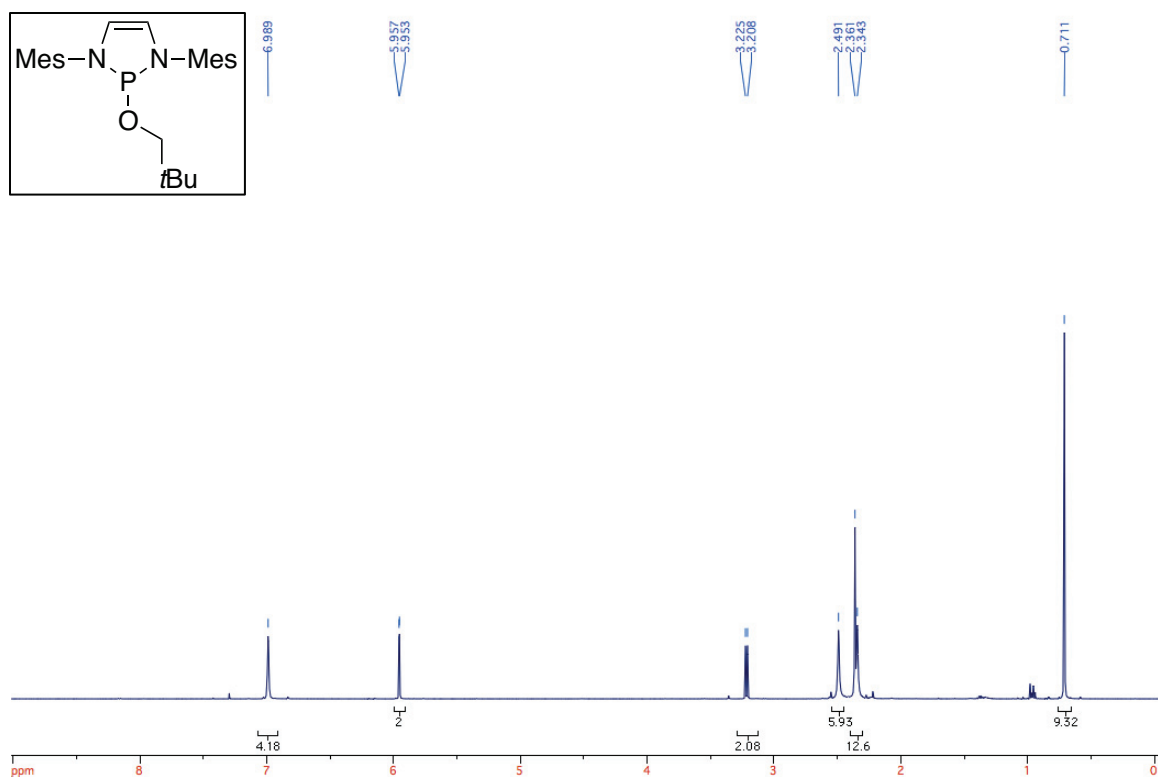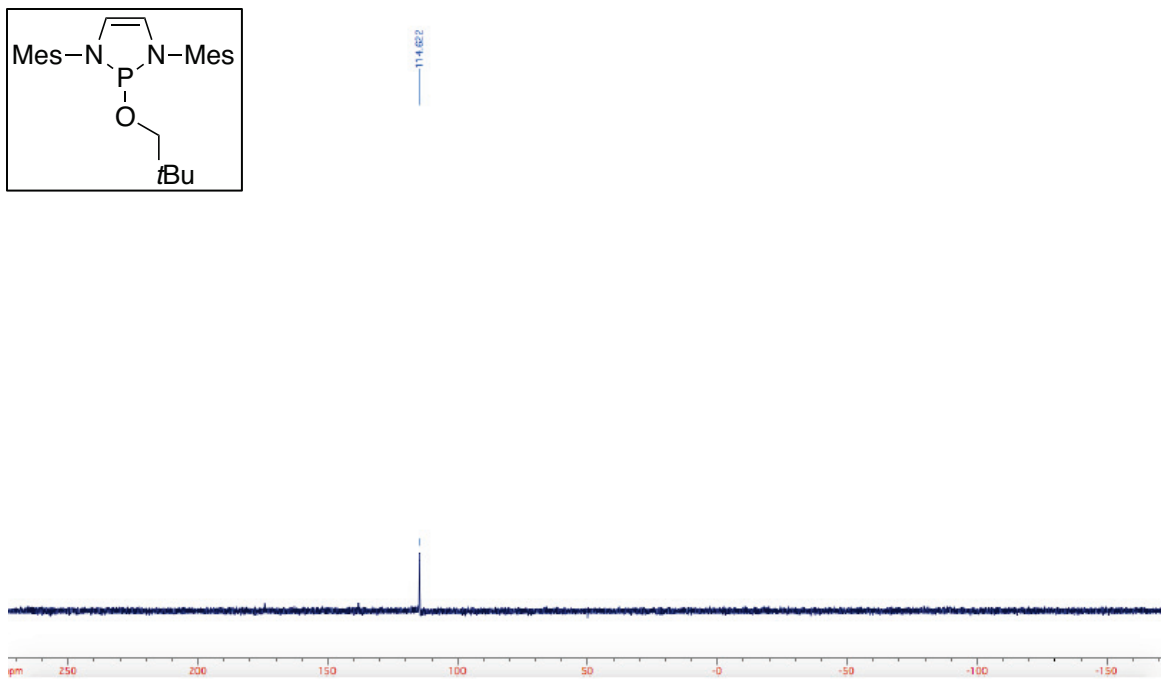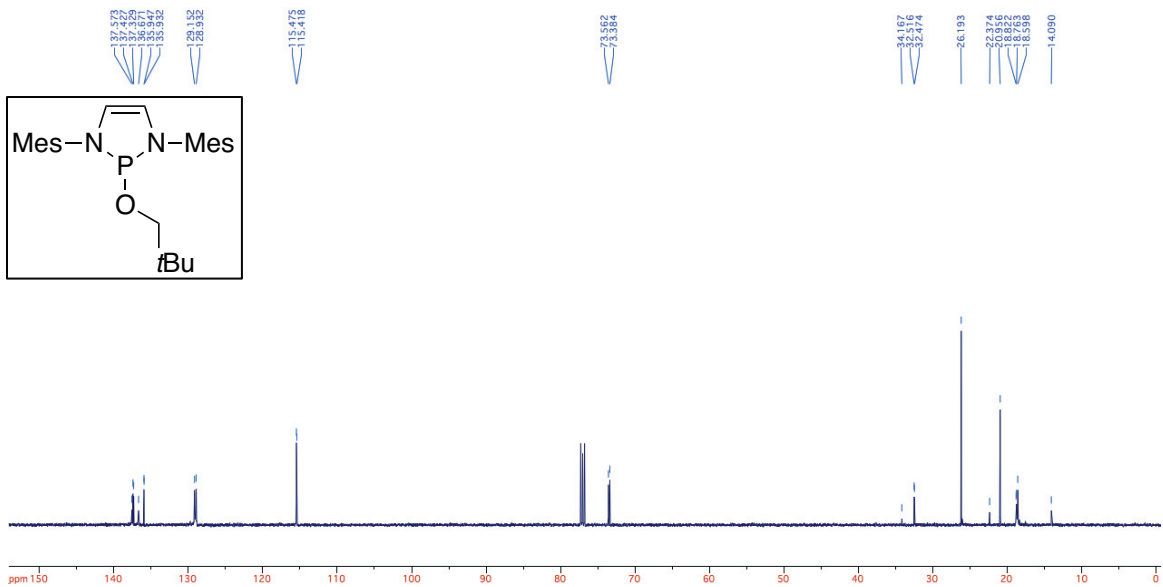
N, N-Di-*tert*-butylethane-1,2-diamine (2.12):
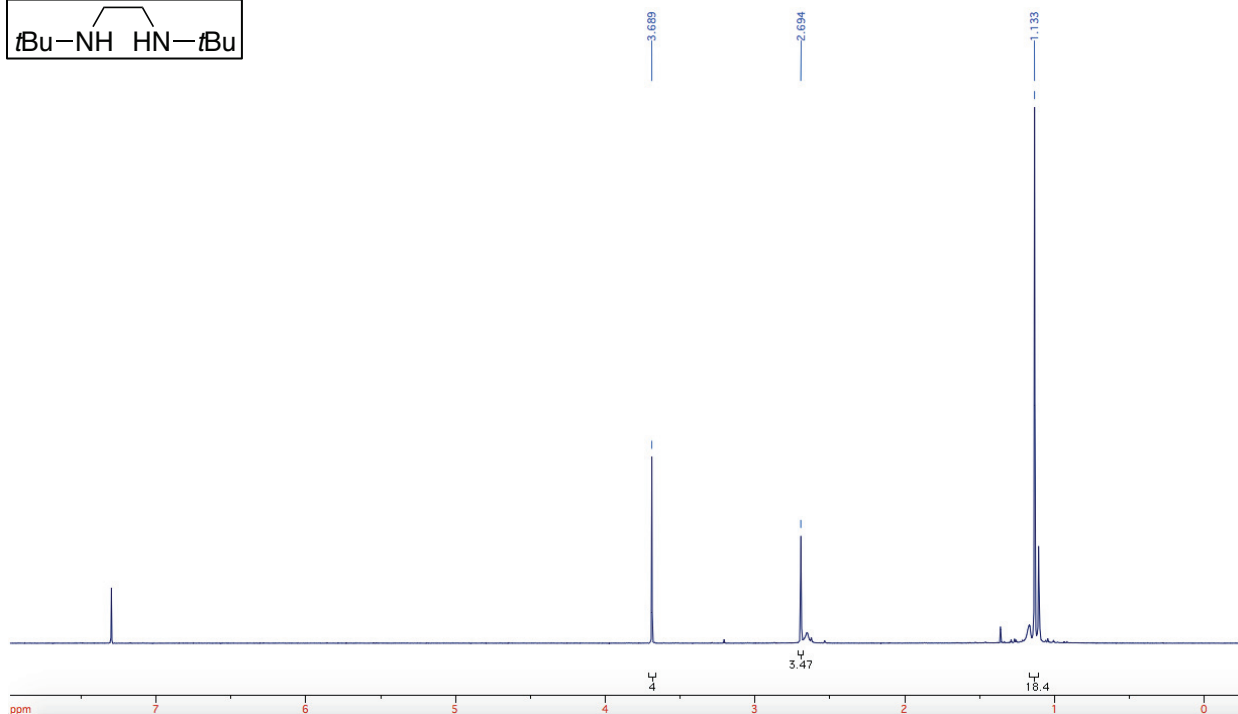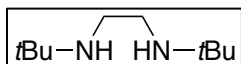
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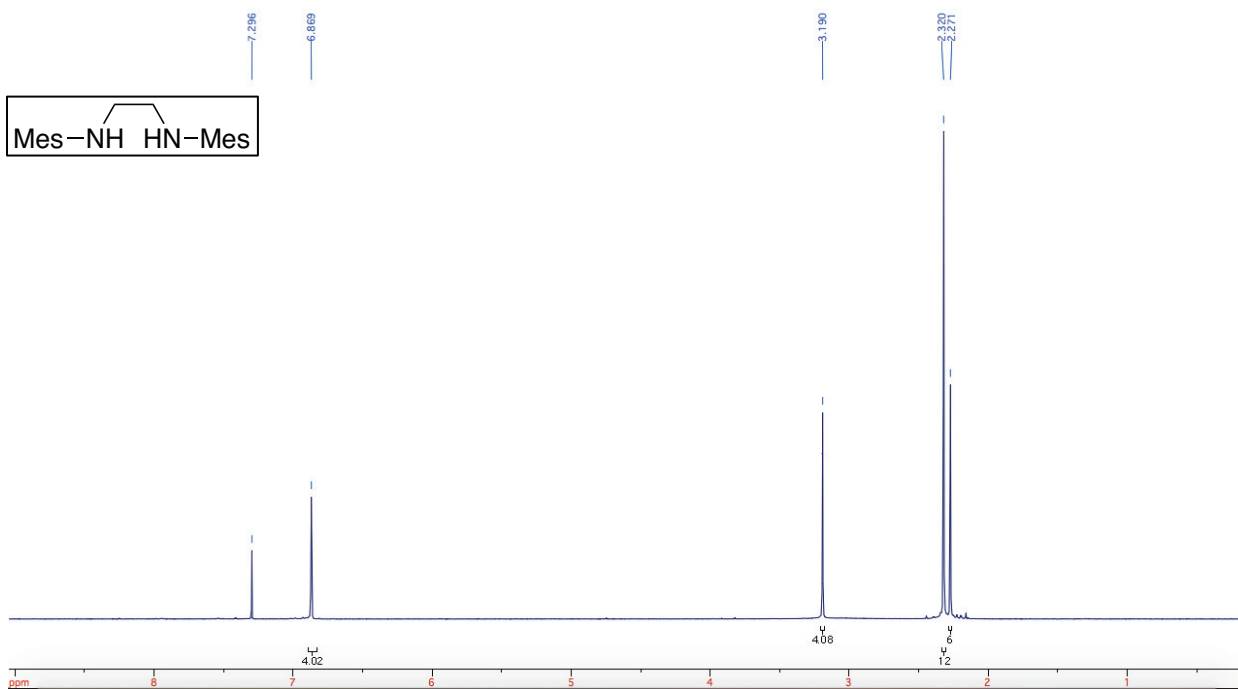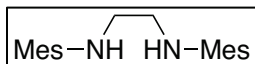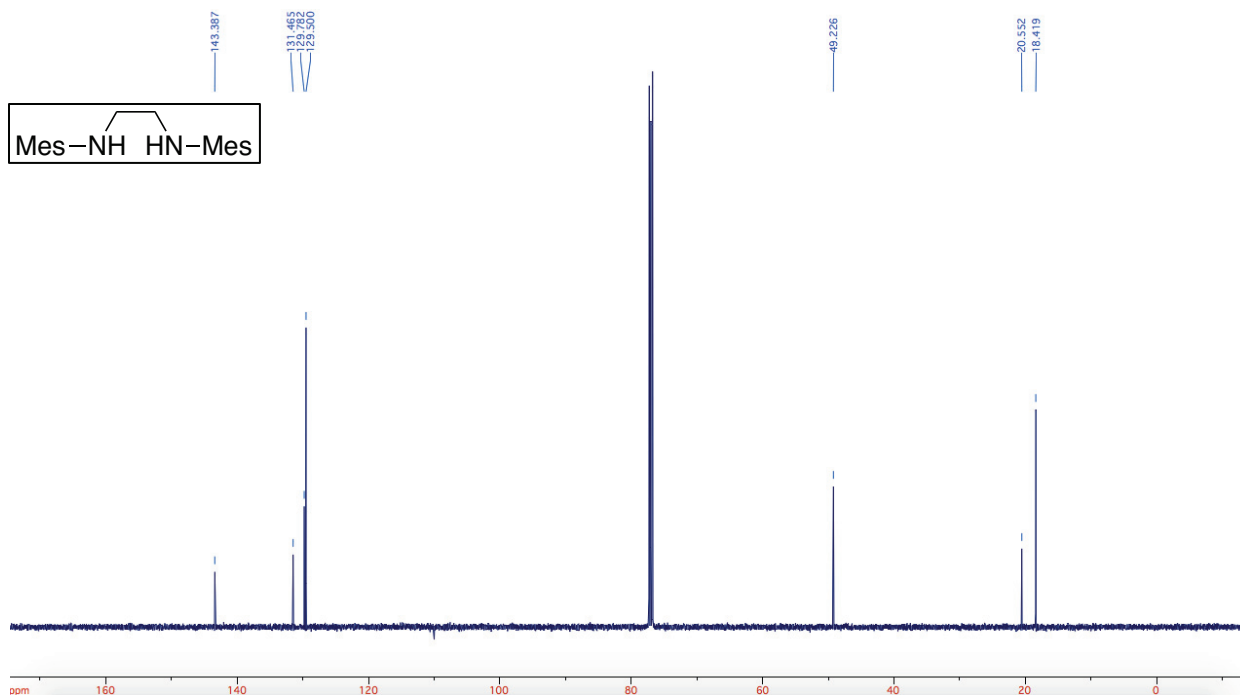
Mes—NH   HN—Mes

2-Bromo-1,3-di-*tert*-butyl-1,3,2-diazaphospholidine (2.14):

*t*Bu—N   N—*t*Bu
      \P/
       |
       Br

tBu—N—N—tBu P Br

129.030
128.217
125.293

54.725
54.641
46.373
46.291

28.376
28.026
27.995

ppm 220 200 180 160 140 120 100 80 60 40 20 0

tBu—N—N—tBu P Br

193.000

ppm 350 300 250 200 150 100 50 -0 -50 -100

197
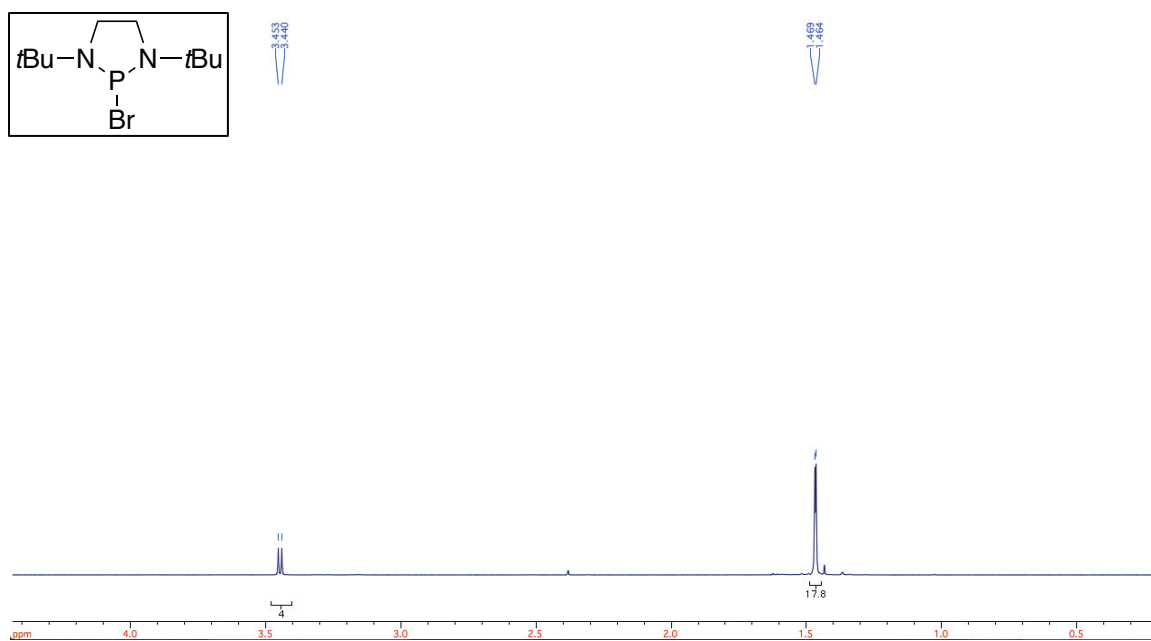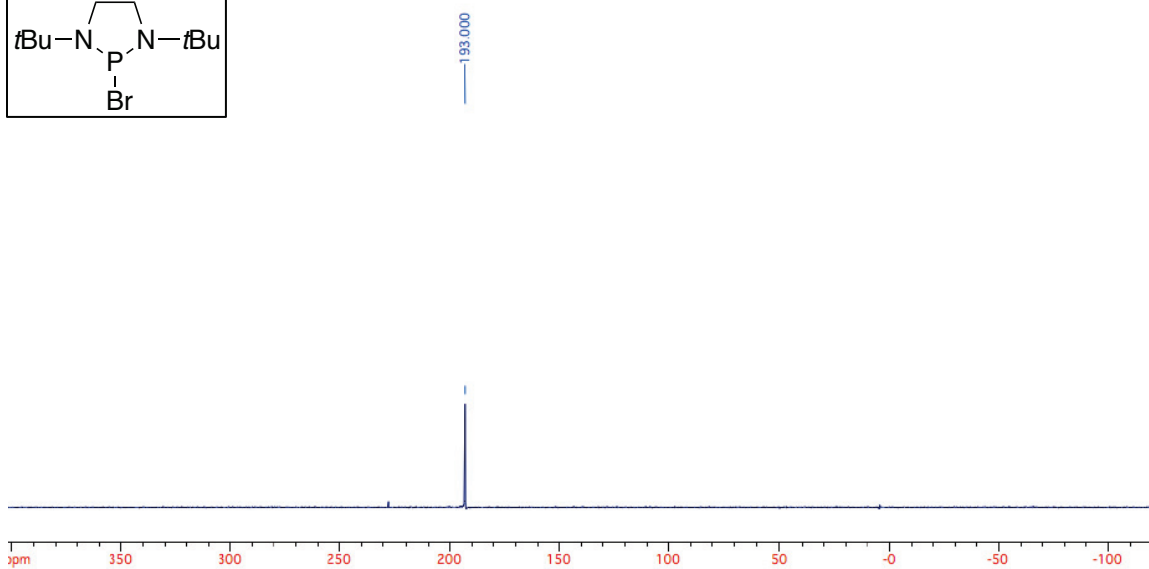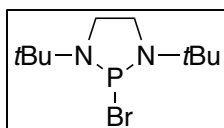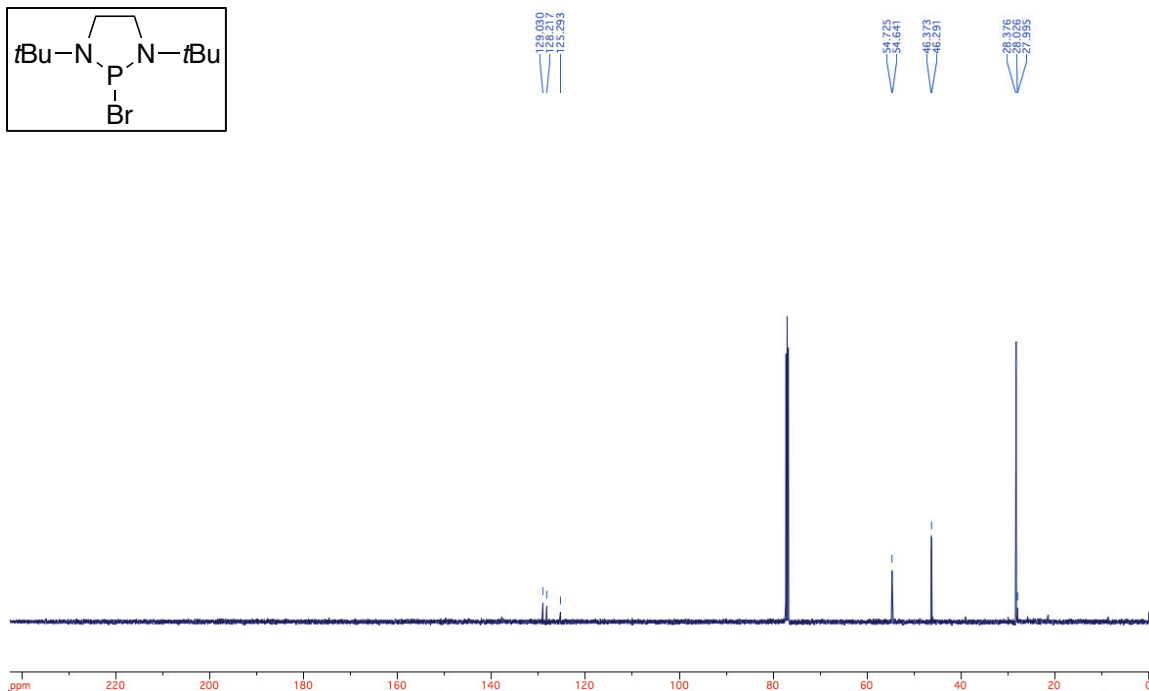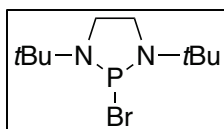
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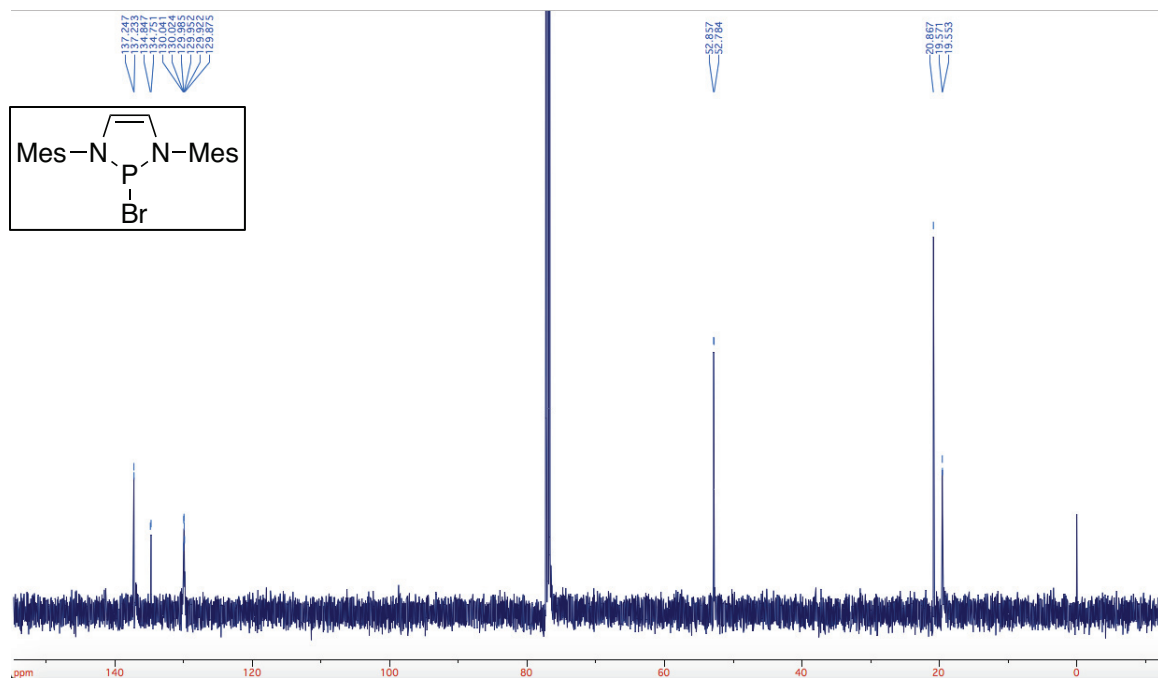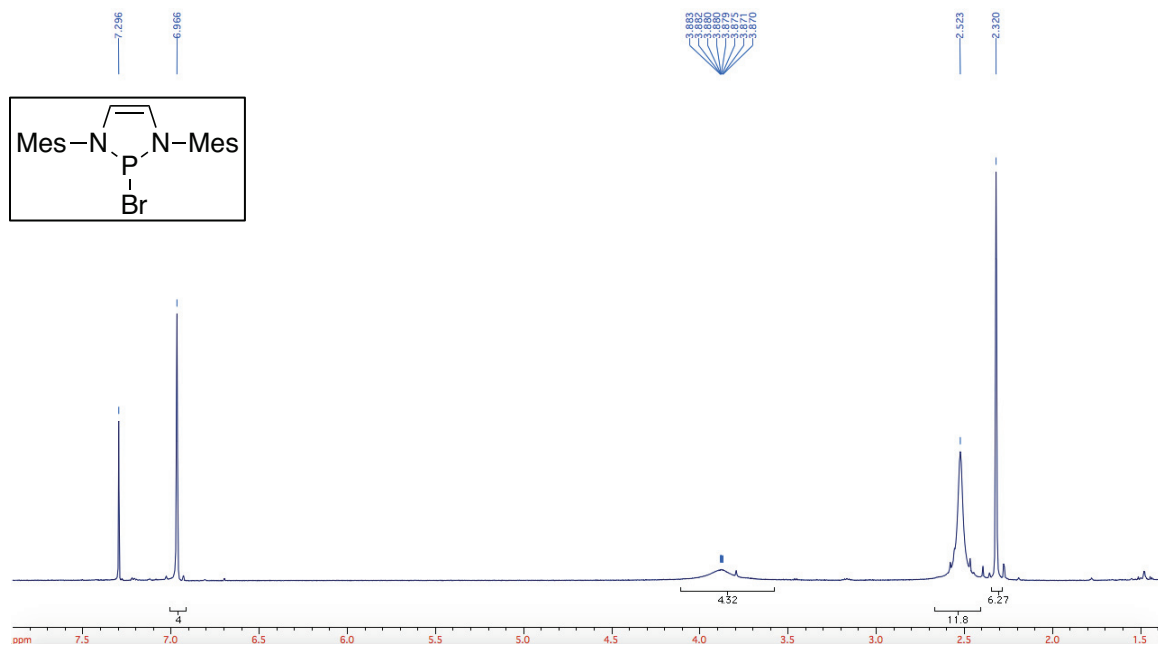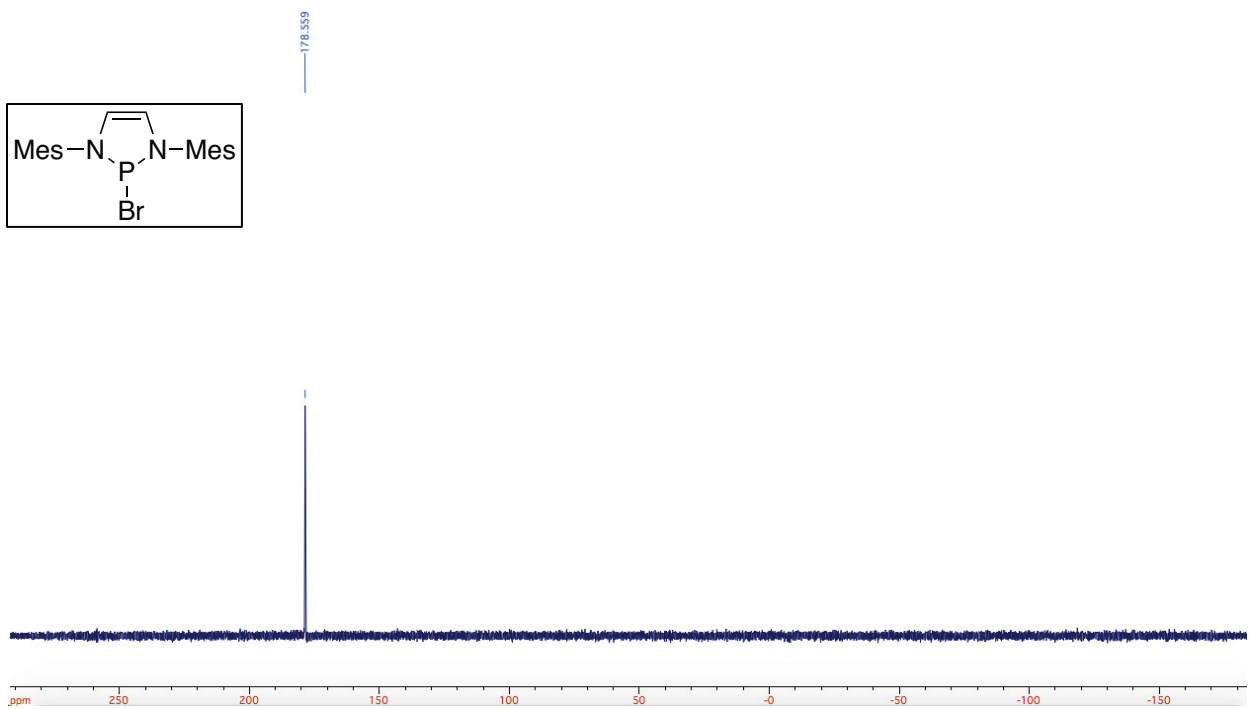
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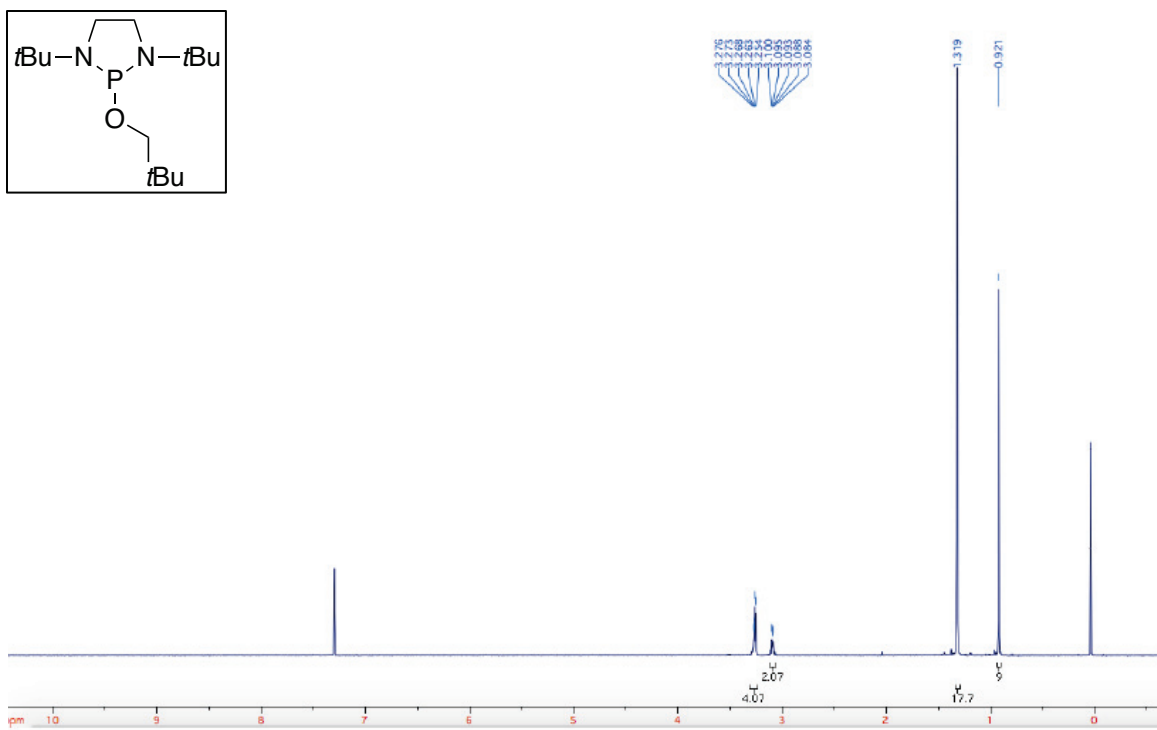
1,3-Di-mesityl-2-neopentyloxy-1,3,2-diazaphospholidine (2.17):
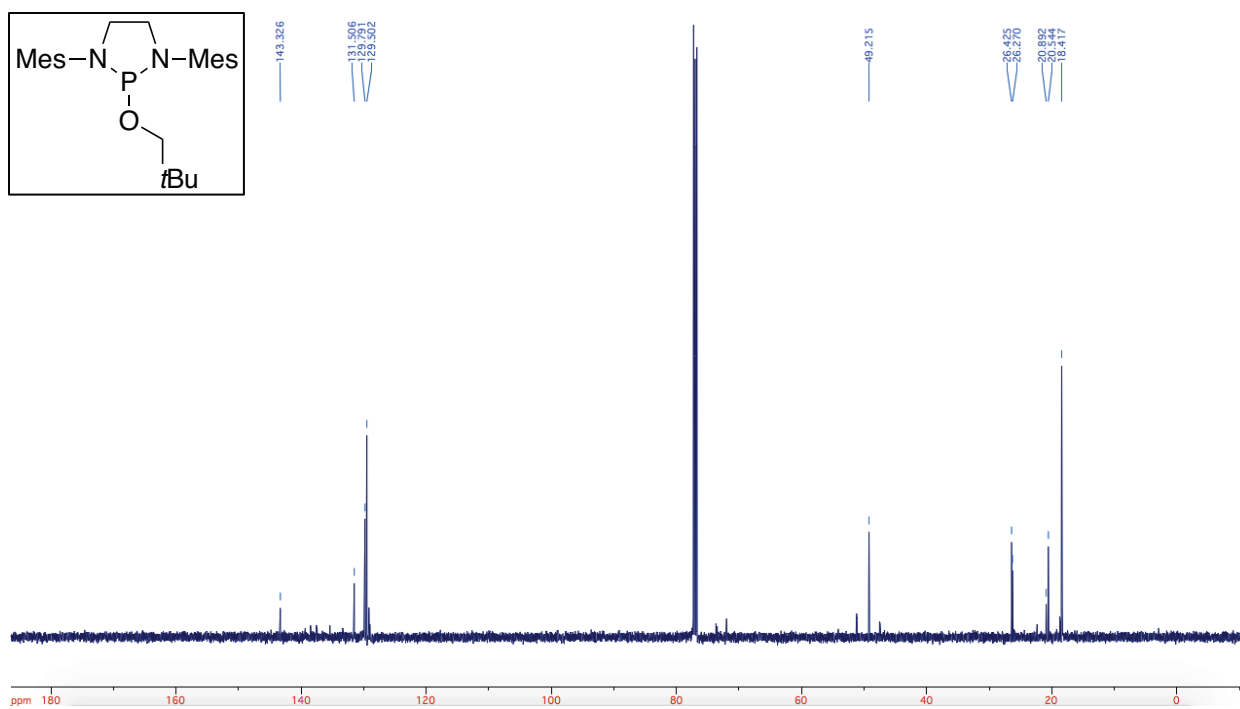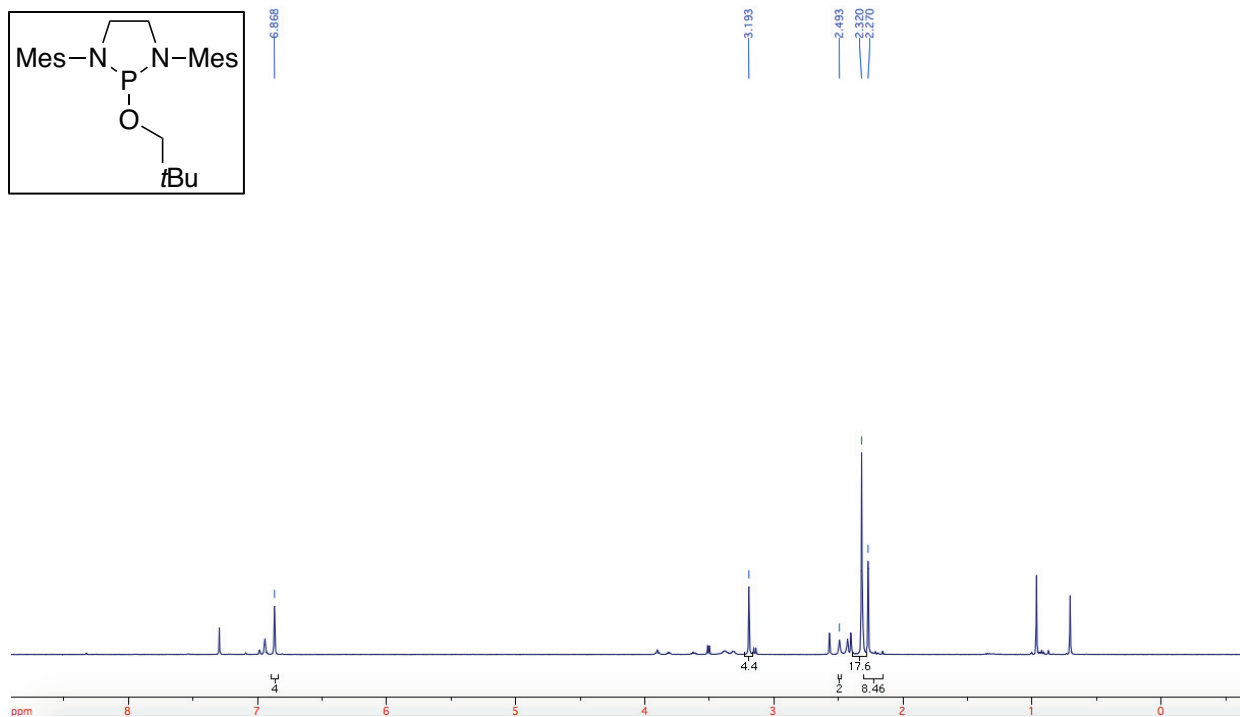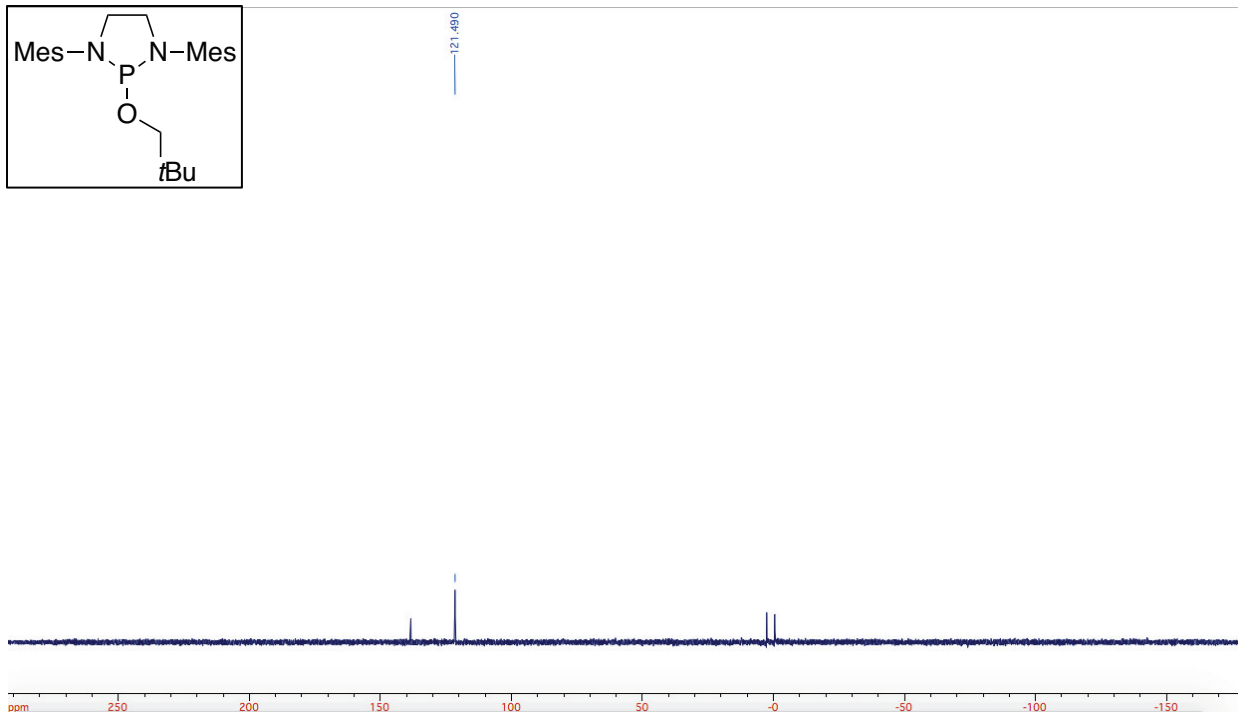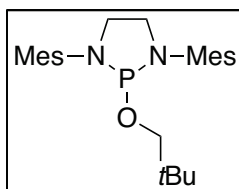
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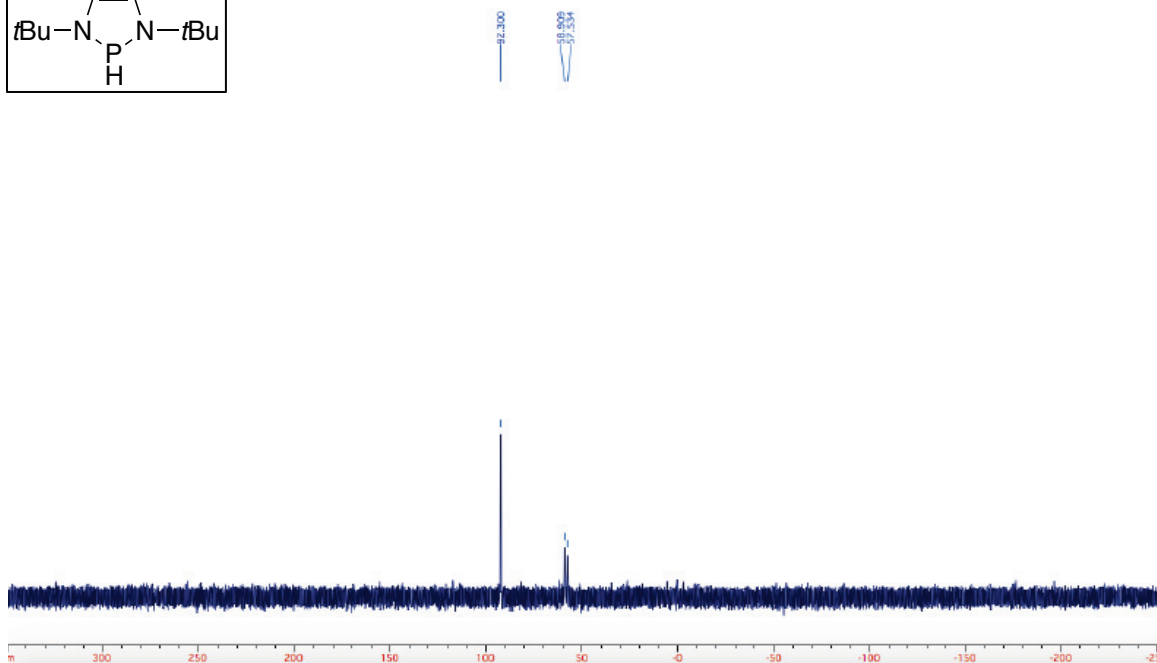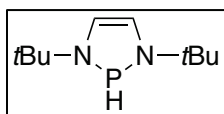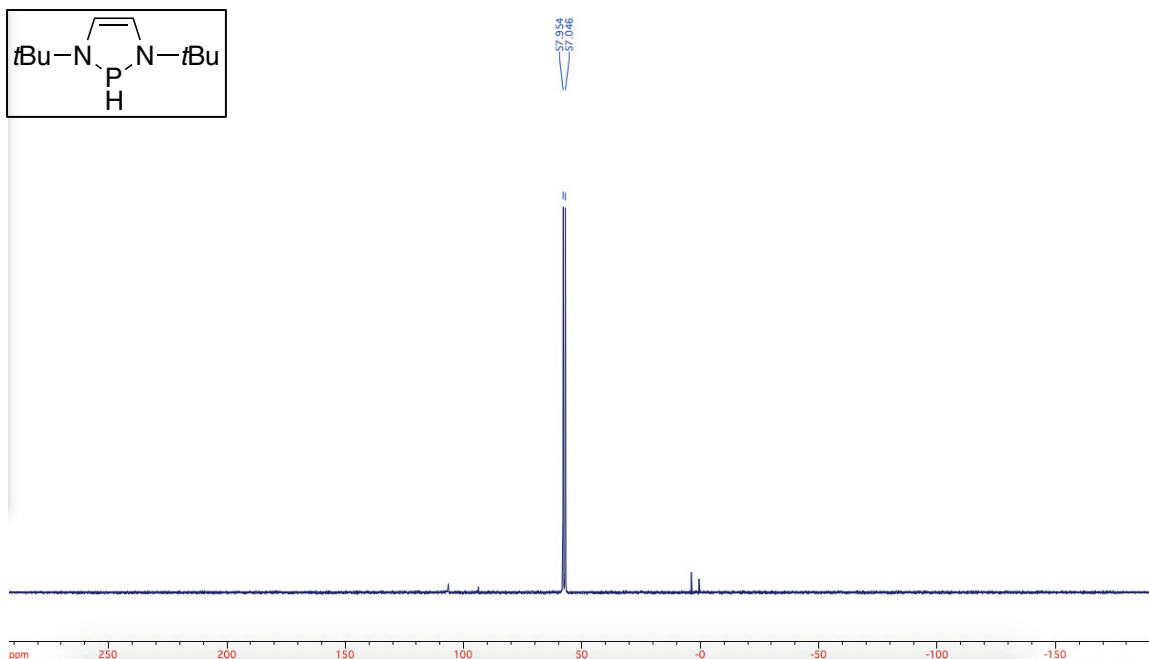
1,3-Di-mesityl-2-*H*-1,3,2-diazaphospholidine (2.19):

203

***N*-Benzyl-1-phenylethanamine (2.20):**
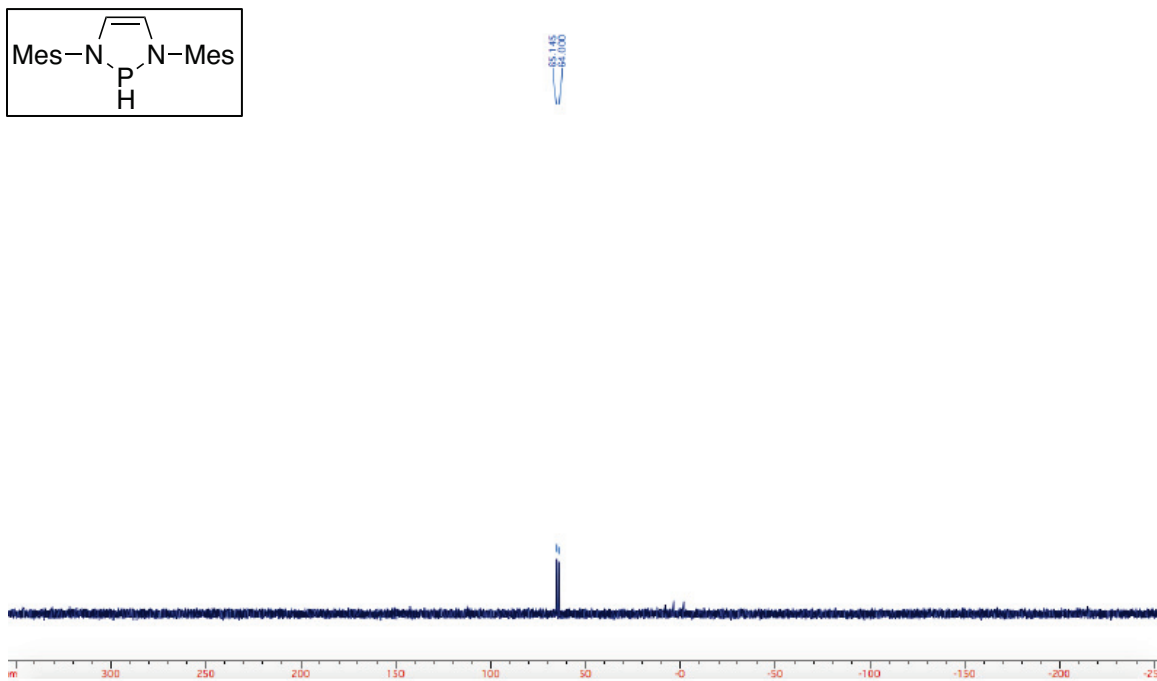
_N_-Benzyl-2,3-dihydro-1_H_-inden-1amine (2.21):
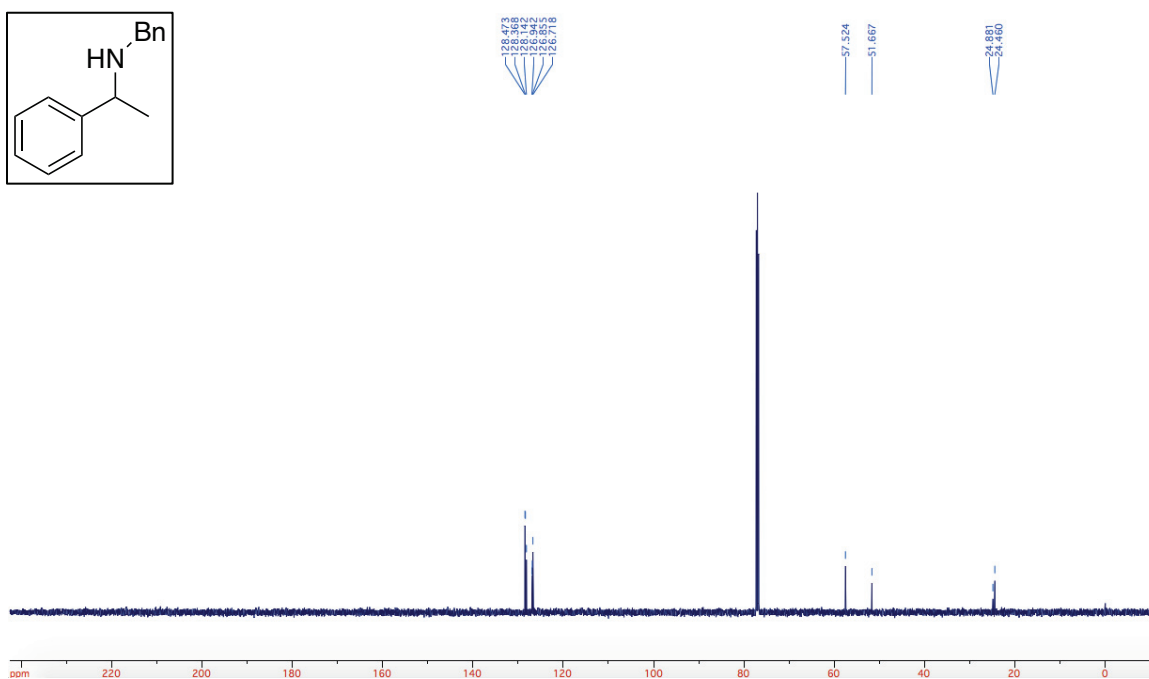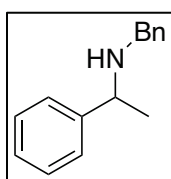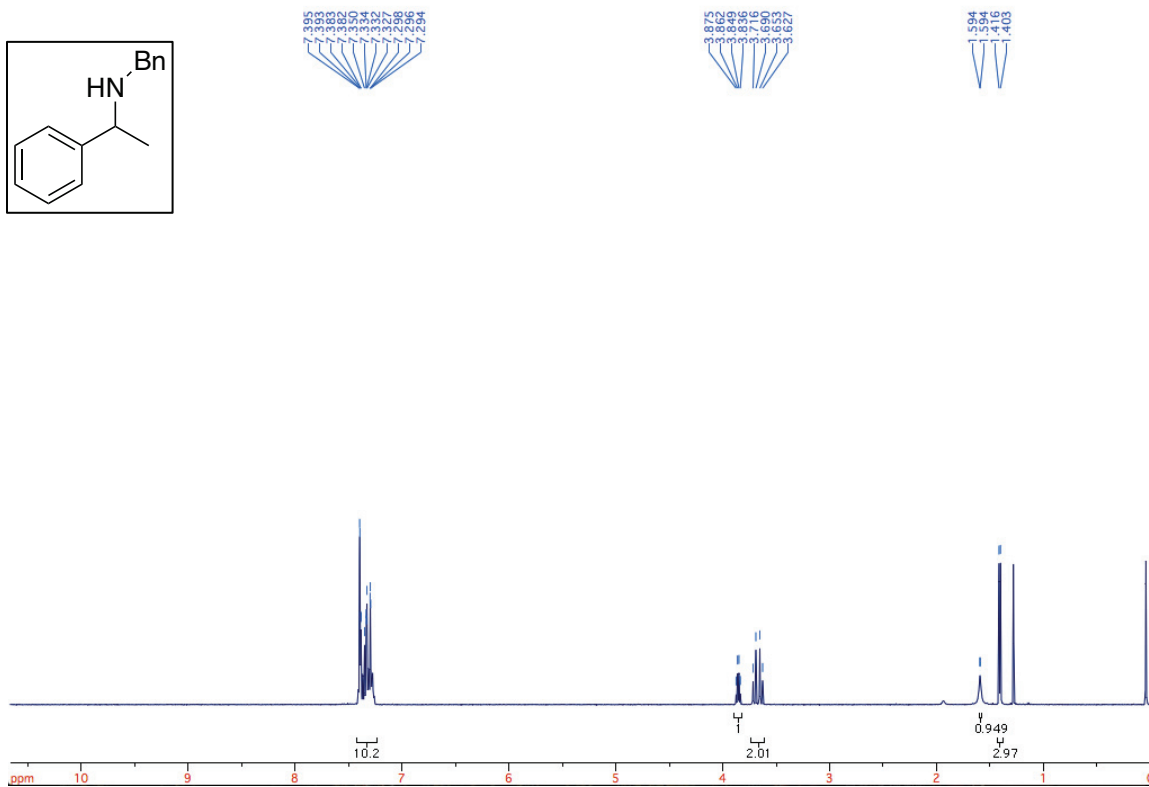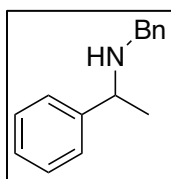
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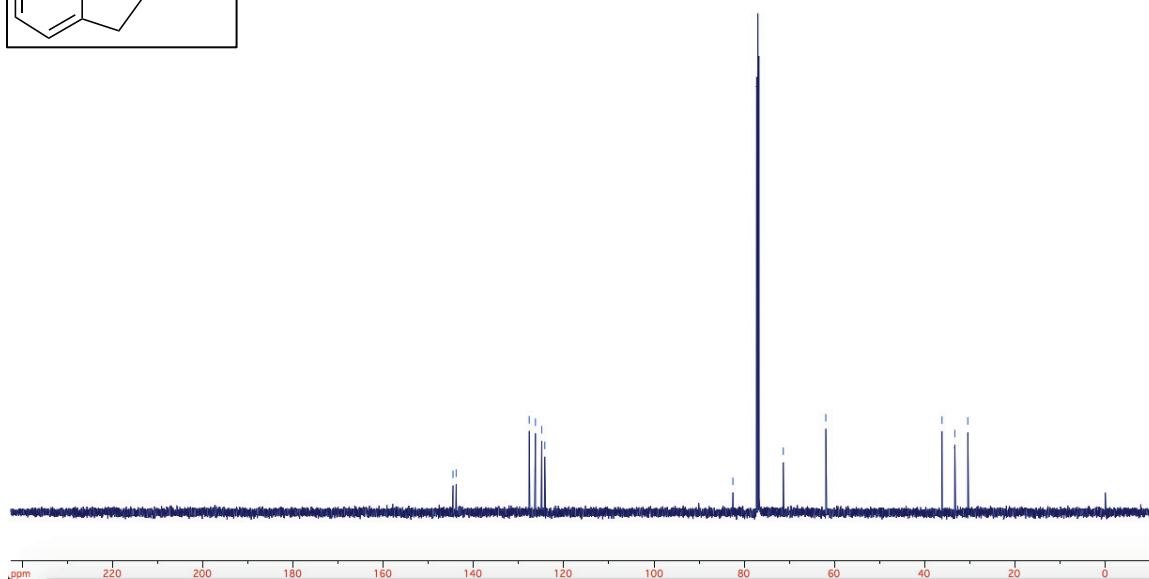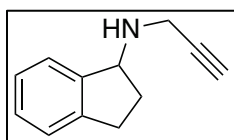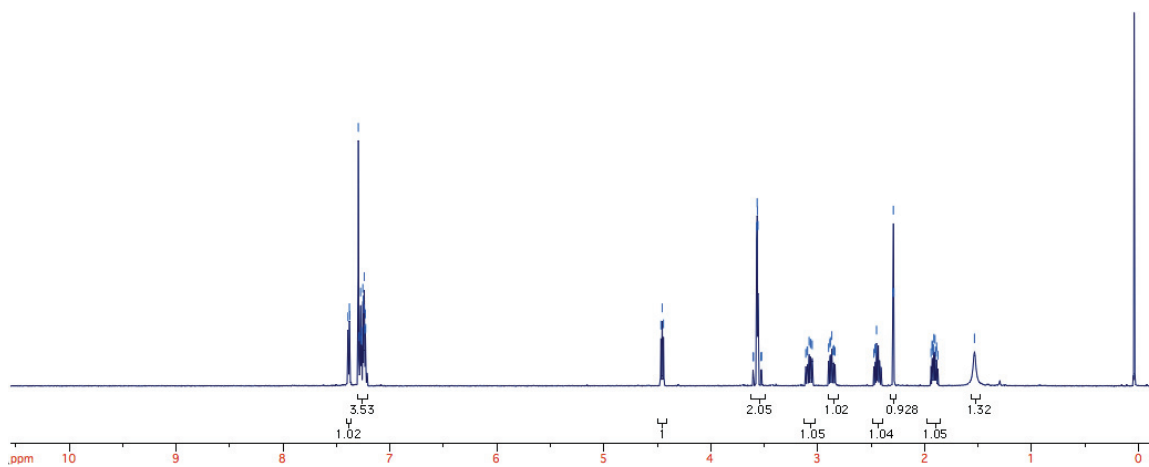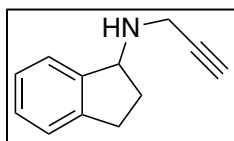
N-(4-Methoxybenzyl)-1-phenylethanamine (2.23):
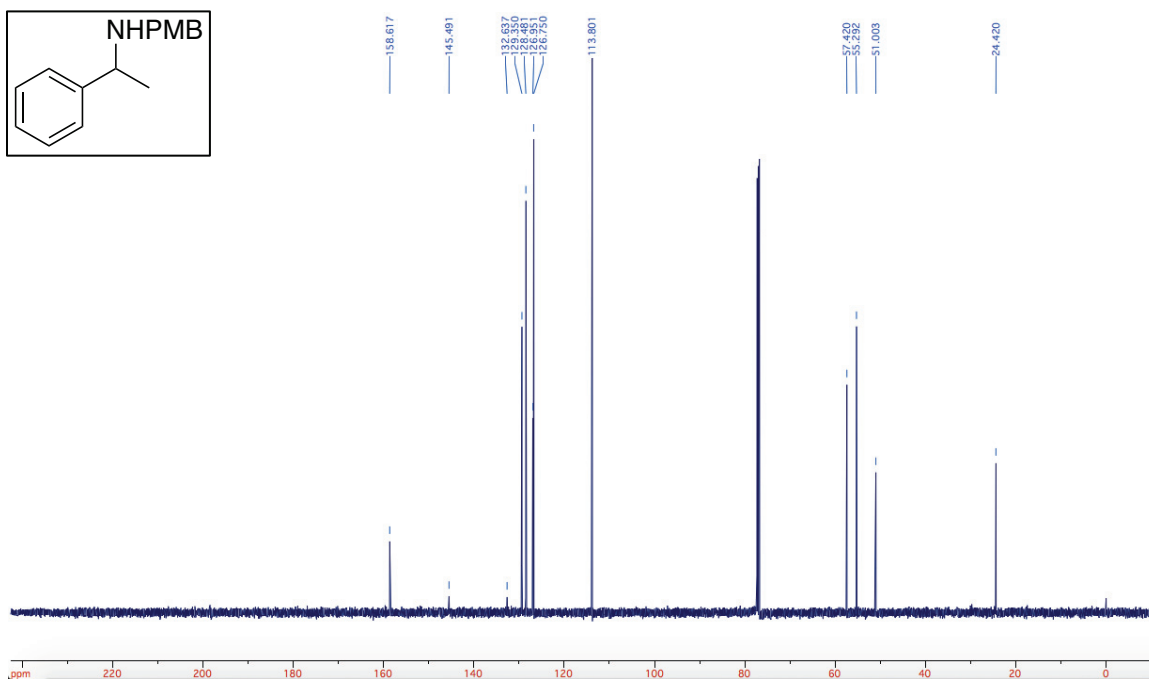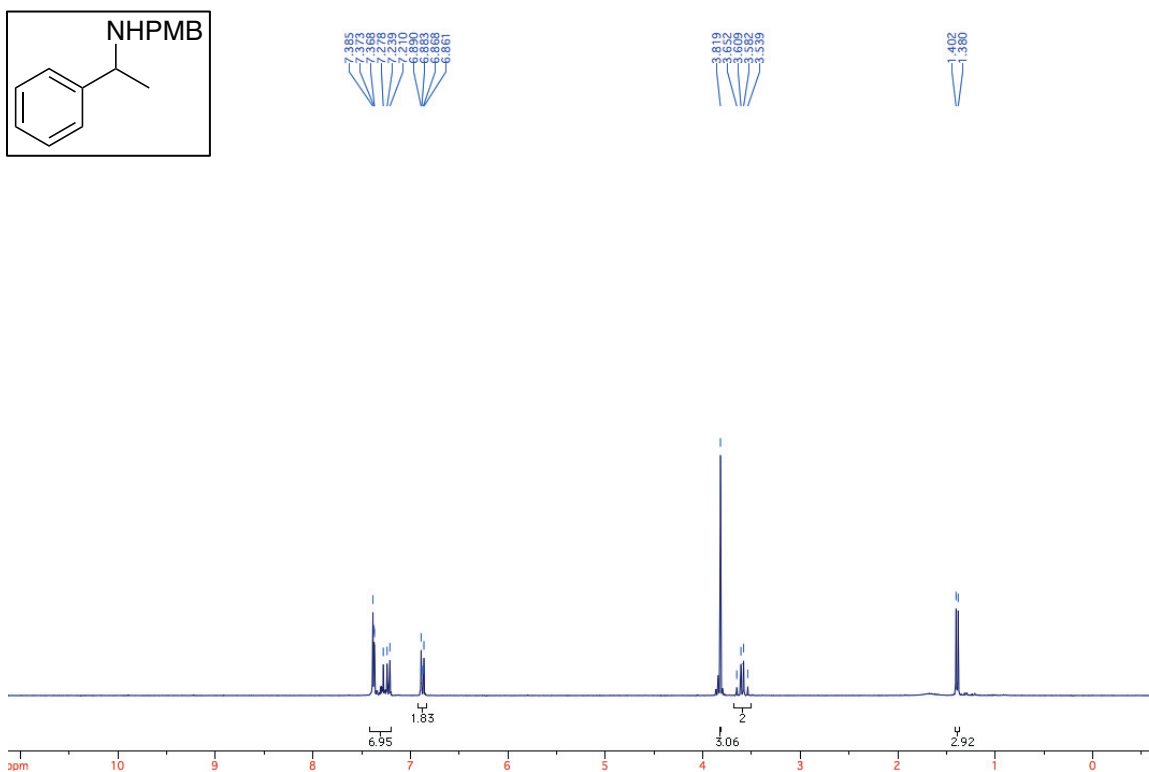
***N*-Benzyl-1-(pyridin-2-yl)ethanamine (2.24):**
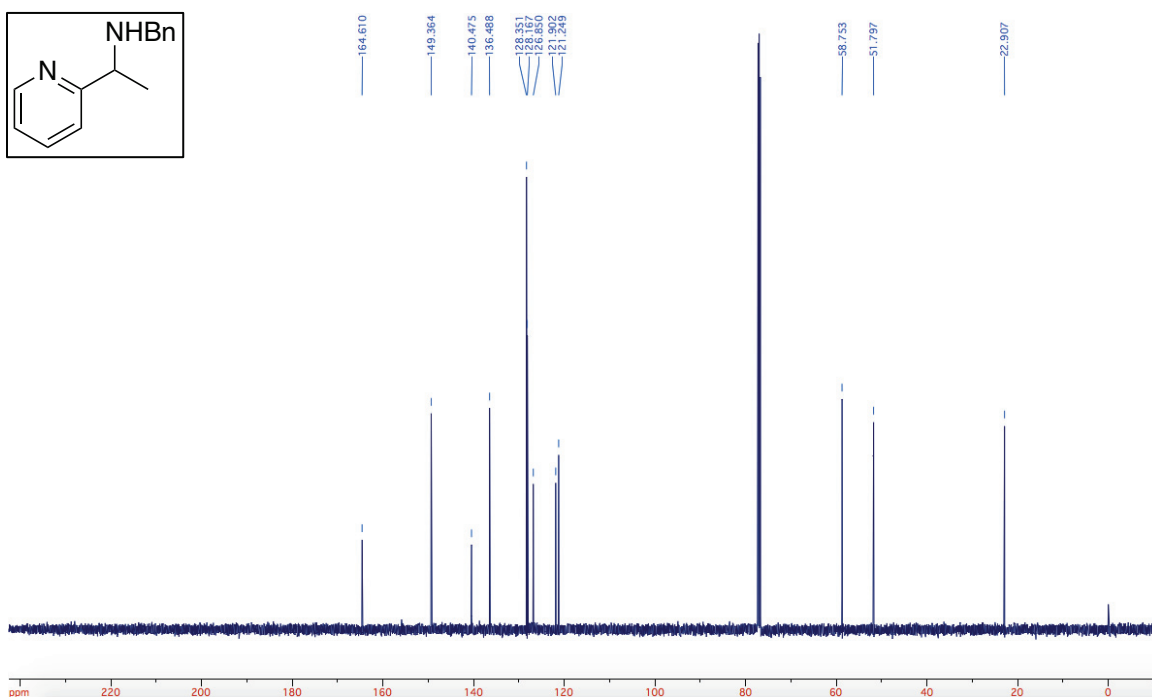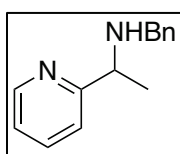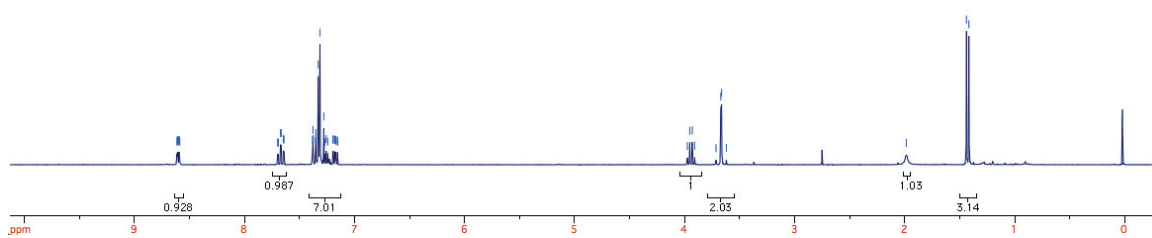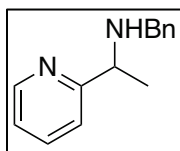
***N*-Benzyl(4-methoxyphenyl)methanamine (2.25):**

***N*-Benzyl-2-methylpropan-2-amine(2.26):**

NH*t*Bu

NH*t*Bu
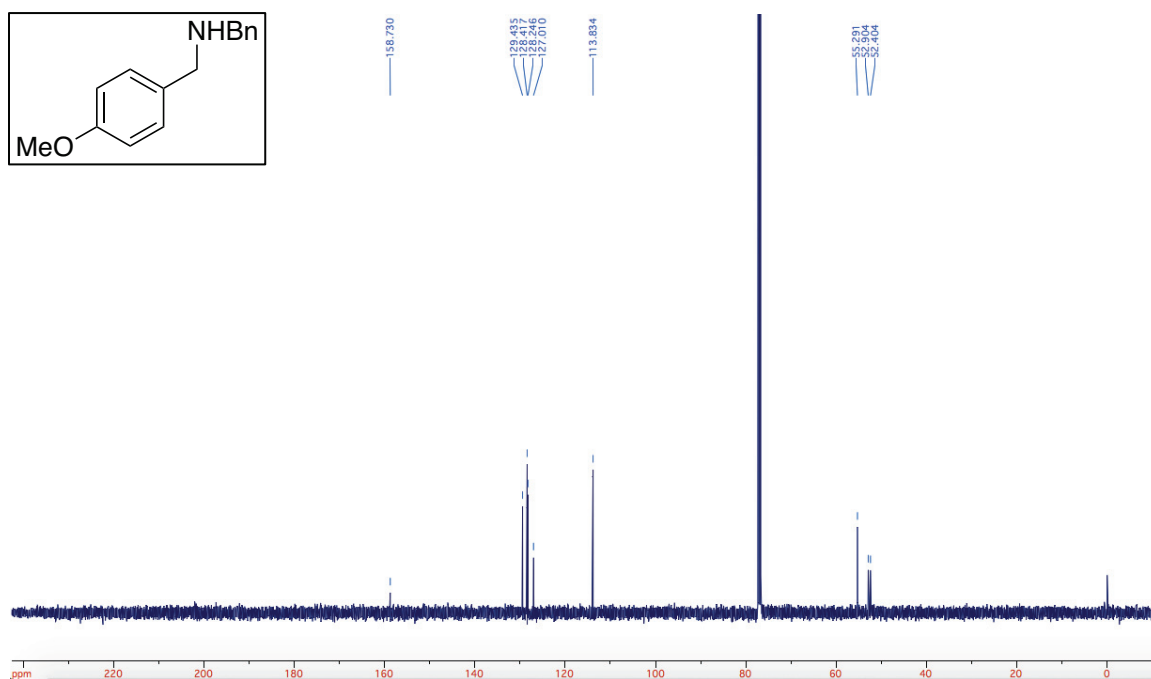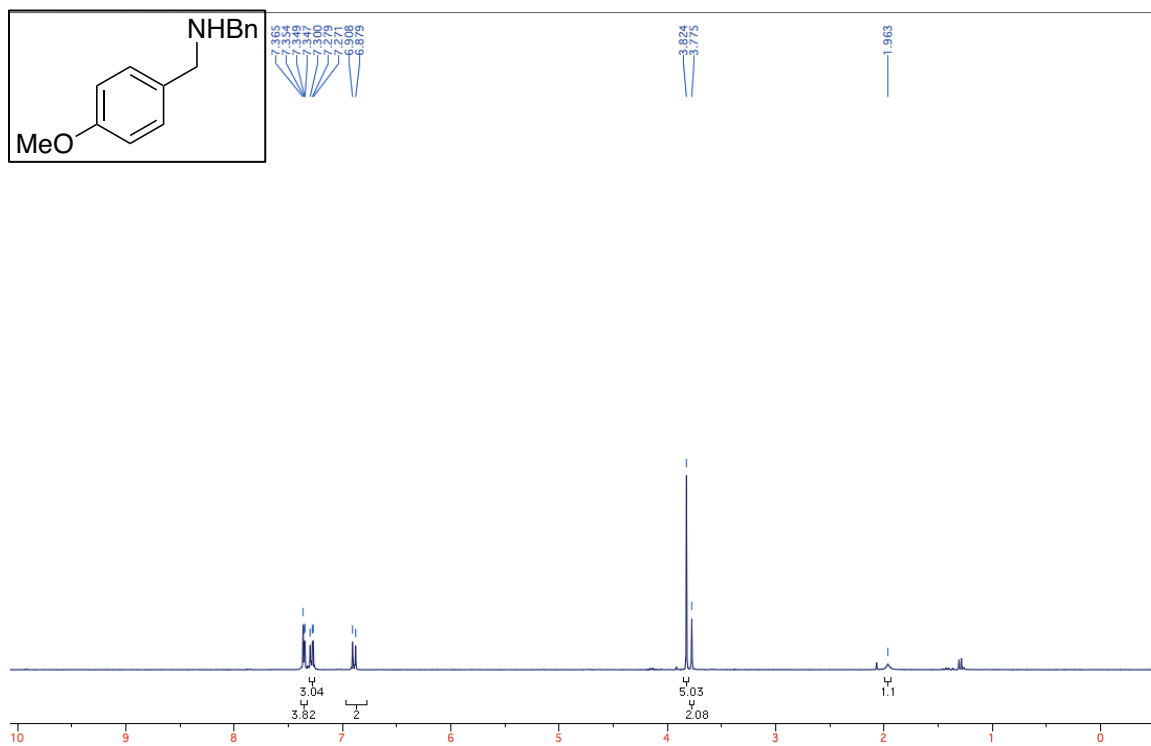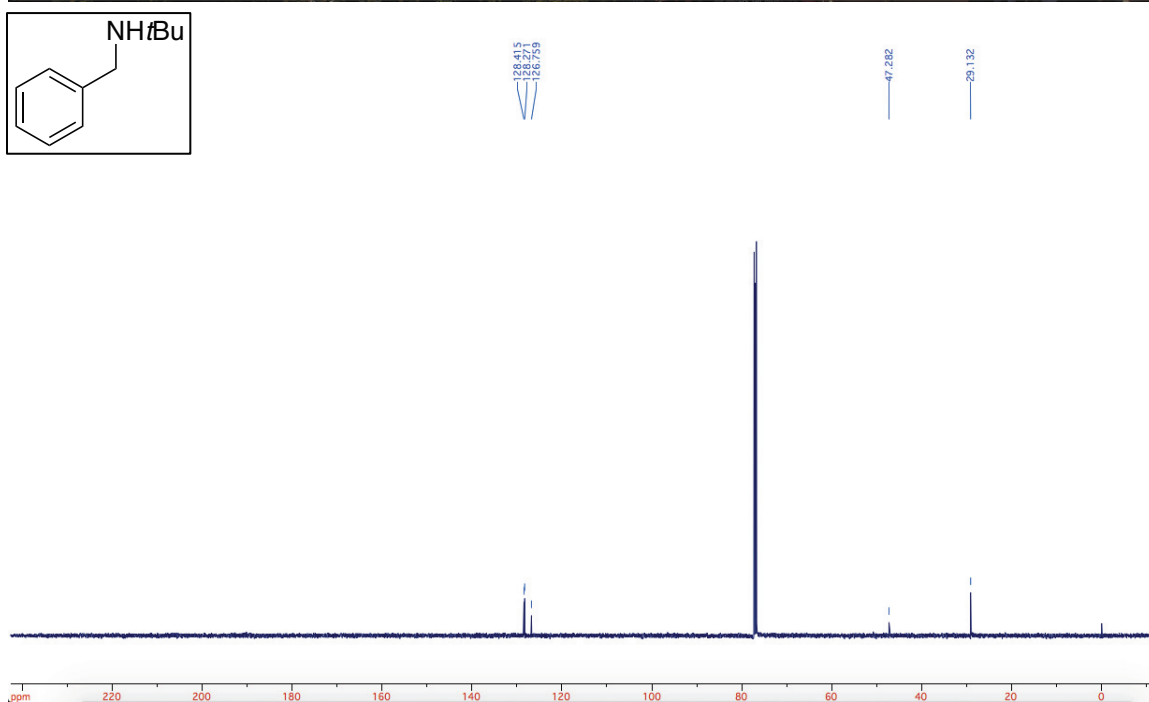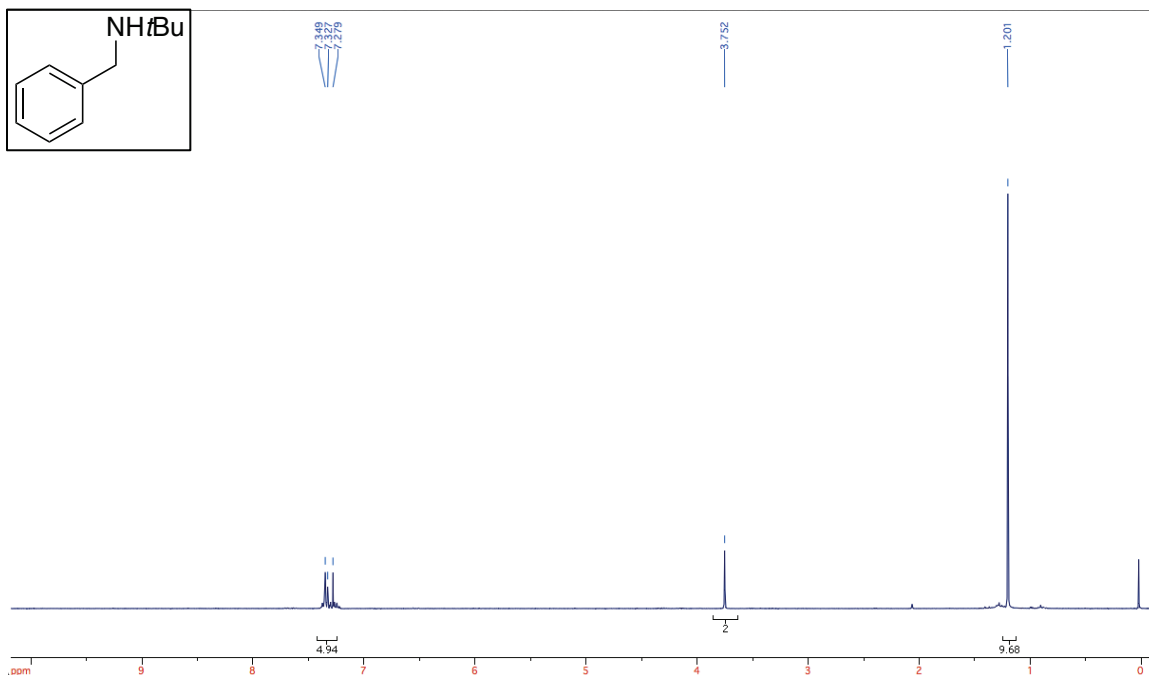
2,6-Diisopropyl-*N*-(pyridin-2-ylmethyl)benzenamine (2.27):
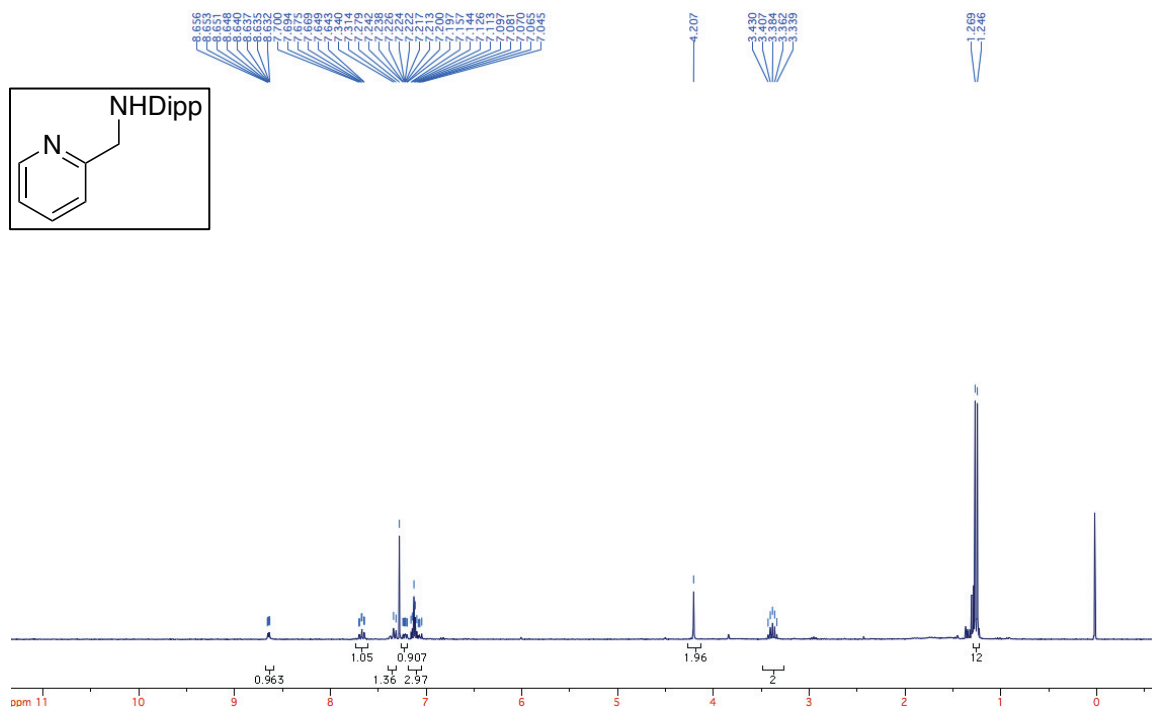
N-(2-(Cyclohexylamino)ethyl)cyclohexanamine (2.28):
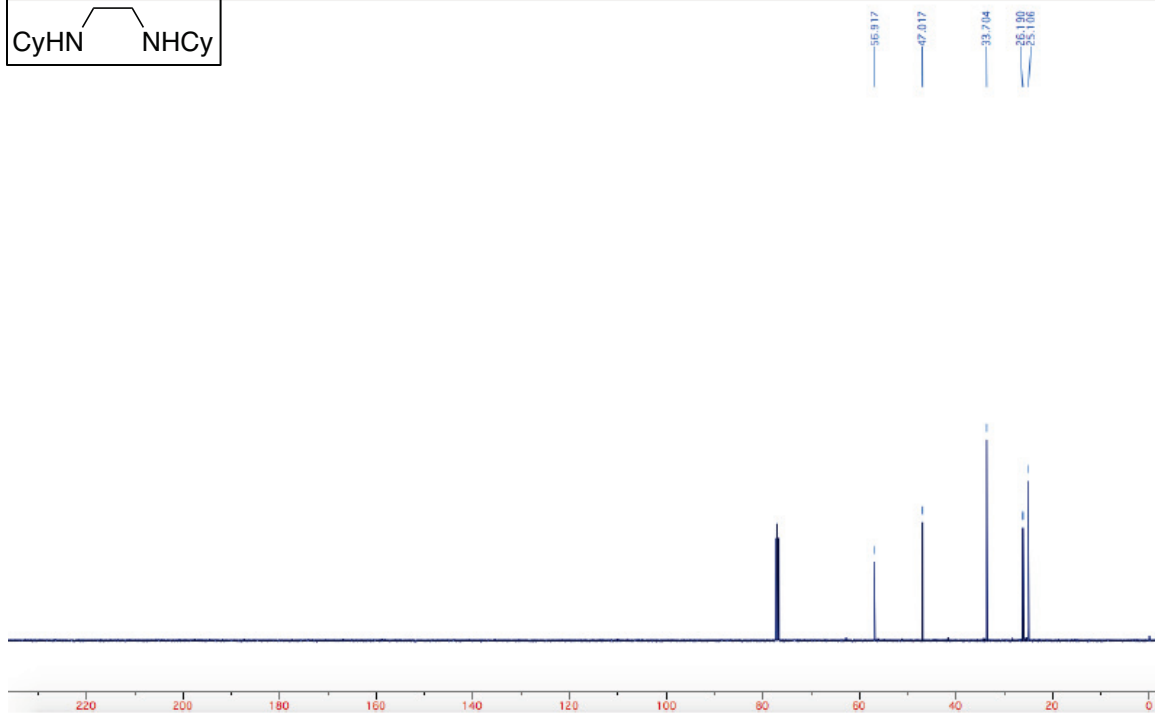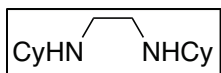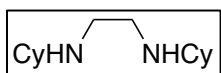
***N*-Benzylcyclohexanamine (2.29):**
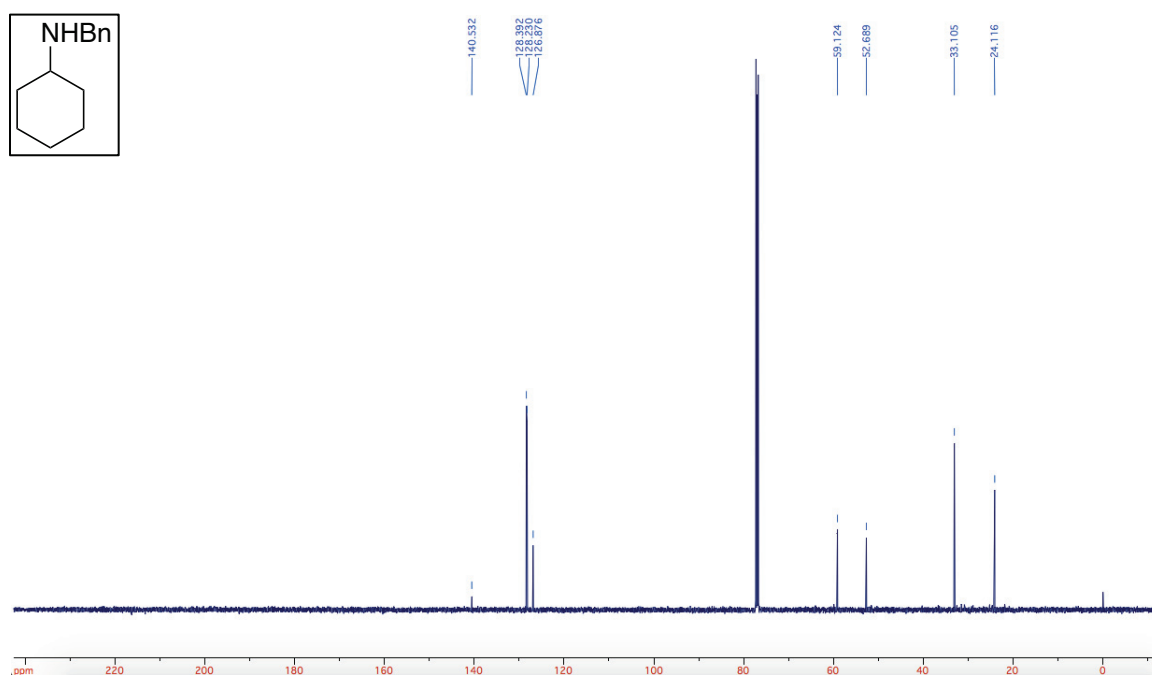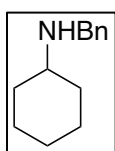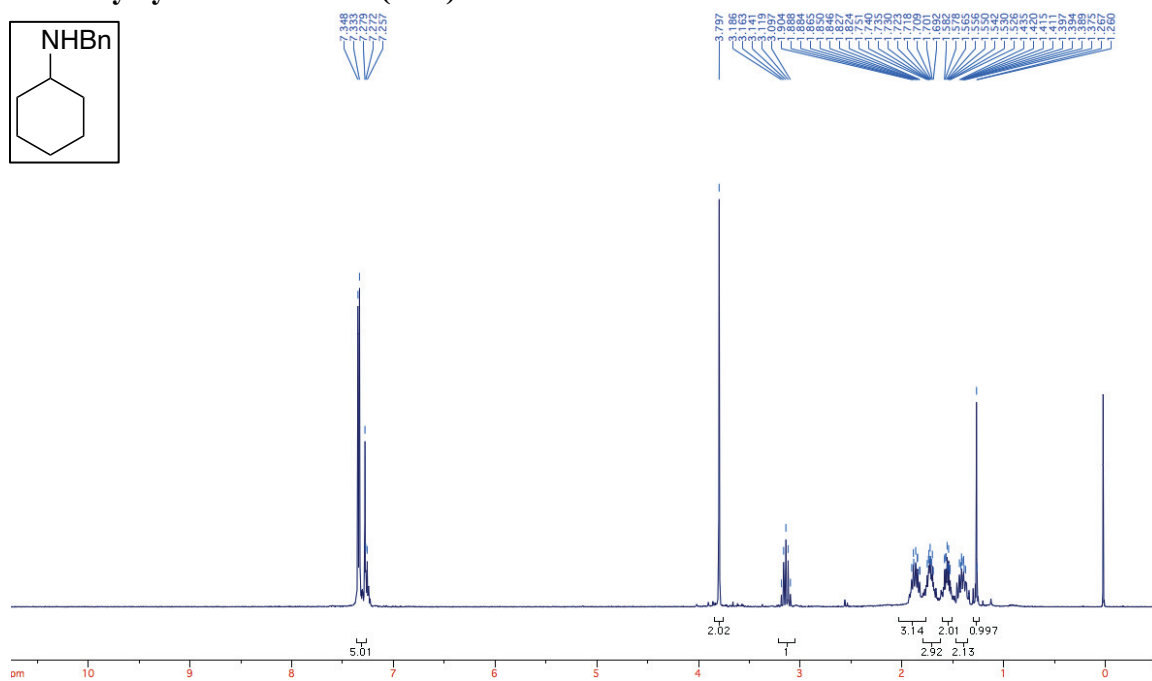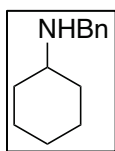
_N_-Benzylcyclooctanamine (2.30):
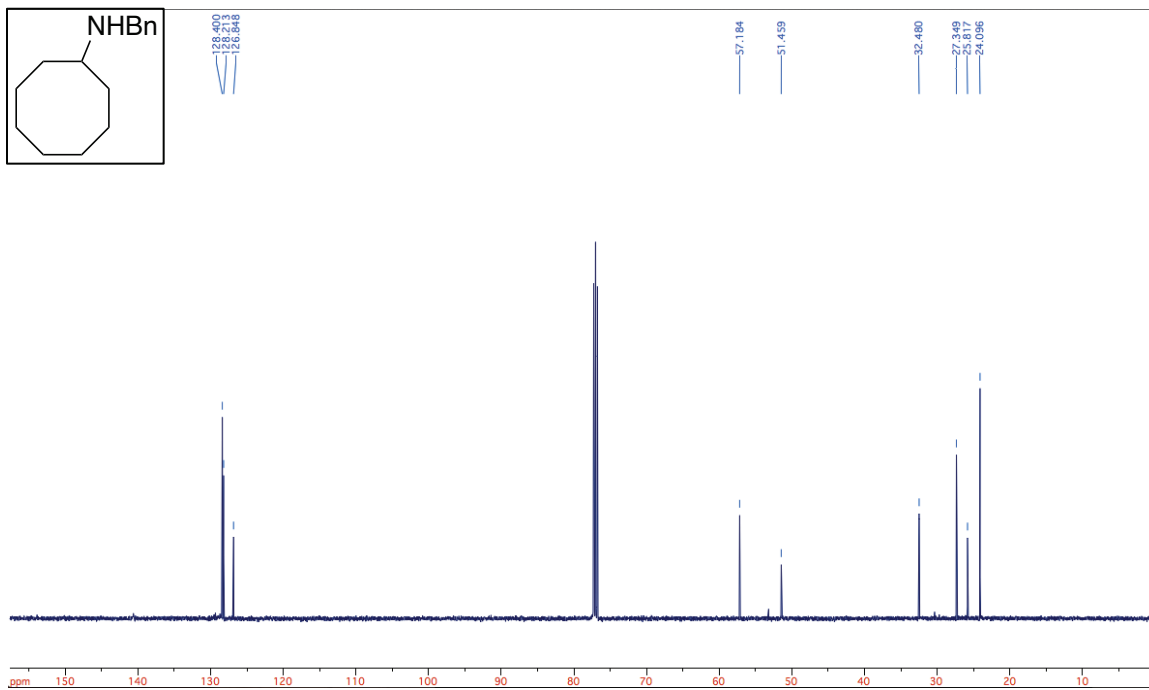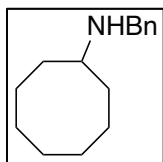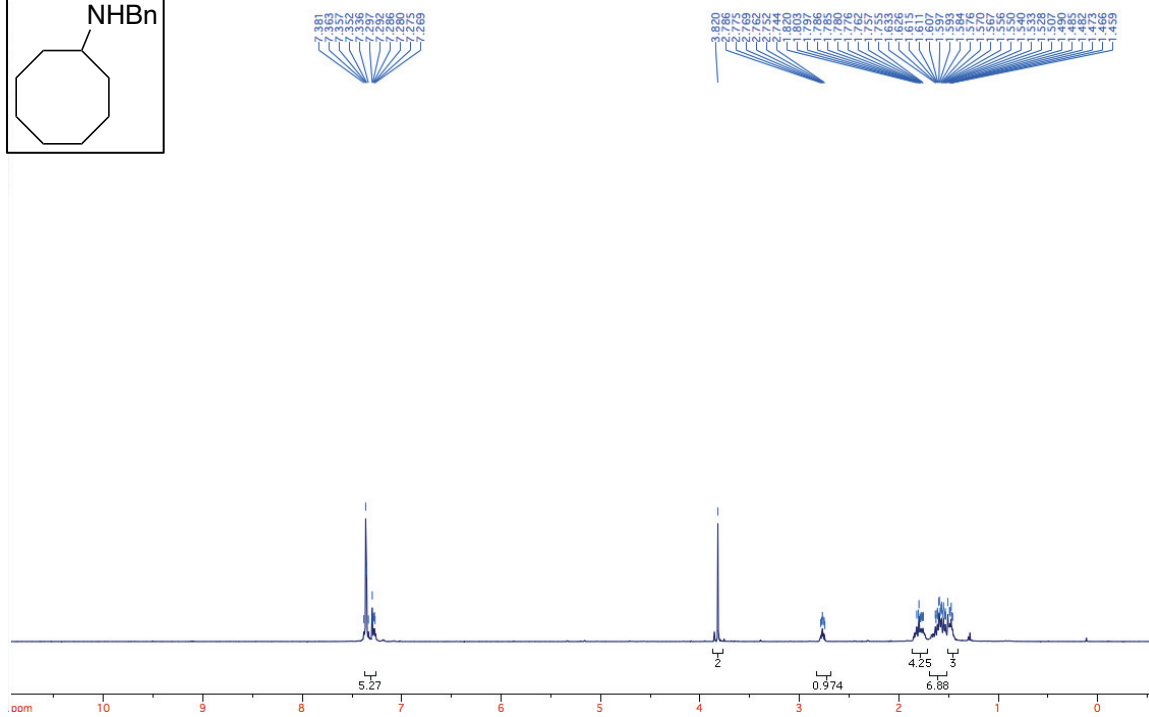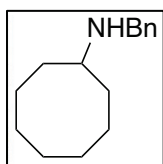
***N*-Benzyl-3,3-dimethylbutan-2-amine (2.31):**
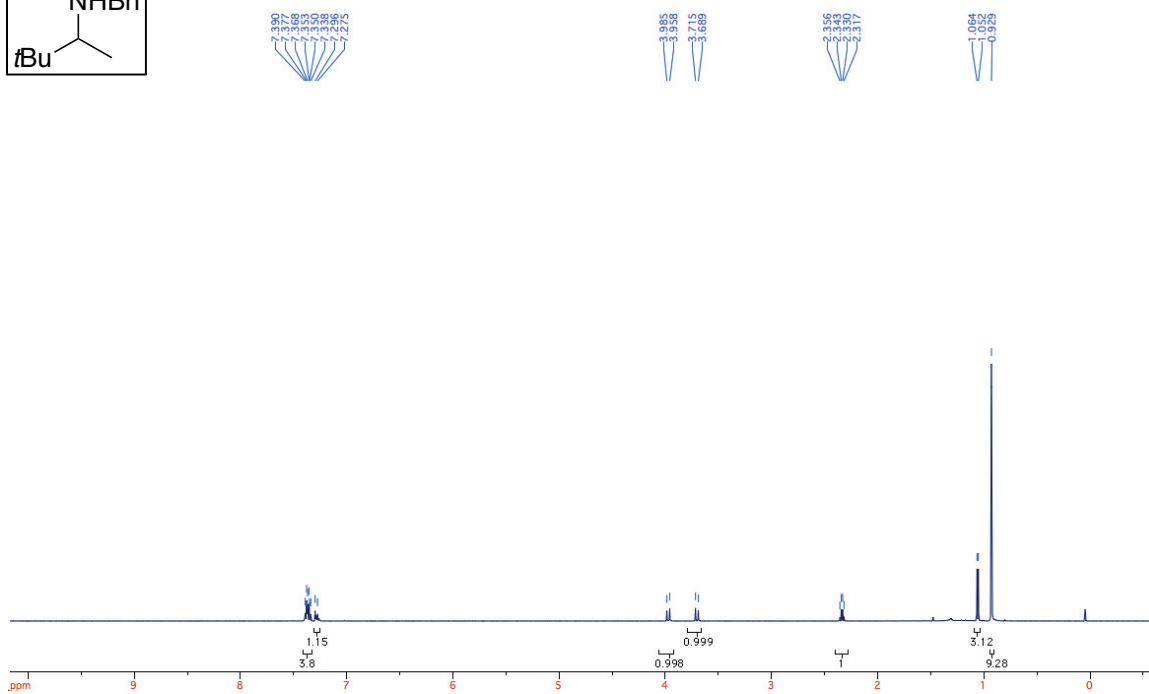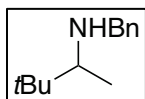
N-Benzyl-1,3-diphenylpropan-2-amine (2.32):
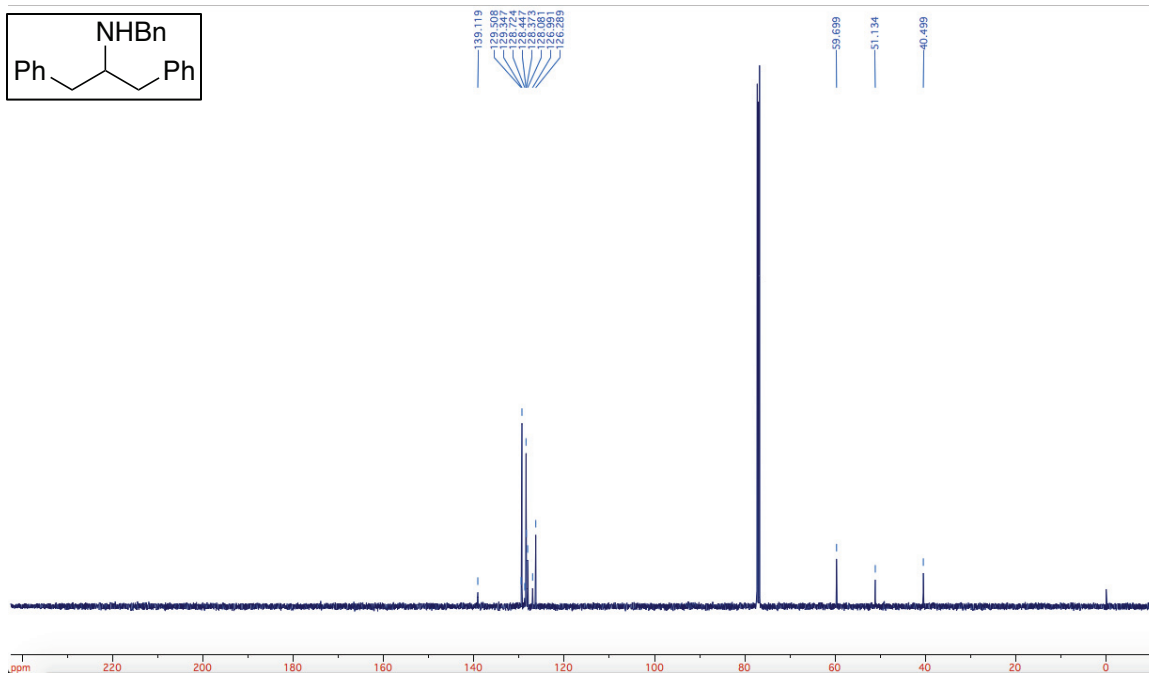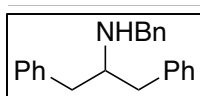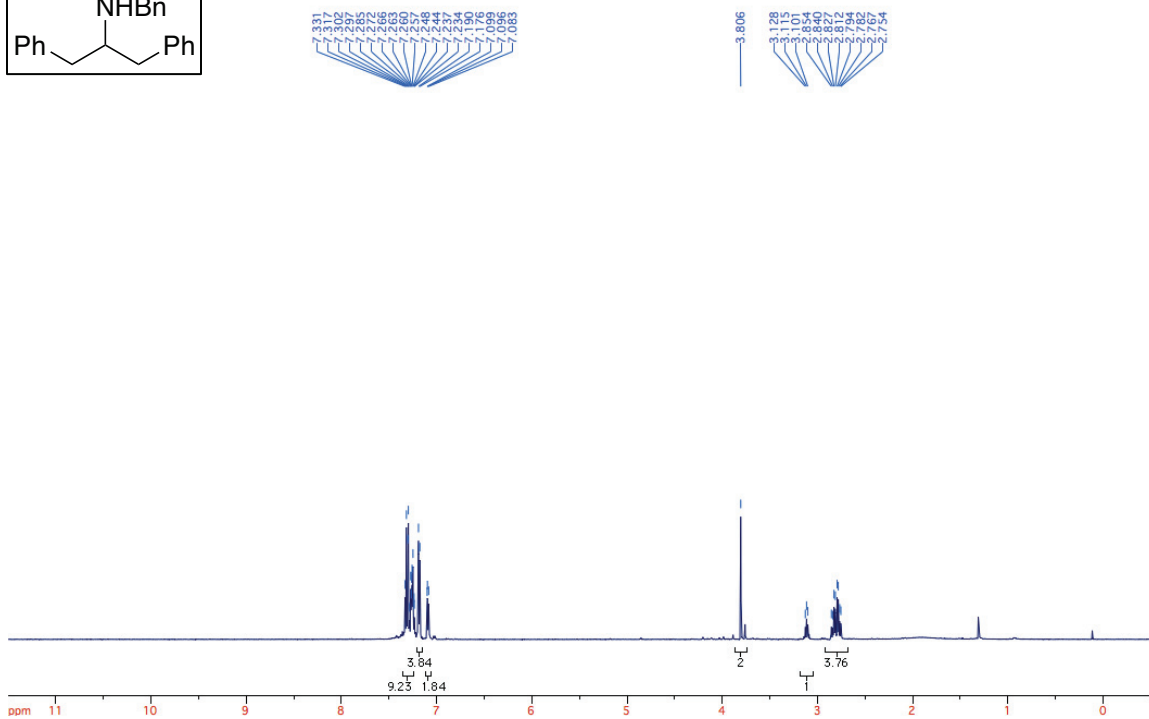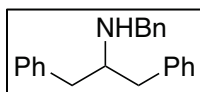
(1*R**,2*R**)-2-Allyl-*N*-benzylcyclohexanamine (2.33):

NHBn

NHBn
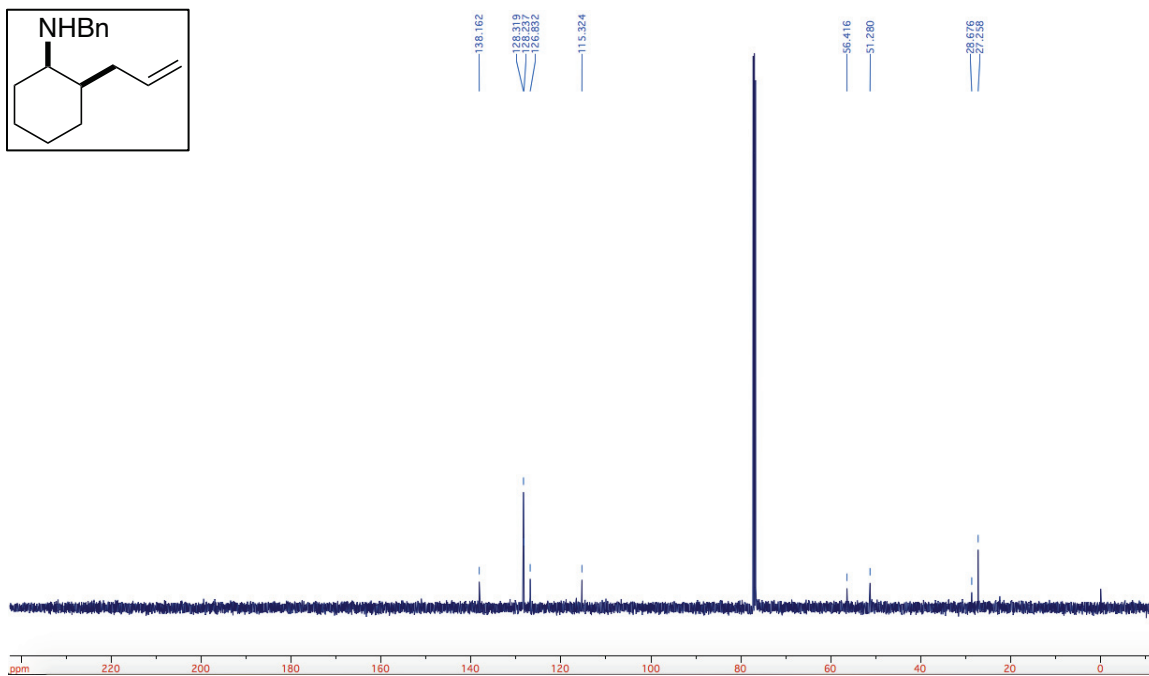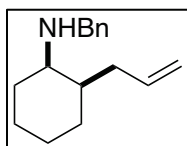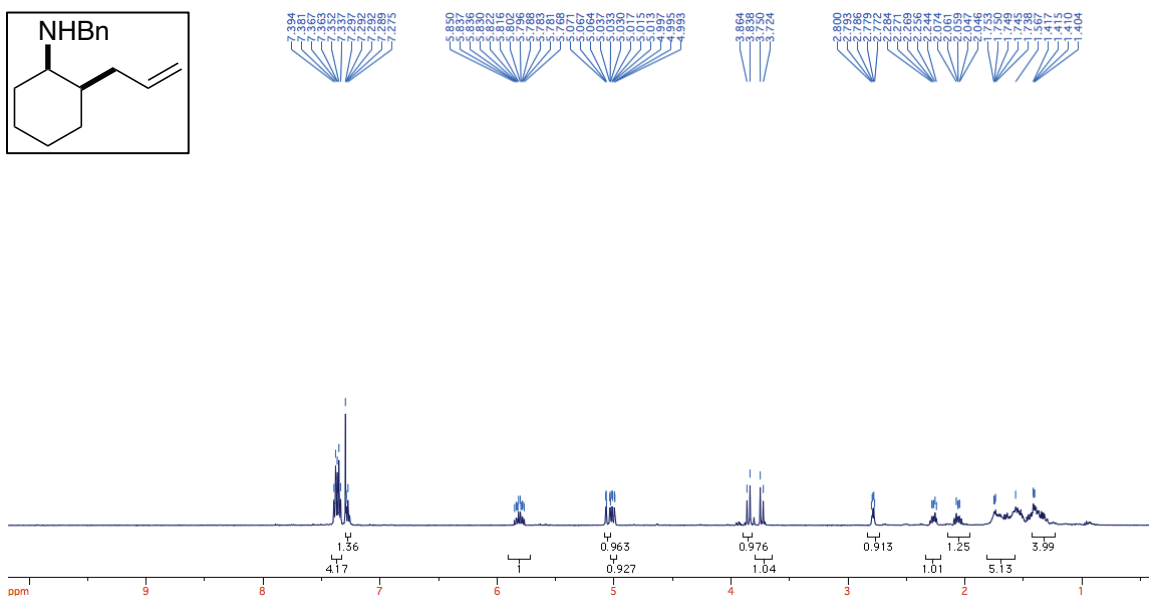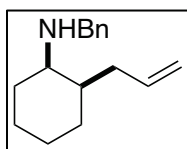
***N*-4-Methylsulfonhydrazine-6-methoxytetralamine (2.34):**
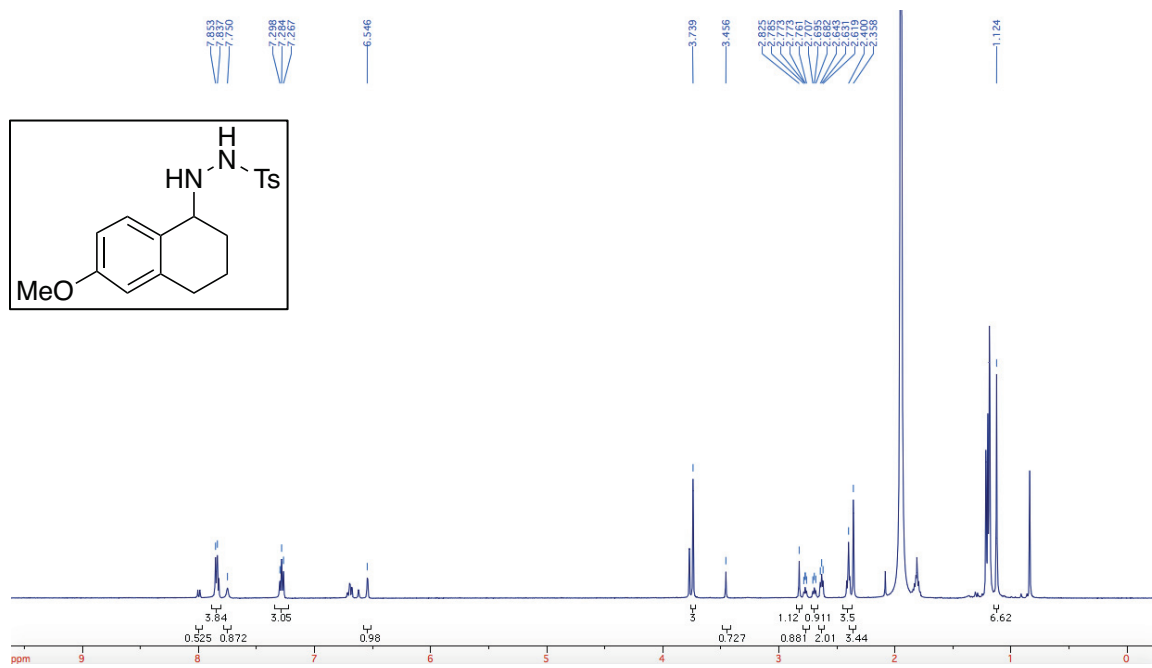
(1*S*,4*S*)-4-(3,4-Dichlorophenyl)-*N*-methyl-1,2,3,4-tetrahydronaphthalen-1-amine

(Sertraline) (2.35):
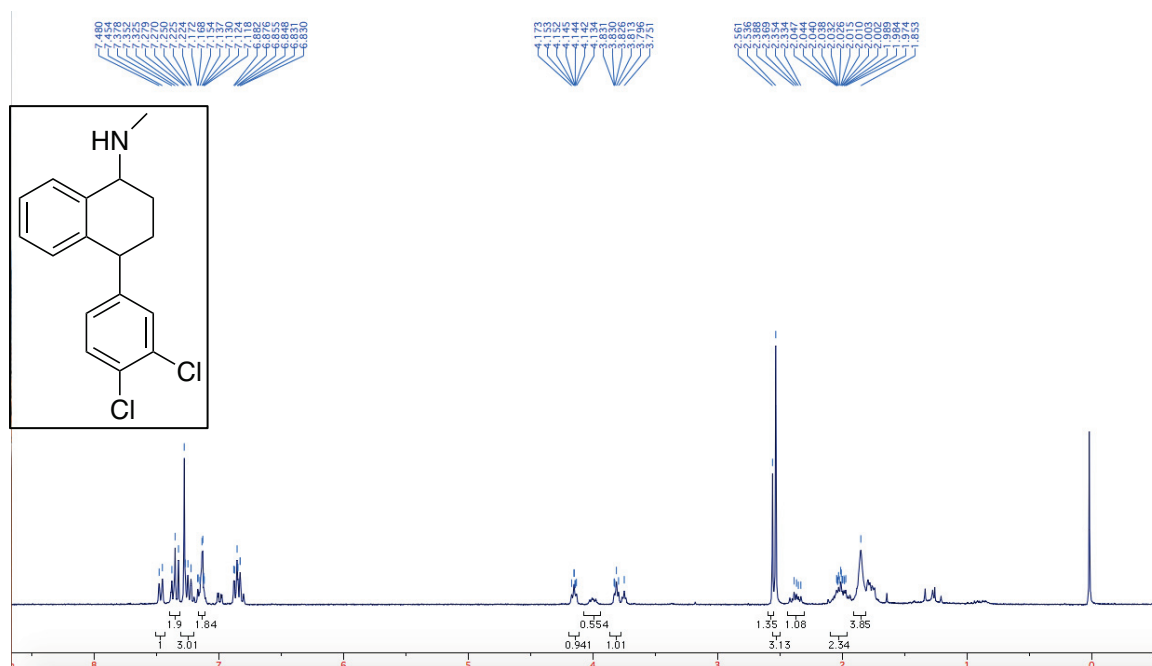
N-Benzyl-tetrahydroquinoline (2.36):
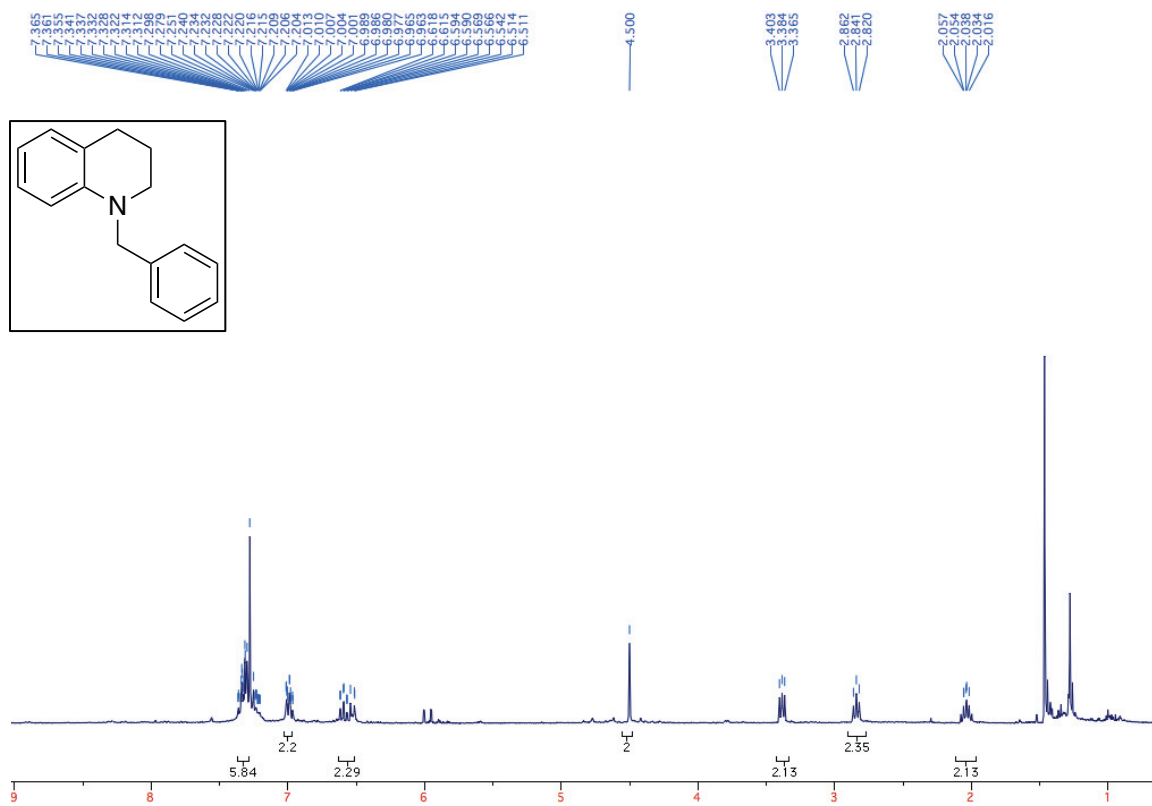
2-Dibenzylamido-1,3-di-*tert*-butyl-1,3,2-diazaphosphole (2.42):
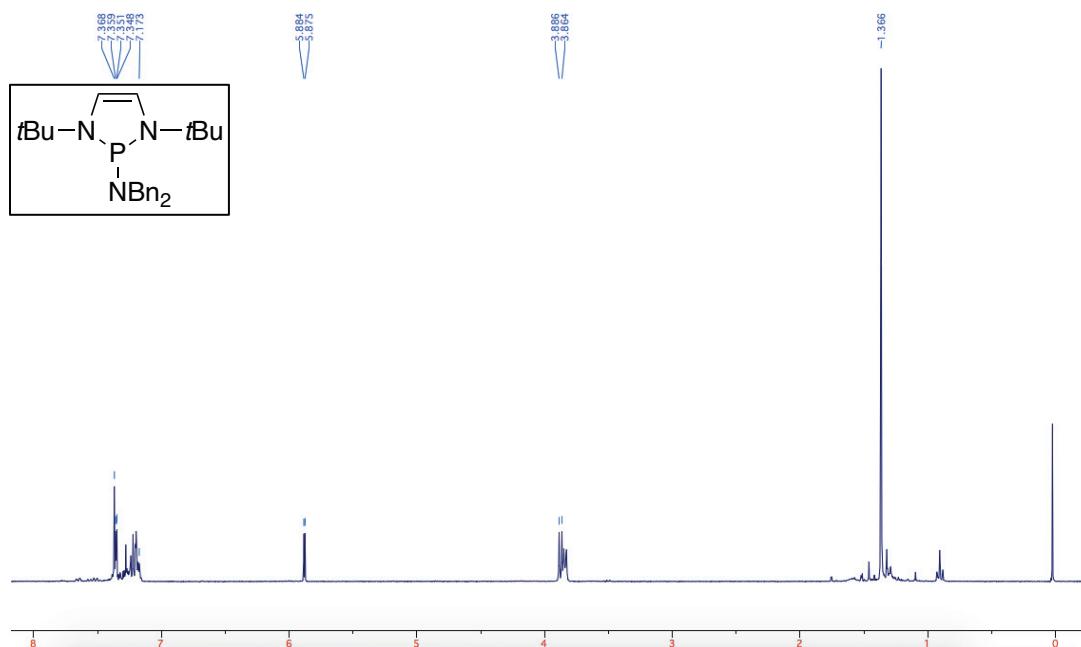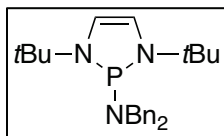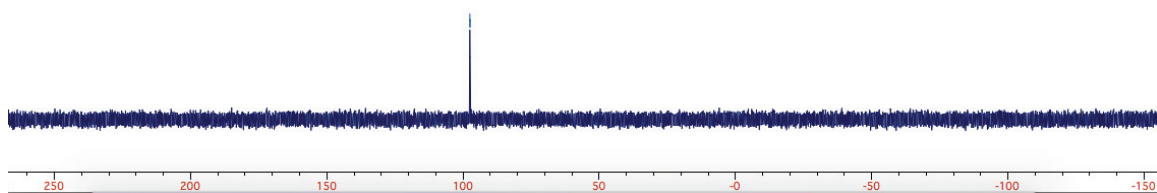
N-Benzyl-phenylmethanamine (2.43):

Bn—NH—Ph

140.273
128.423
128.189
126.978
53.172

ppm 220 200 180 160 140 120 100 80 60 40 20 0

Methyl 3-phenylpropanoate (2.44):

ppm 8.0 7.5 7.0 6.5 6.0 5.5 5.0 4.5 4.0 3.5 3.0 2.5 2.0 1.5 1.0 0.5 0.0

221
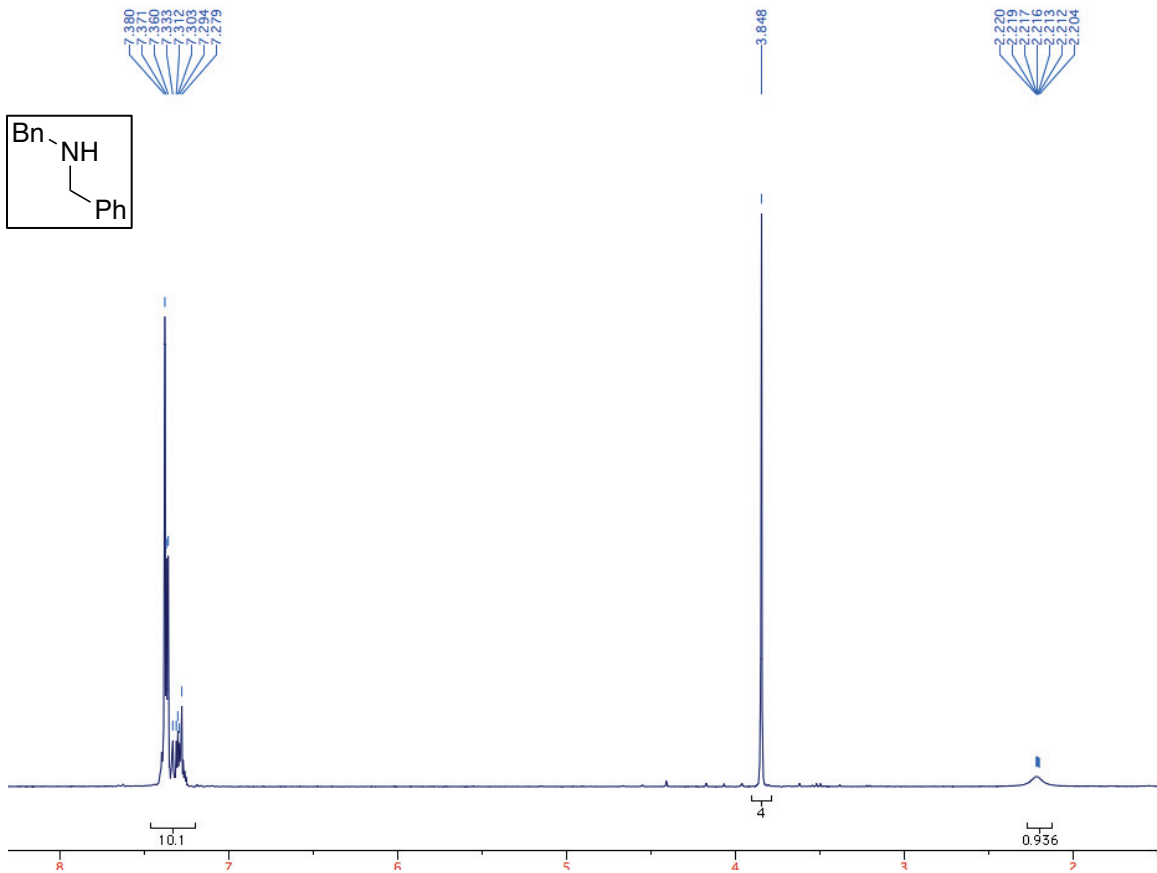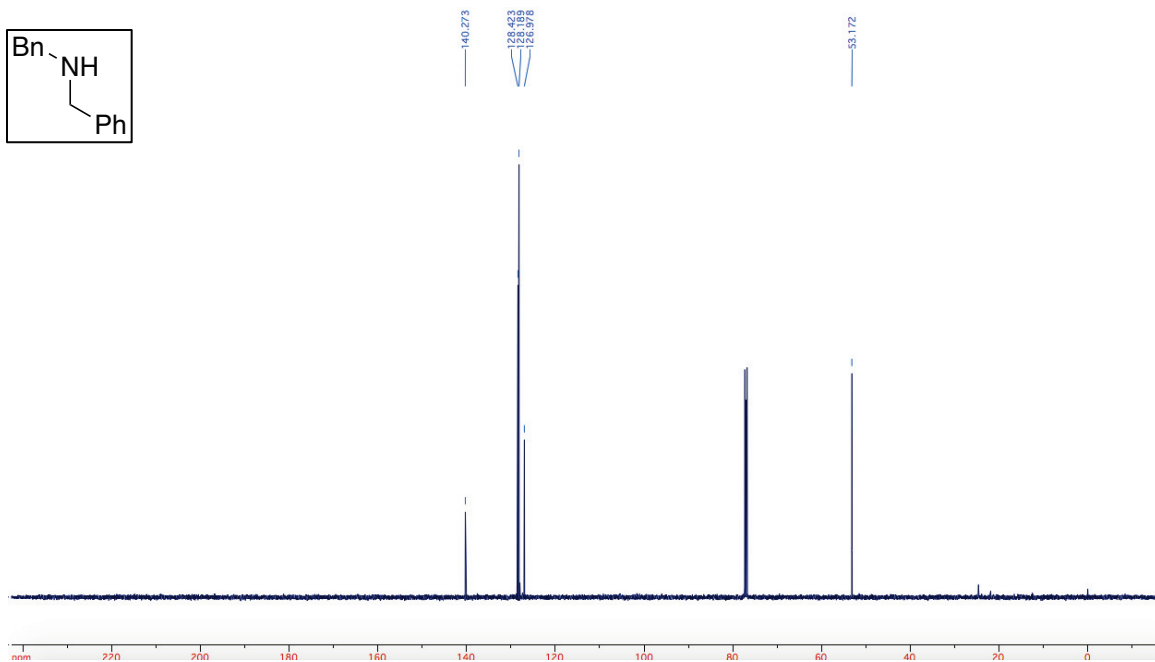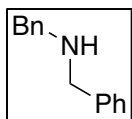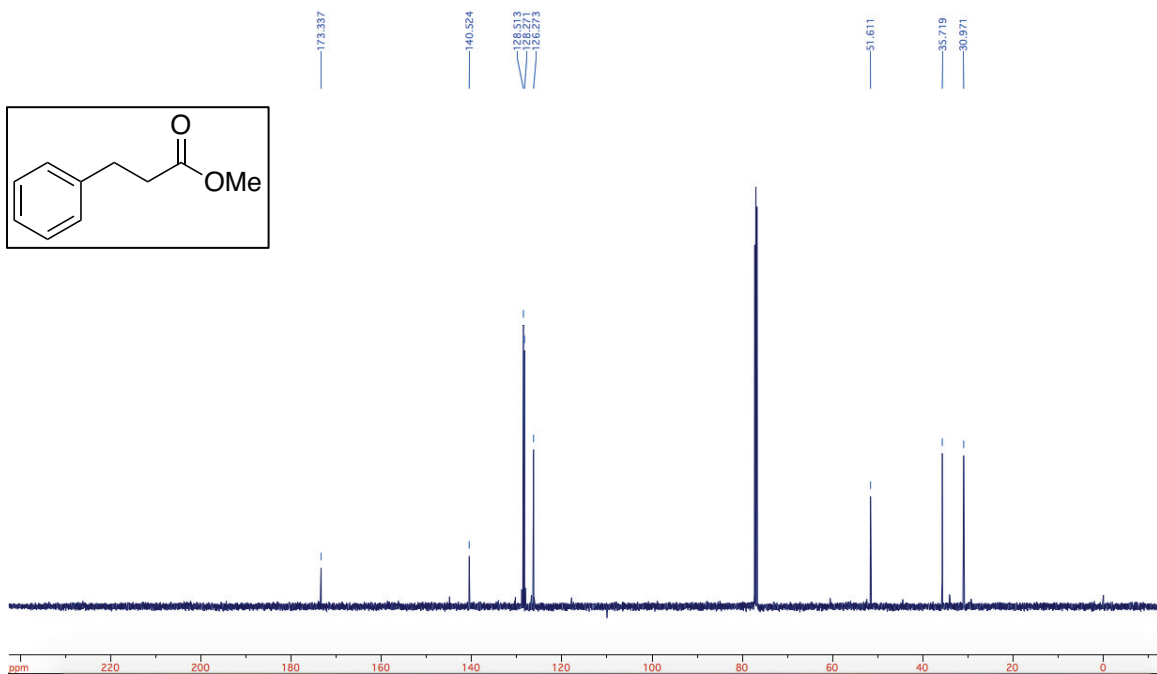
Ethyl 3-phenylbutanoate (2.45):

4-(4-Hydroxy-3-methoxyphenyl)butan-2-one (Zingerone) (2.46):

208.164

146.436
143.944
132.930
120.764
114.359
111.068
55.898
45.552
30.130
29.499

tert-Butyl-3-(benzylamino)butanoate (2.47):

171.745

128.416
128.142
126.909

80.470

51.212
51.202
49.962
42.874
28.140
20.398
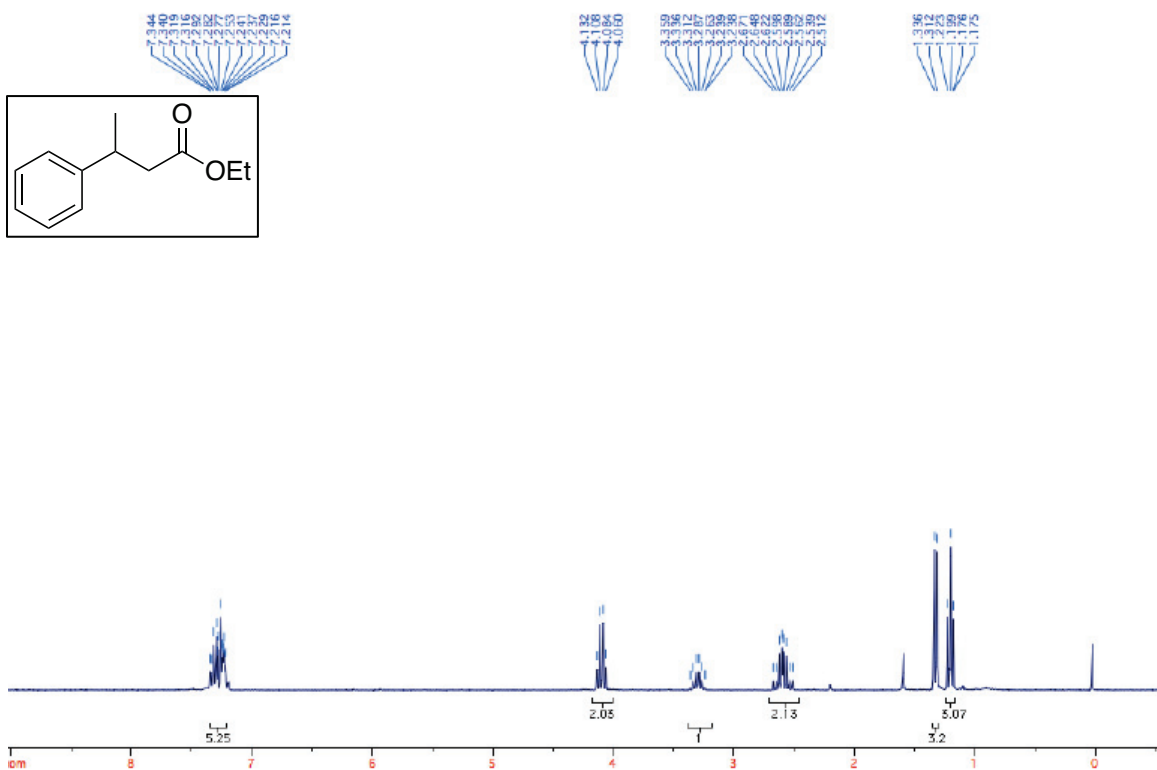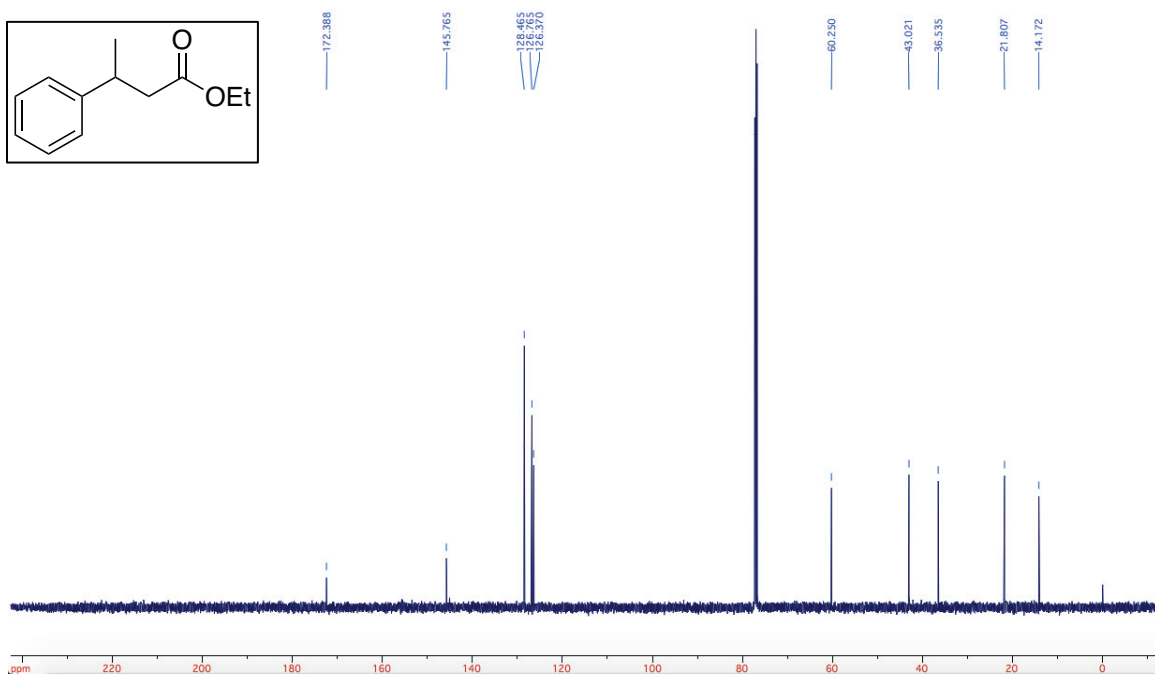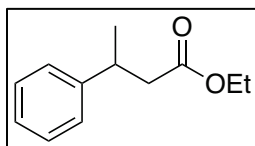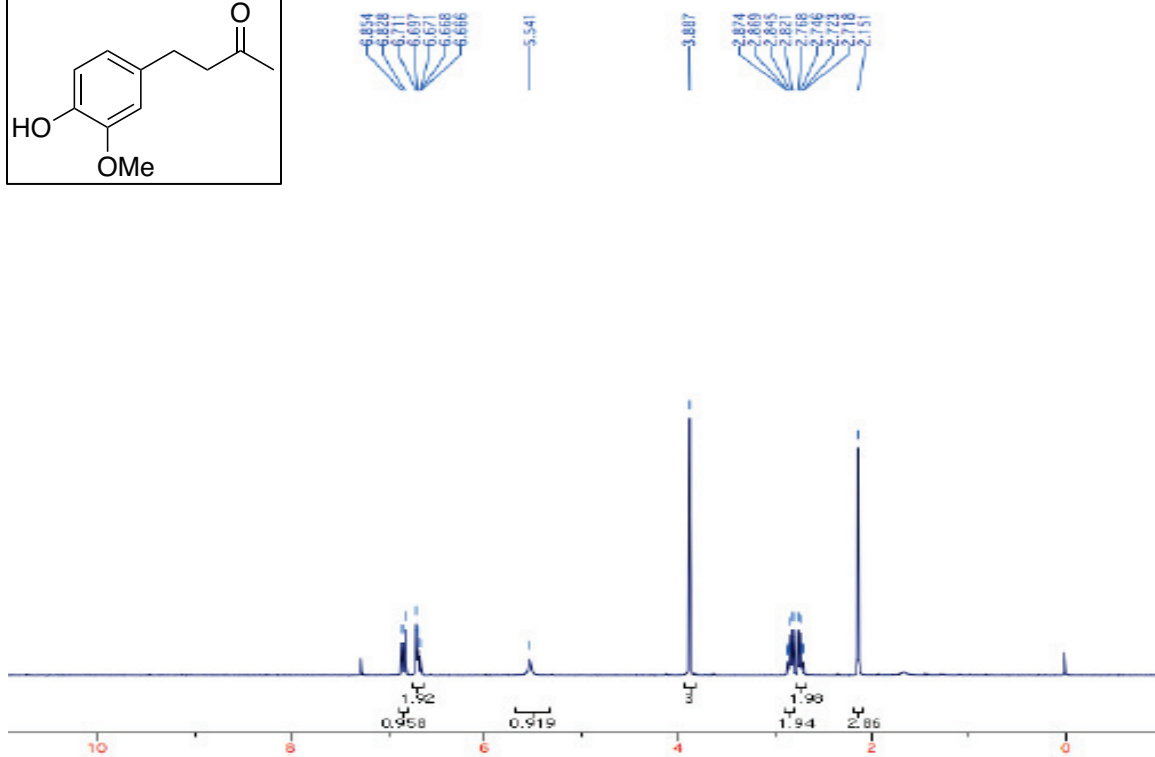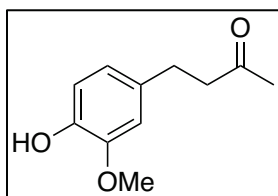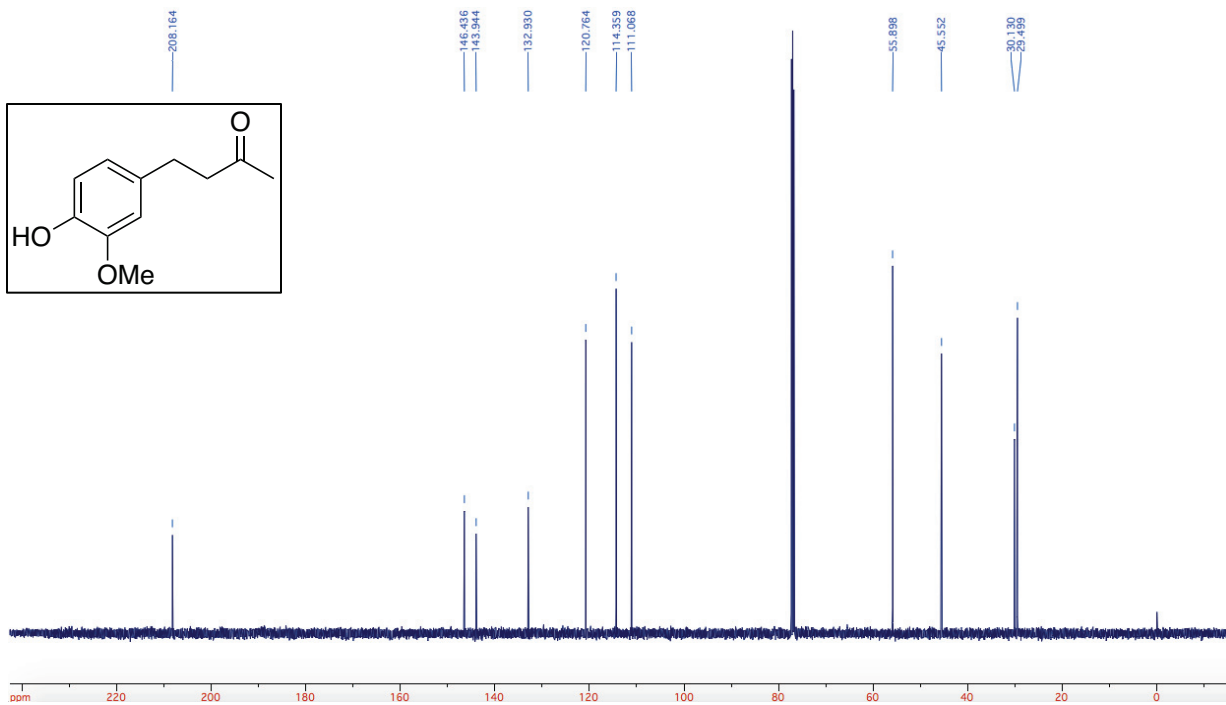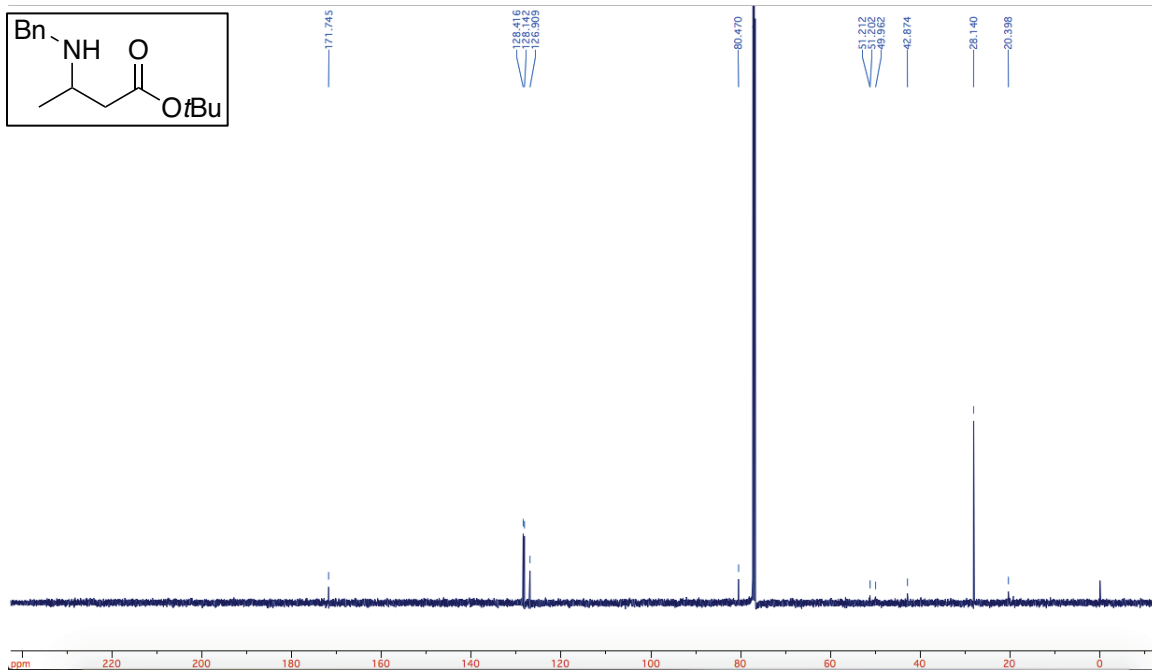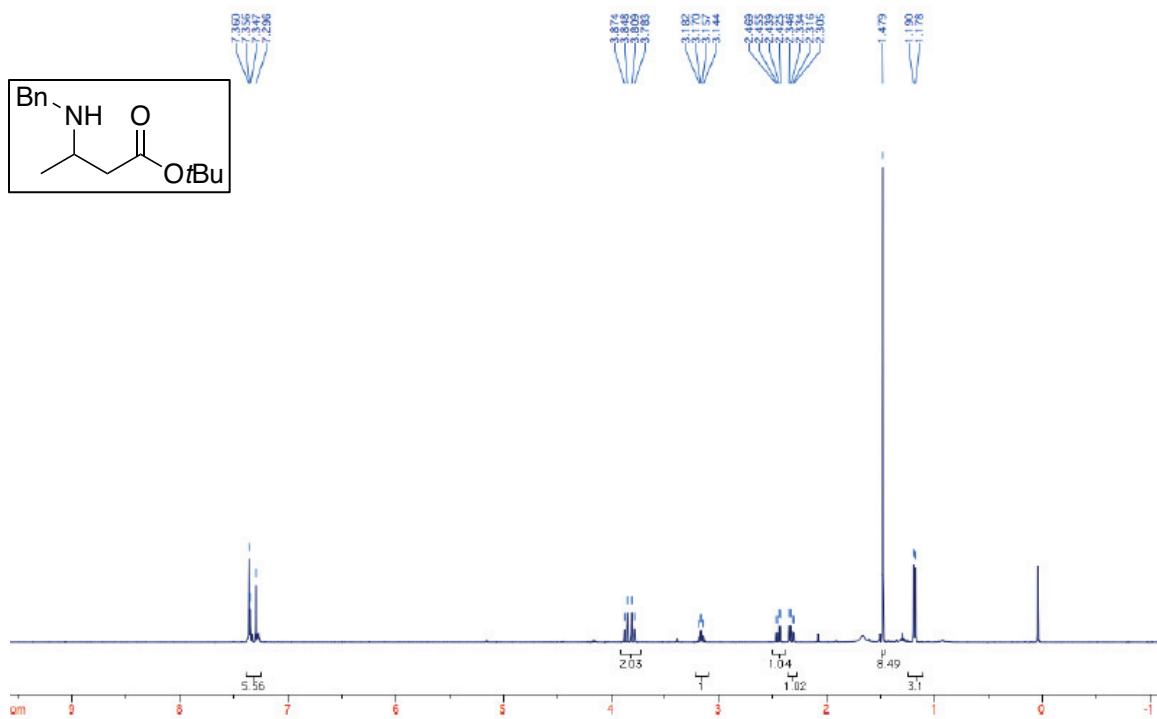
(*S*)-4-Benzyl-3-(3-phenylpropanoyl)oxazolidin-2-one (2.48):
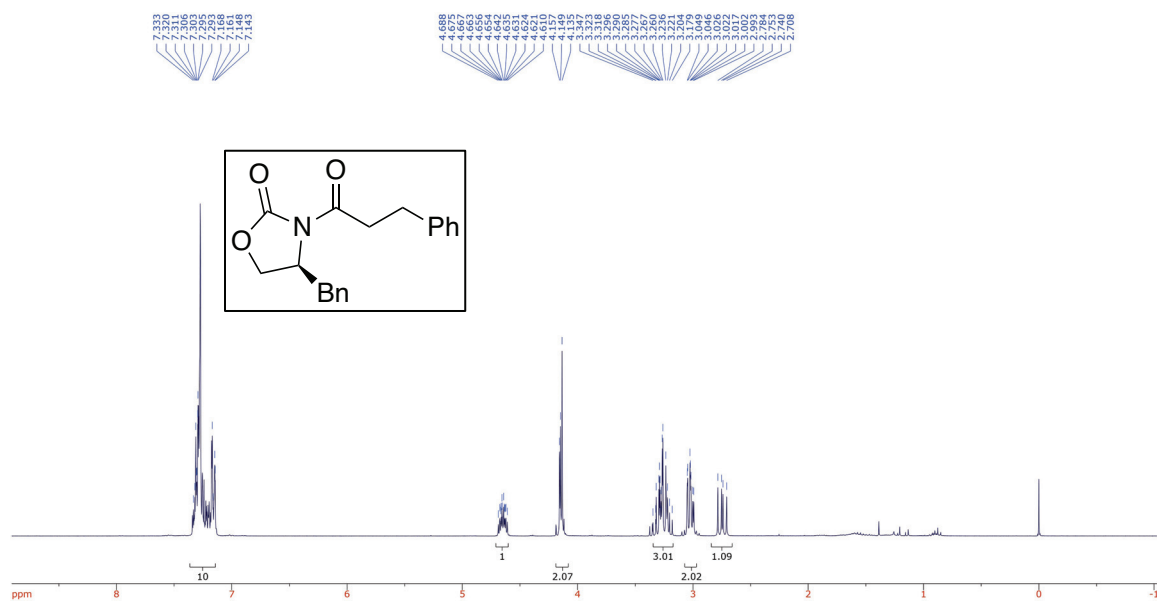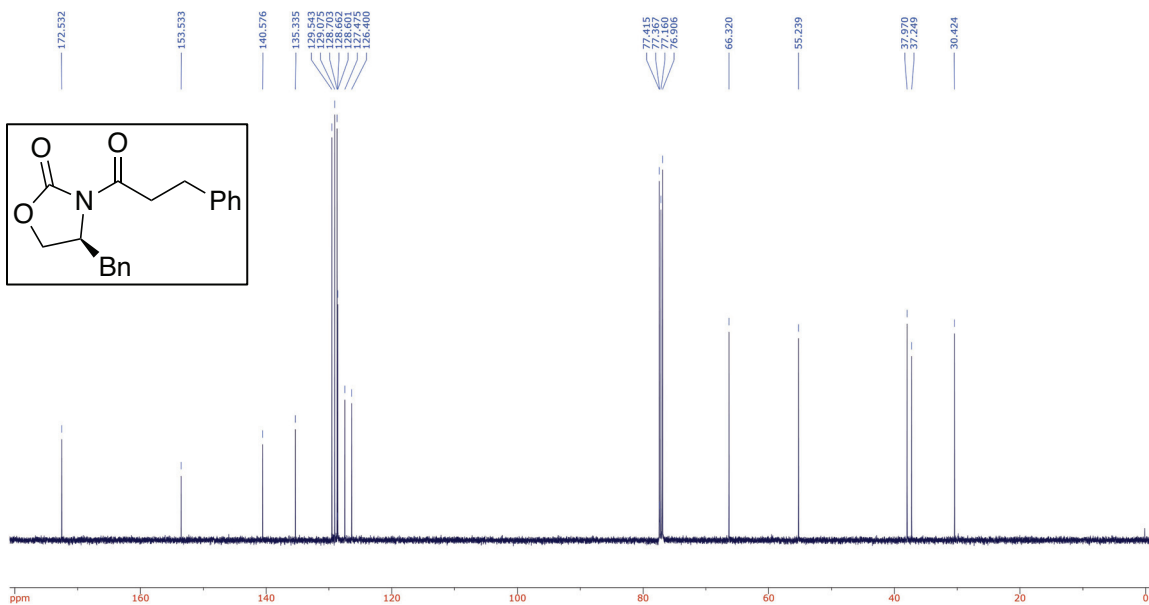
3,7-Dimethyloct-6-enal (Citronellal) (2.49):
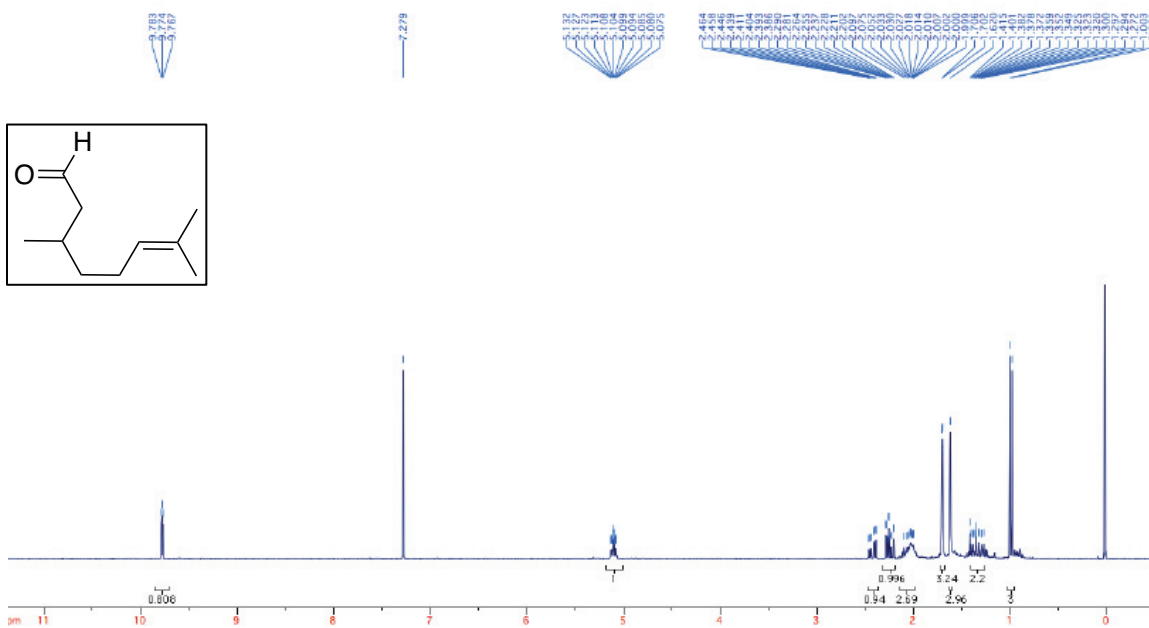
N-Benzyl-2,3-dihydro-1H-inden-1amine (2.61):
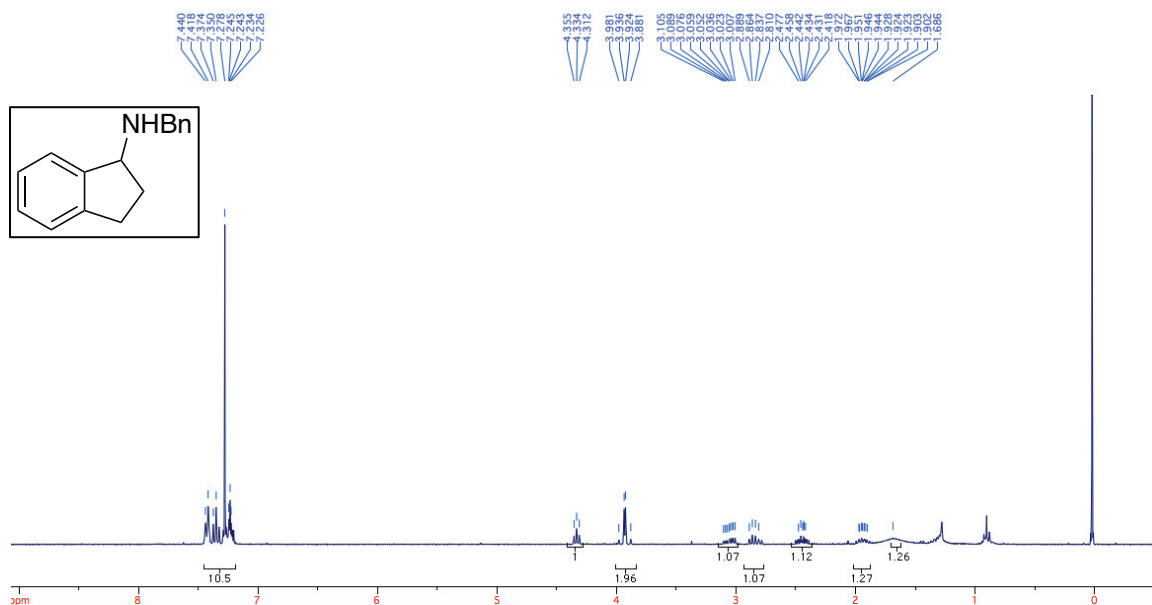
_N_-Propargyl-1-indanamine (2.62):

_N_-Benzyl-1-(_tert_-butyl)ethylamine (2.63):
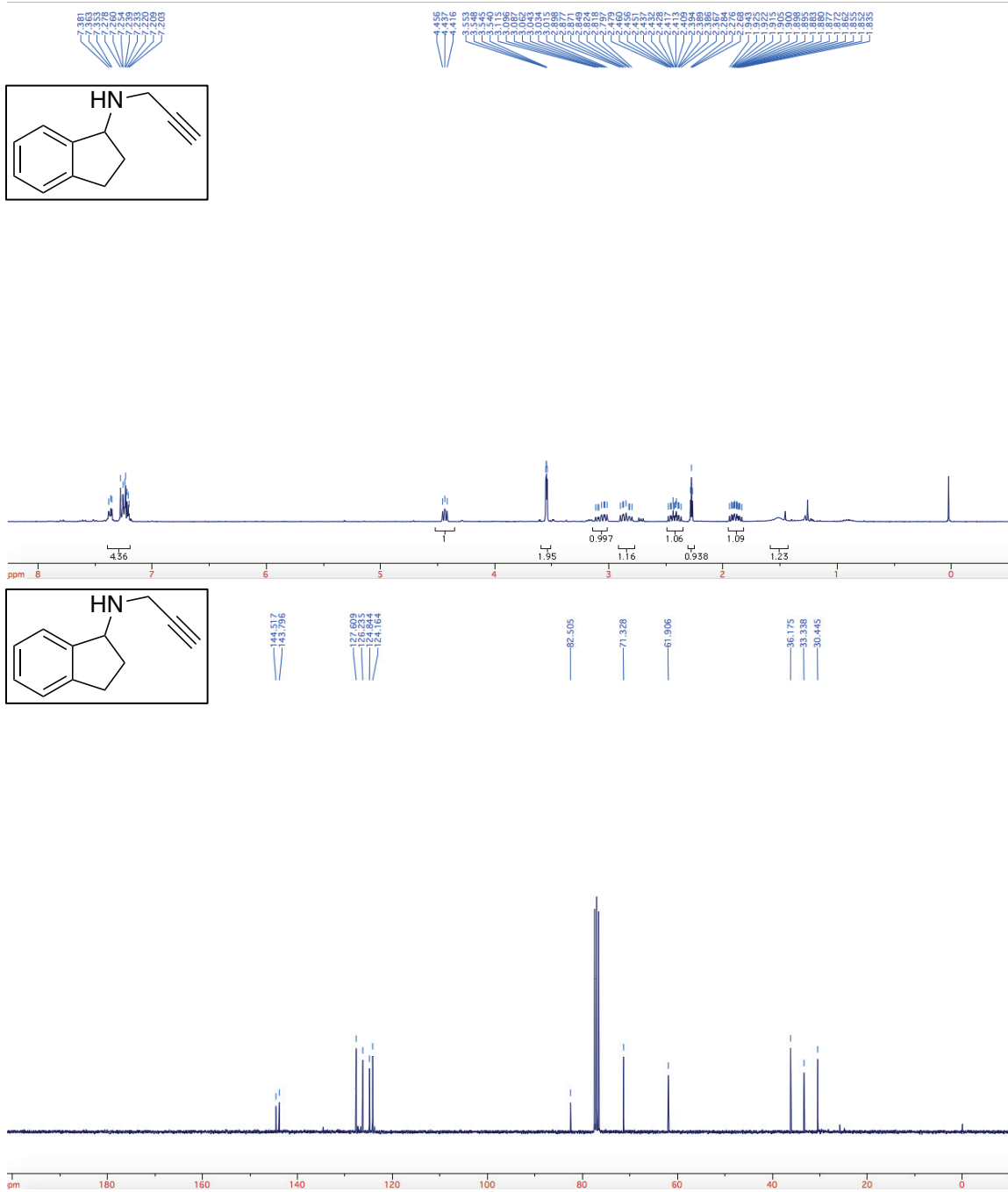
_N_-Benzyl-1-(4-methoxyphenyl)ethylamine (2.64):
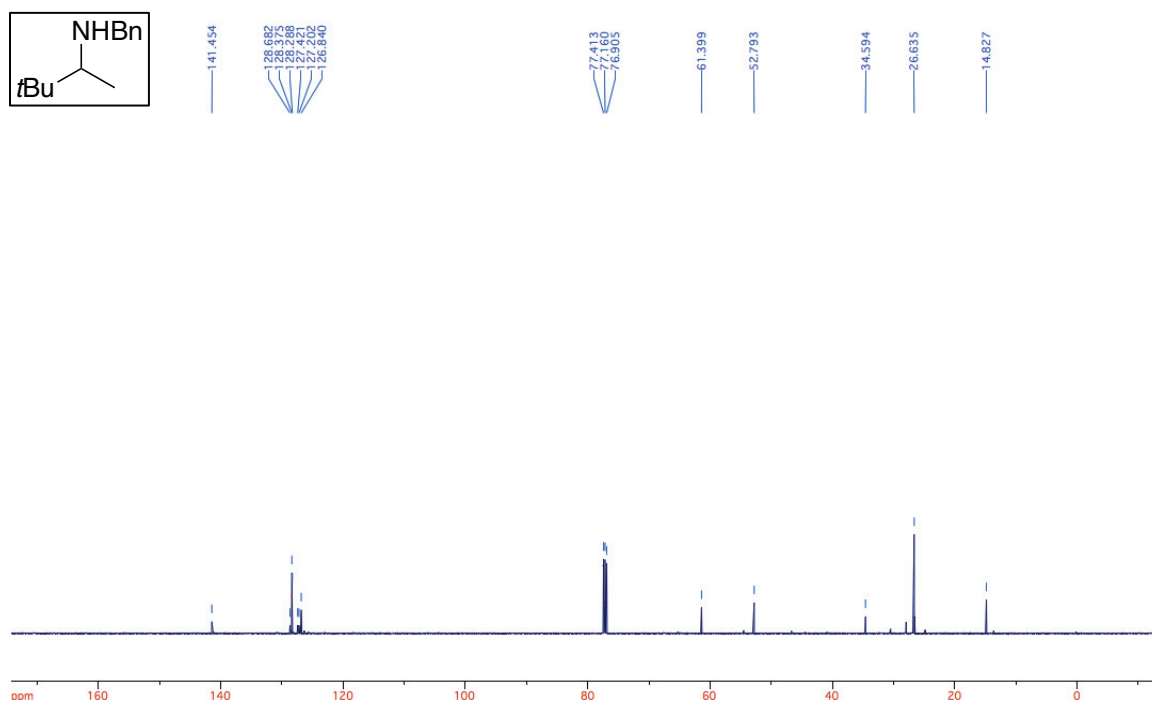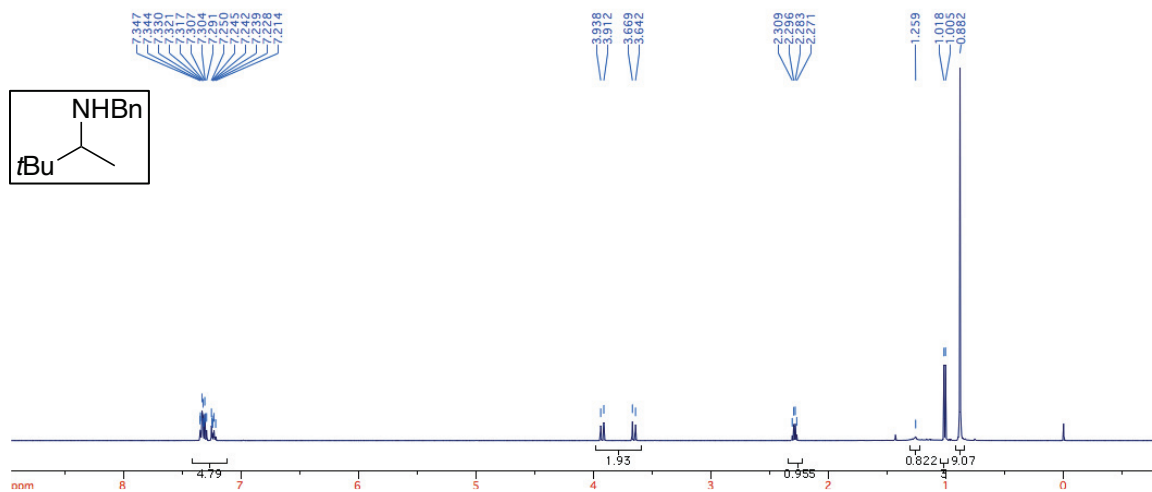
N-(1-Phenylethyl)-3,3-diphenylpropylamine (2.65):
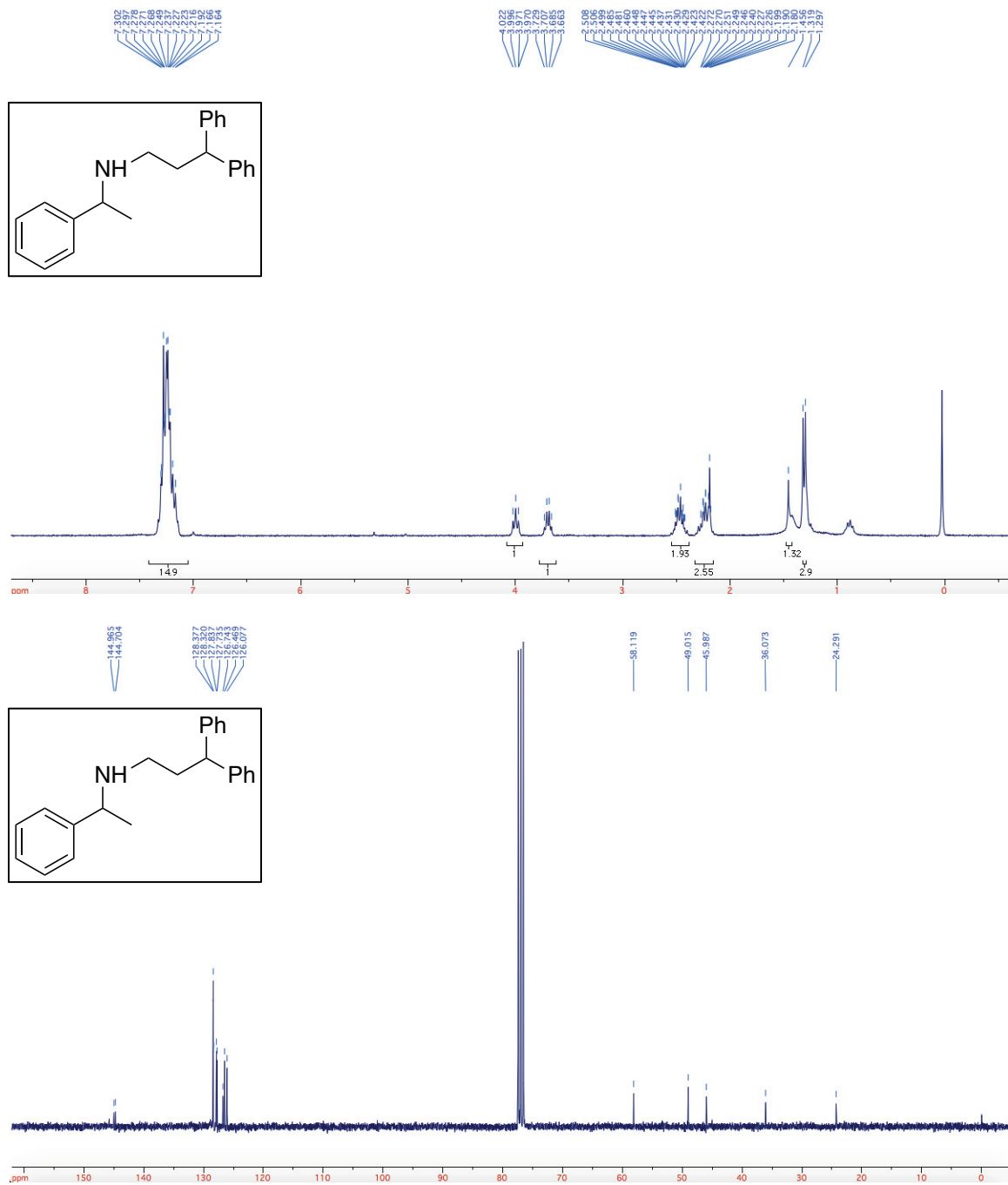
Appendix B: NMR spectra and HPLC data for Chapter 3

(*S*)-1-(1-Naphthyl)-(2,2-dimethyl)propylamine (3.1):

(*R*)-1-(2-Naphthyl)ethylamine (3.2):

(a)
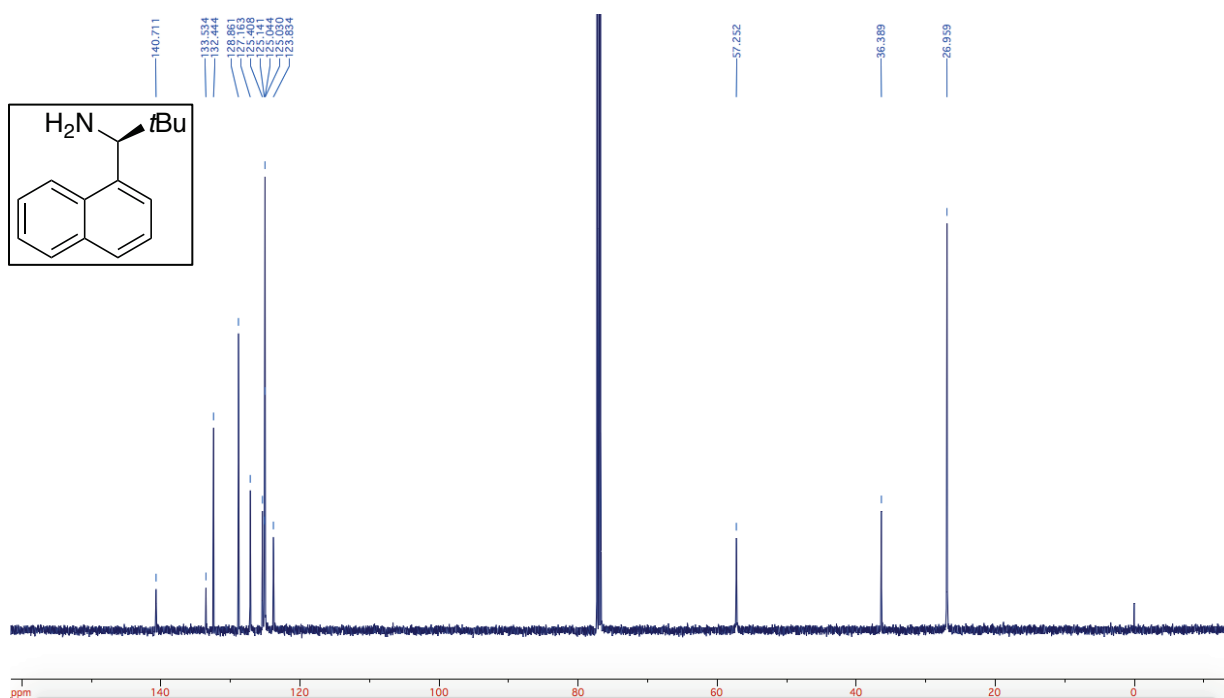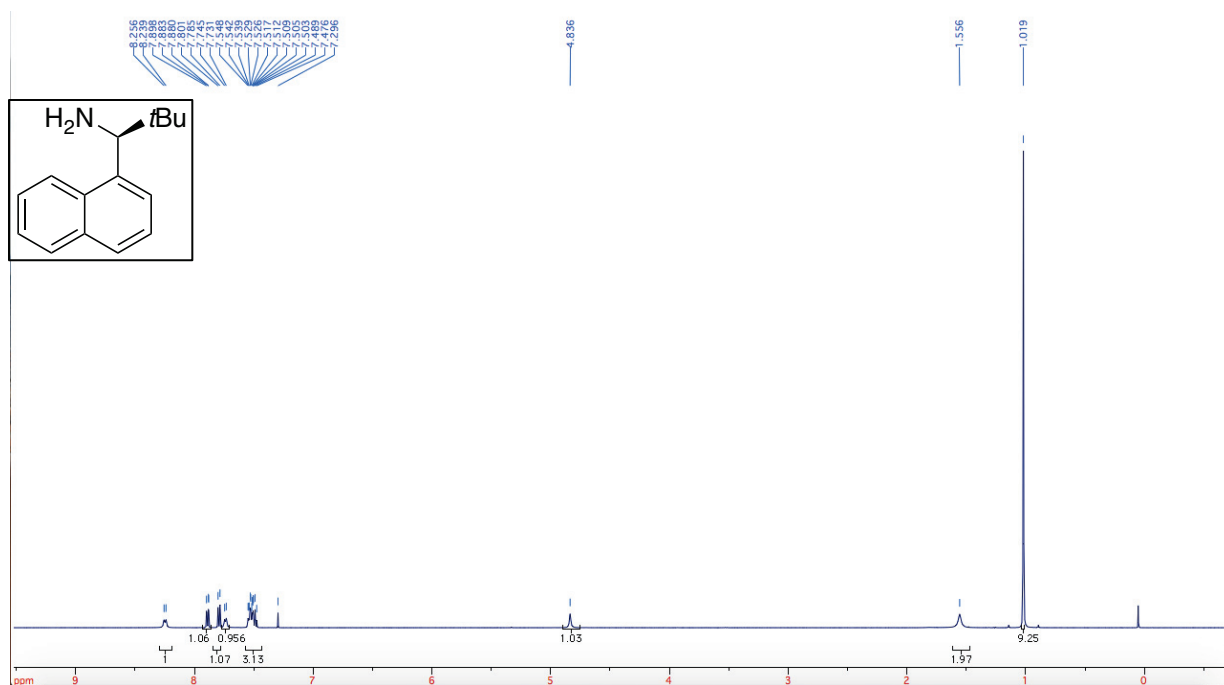
3.2(b)
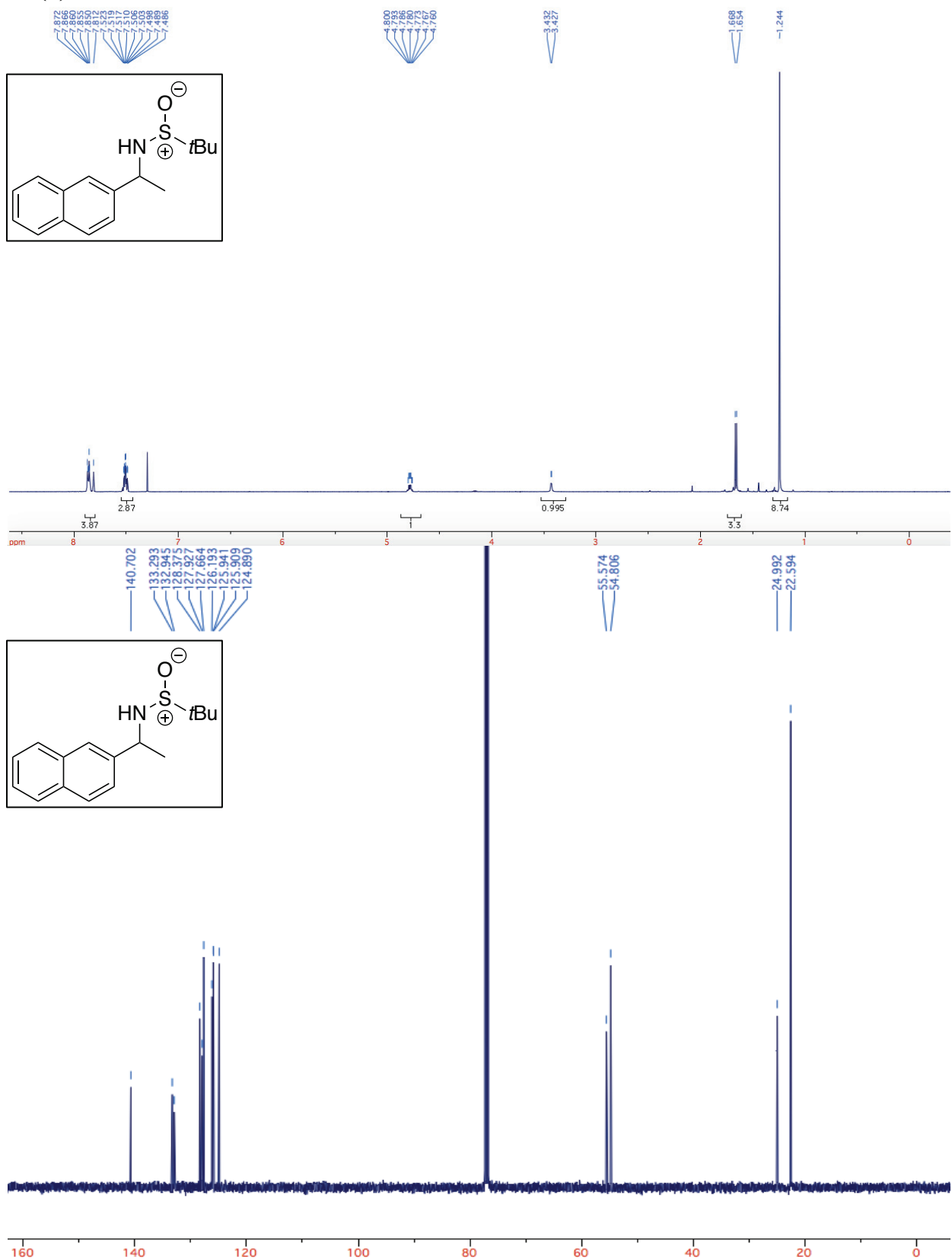
3.2(c)

(*R*)-1-(1-Naphthyl)propylamine (3.3): (a)

3.3(b)
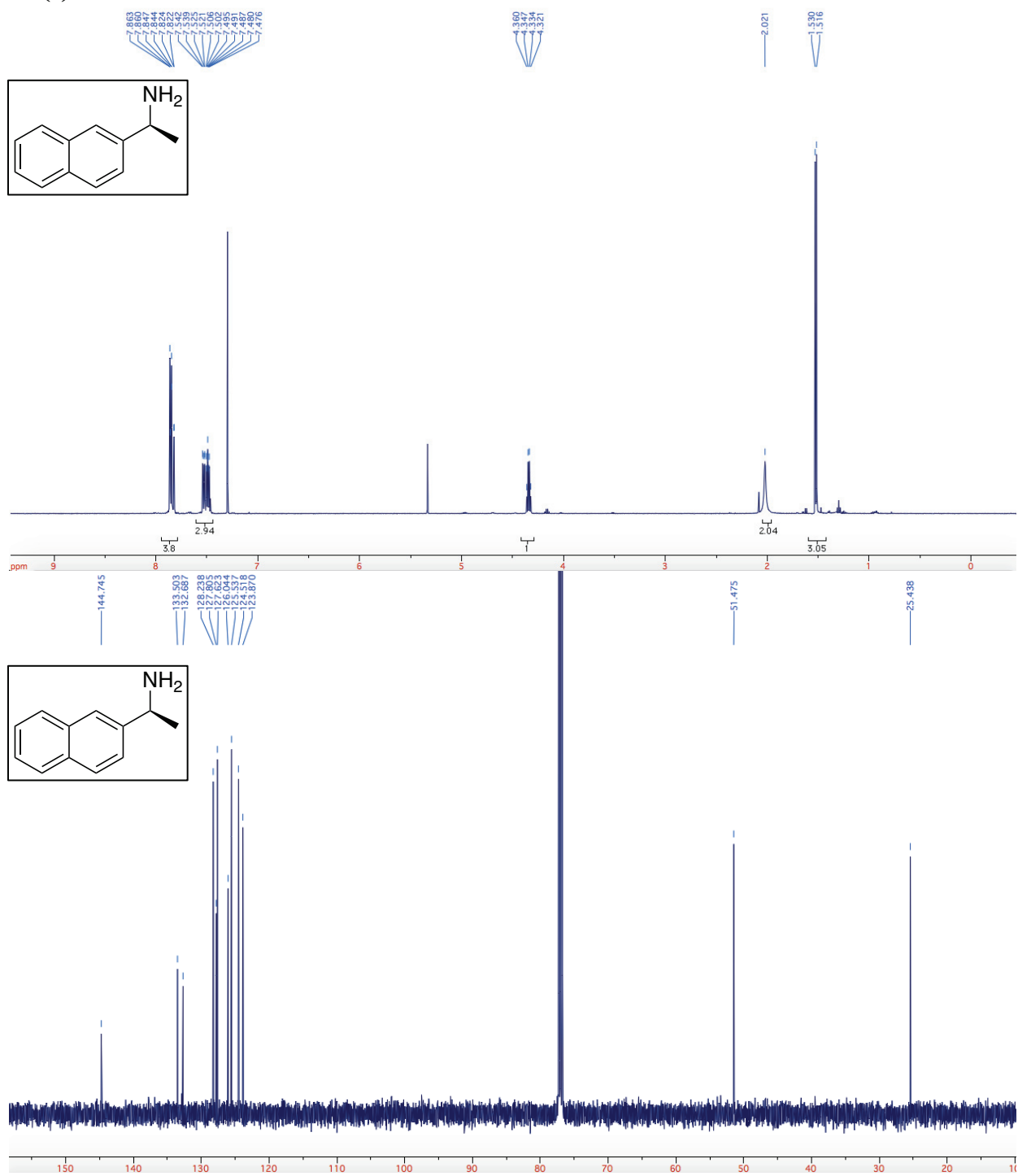
(*S*)-1-(3,5-*Bis*-trifluoromethylphenyl)ethylamine (3.4): (a)
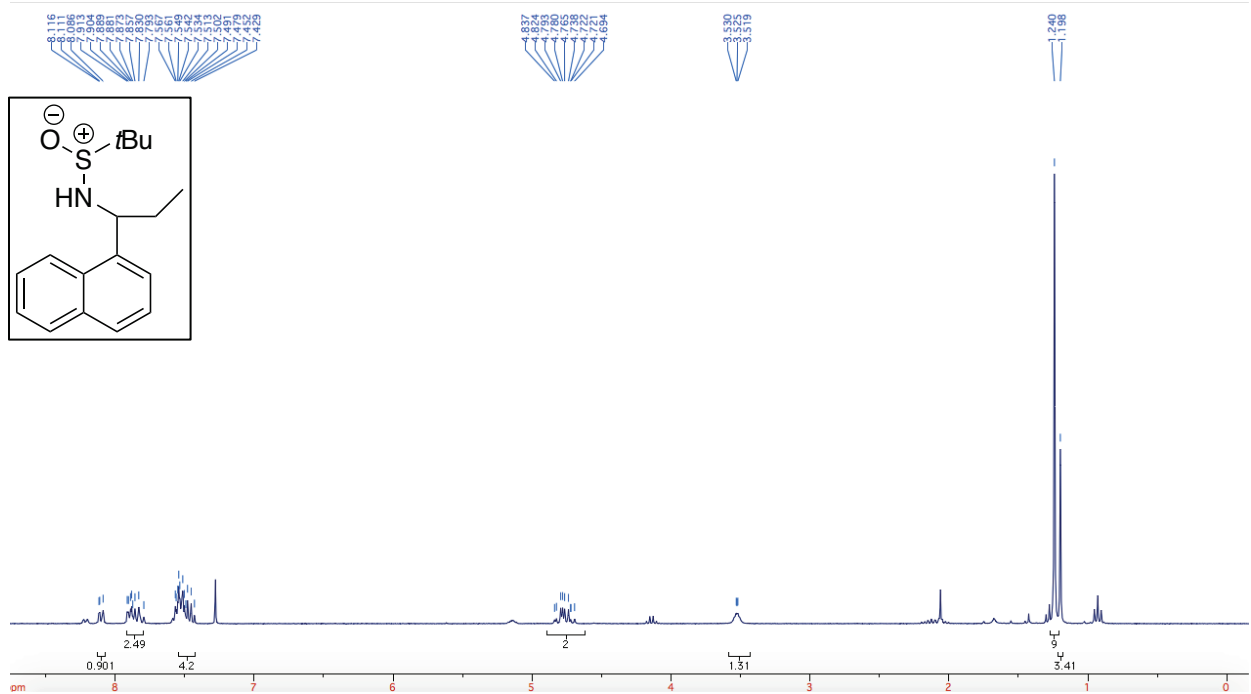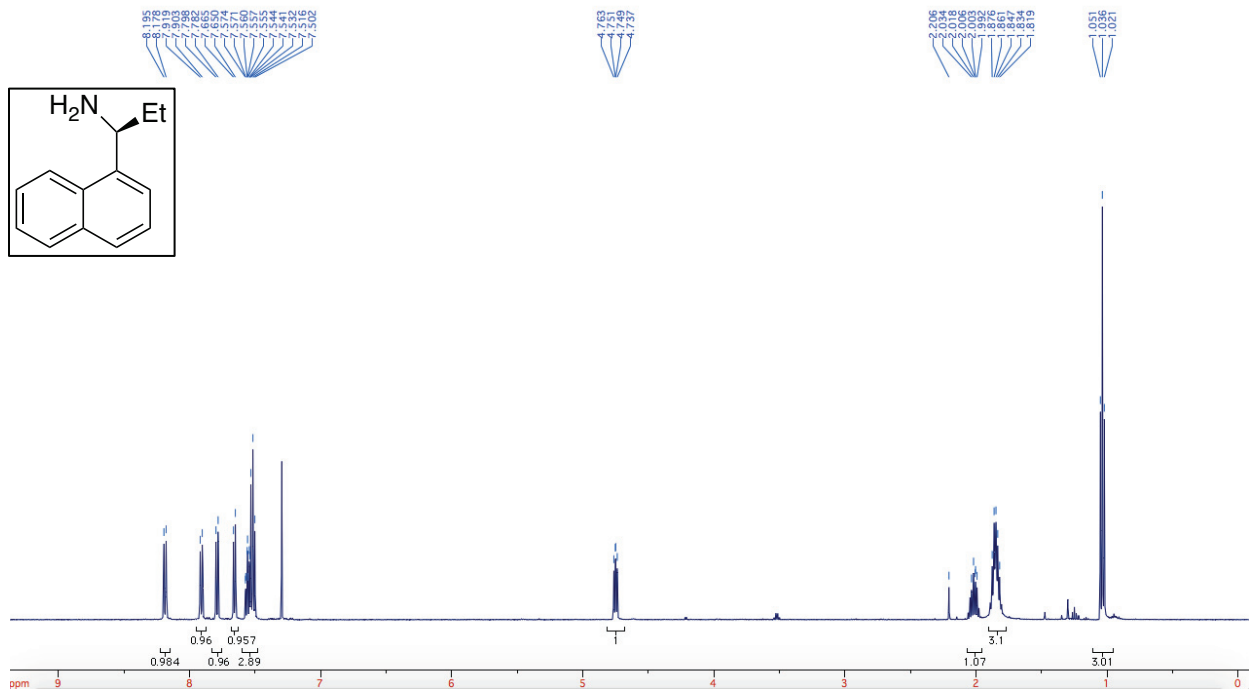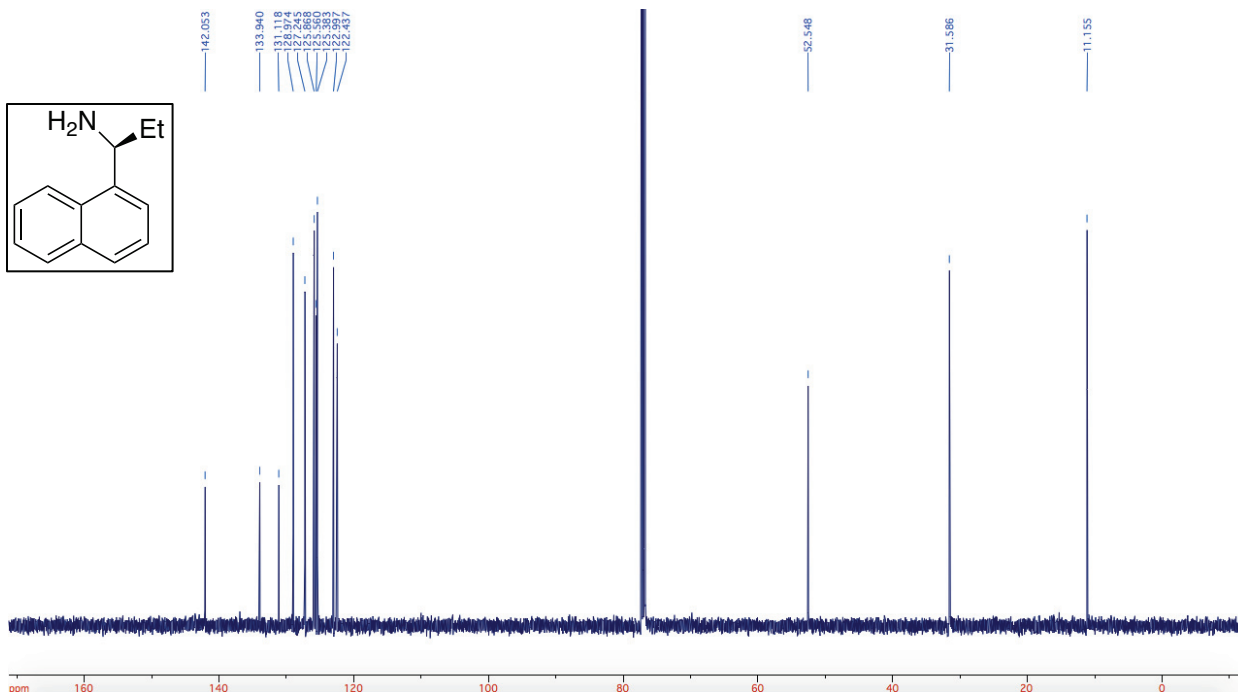
3.4 (b)
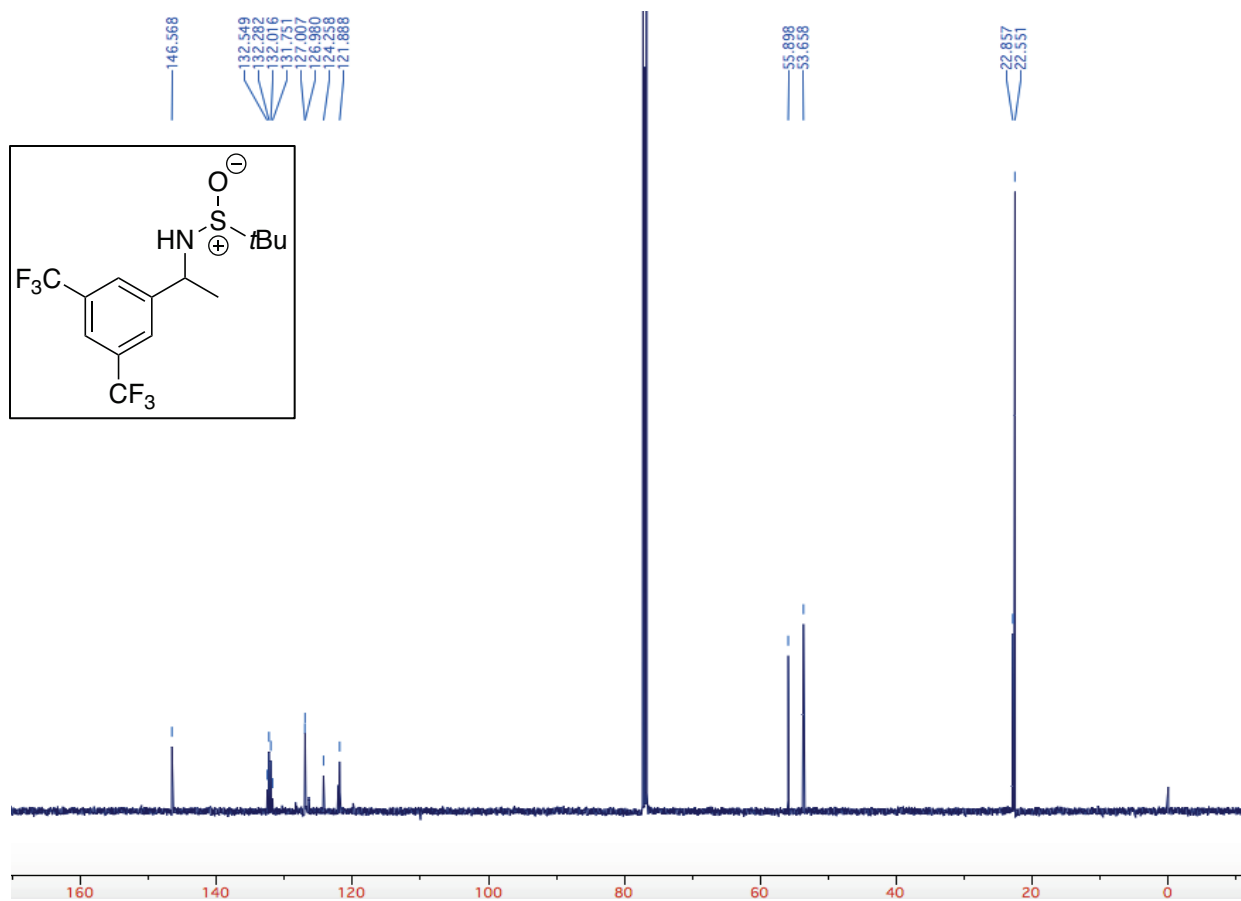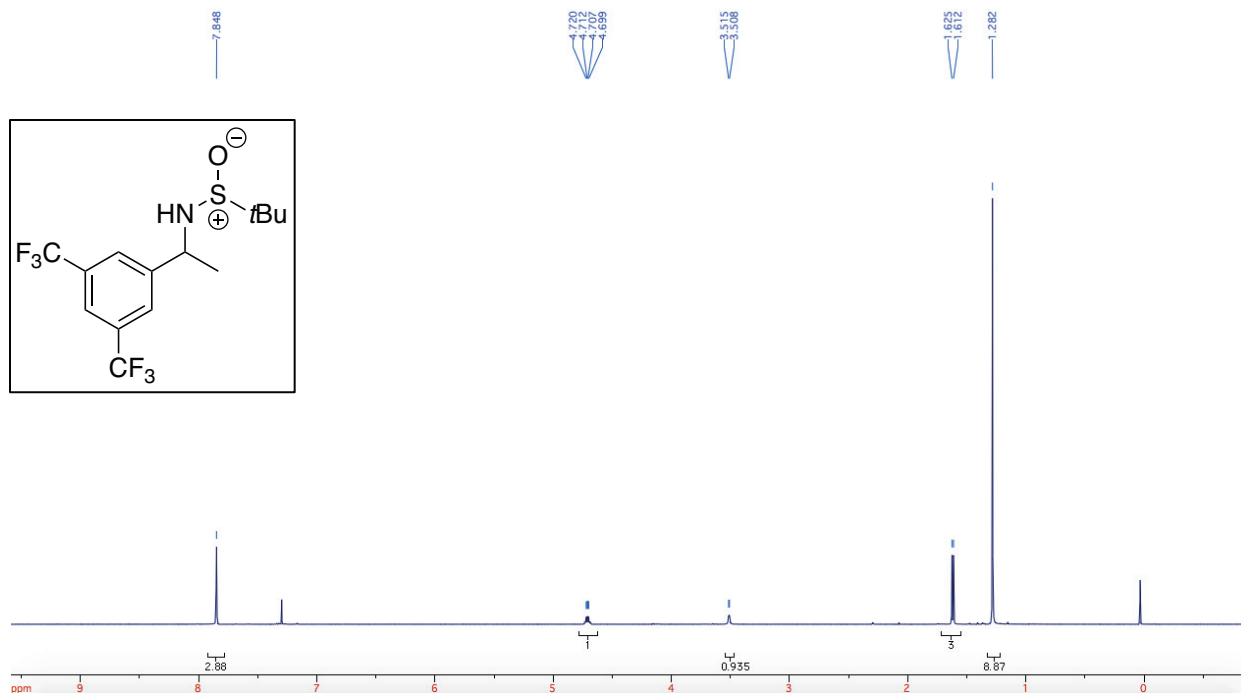
3.4 (c)
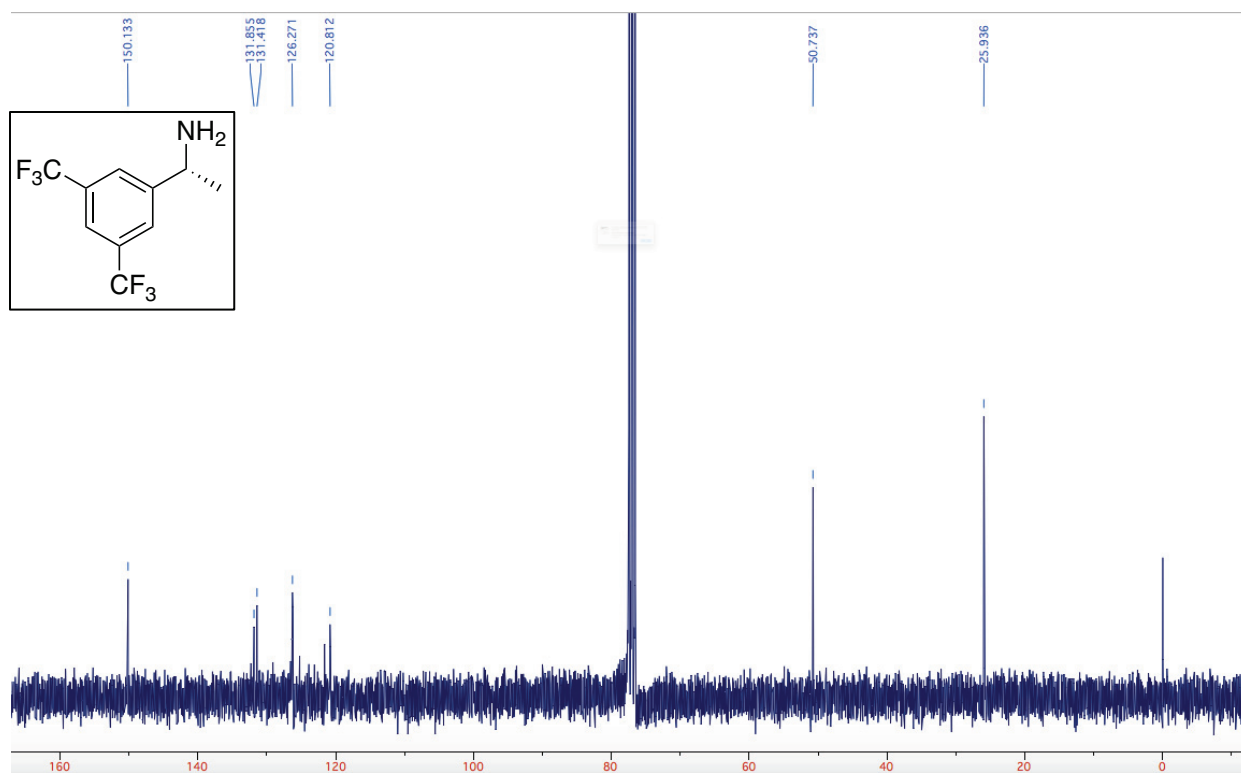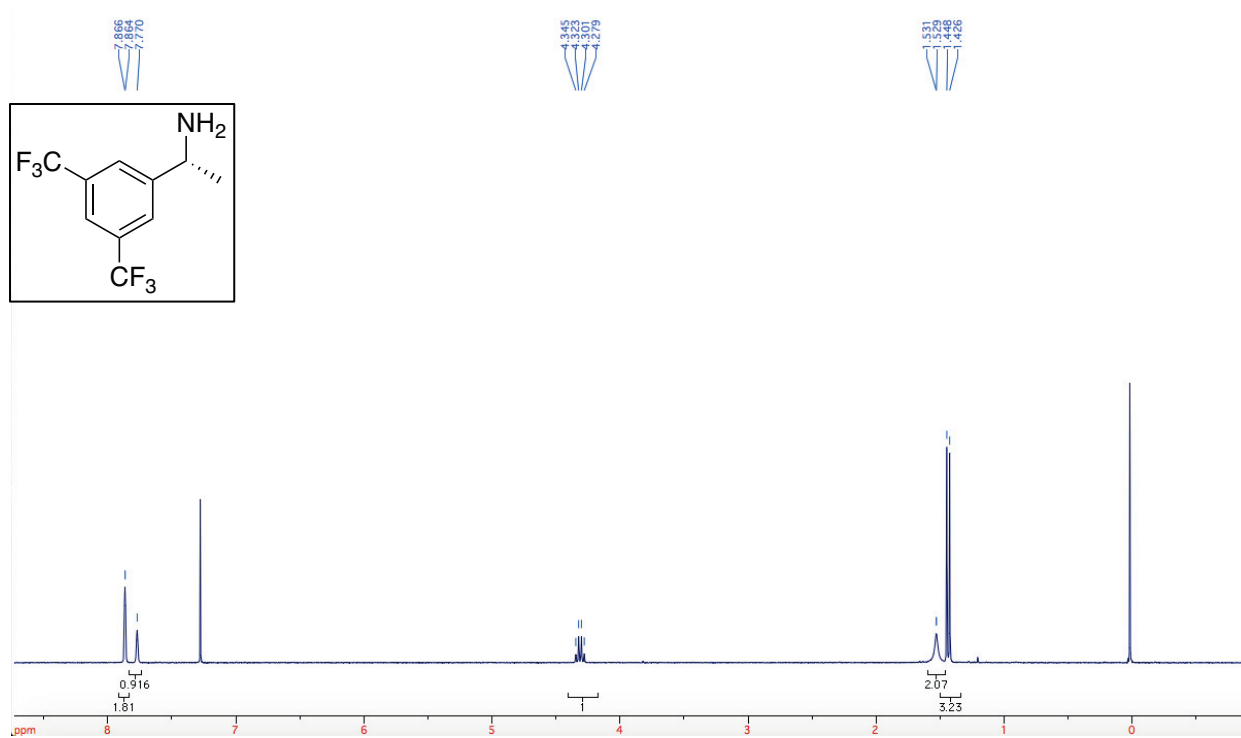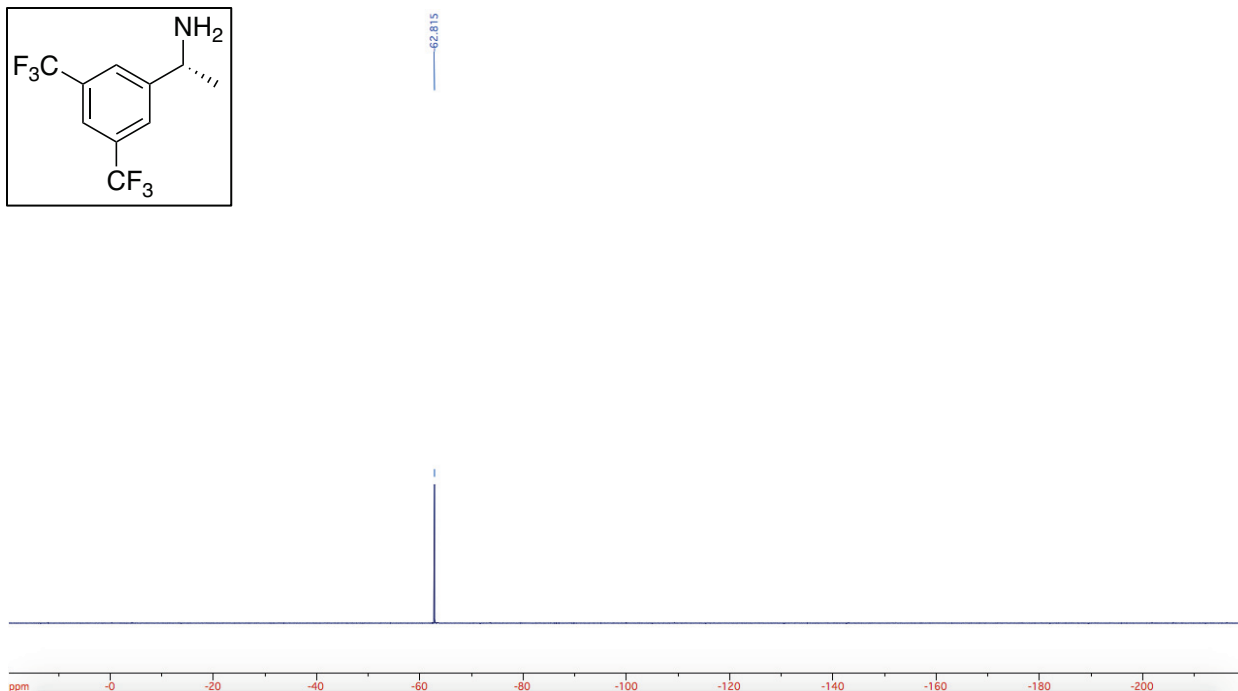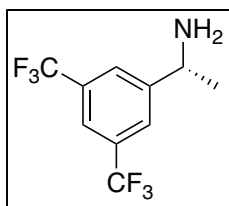
(S)-2-(Pyridyl)ethylamine (3.5): (a)

3.5 (b)
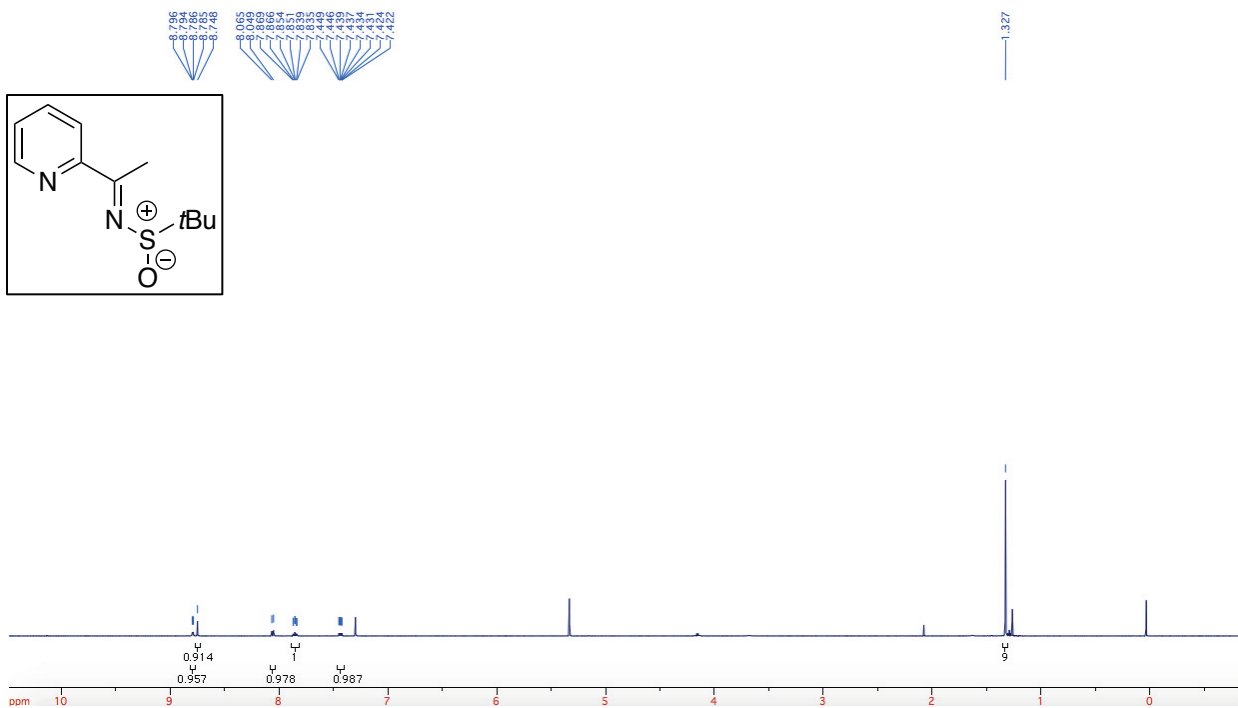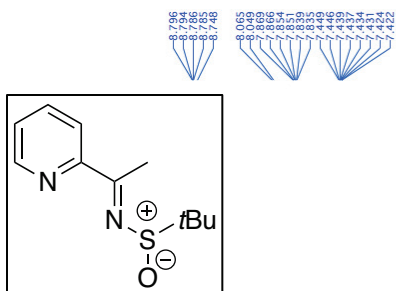
3.5 (c)
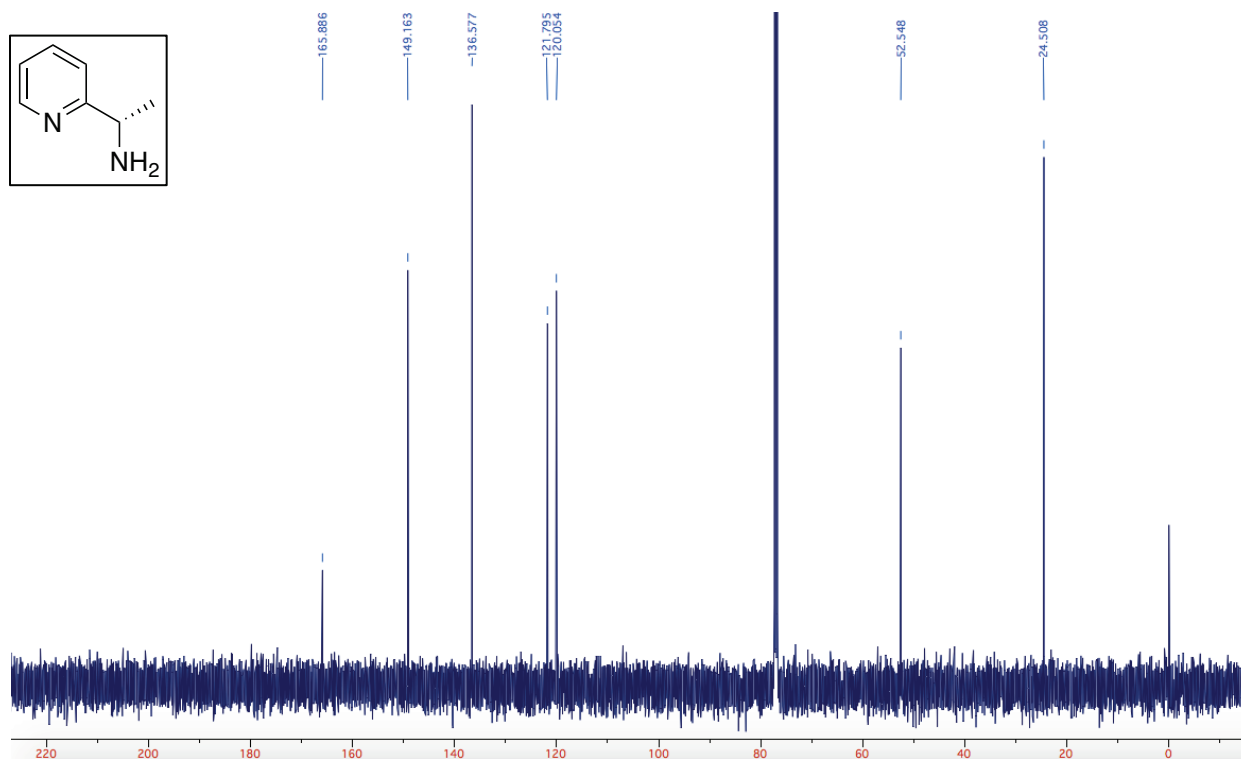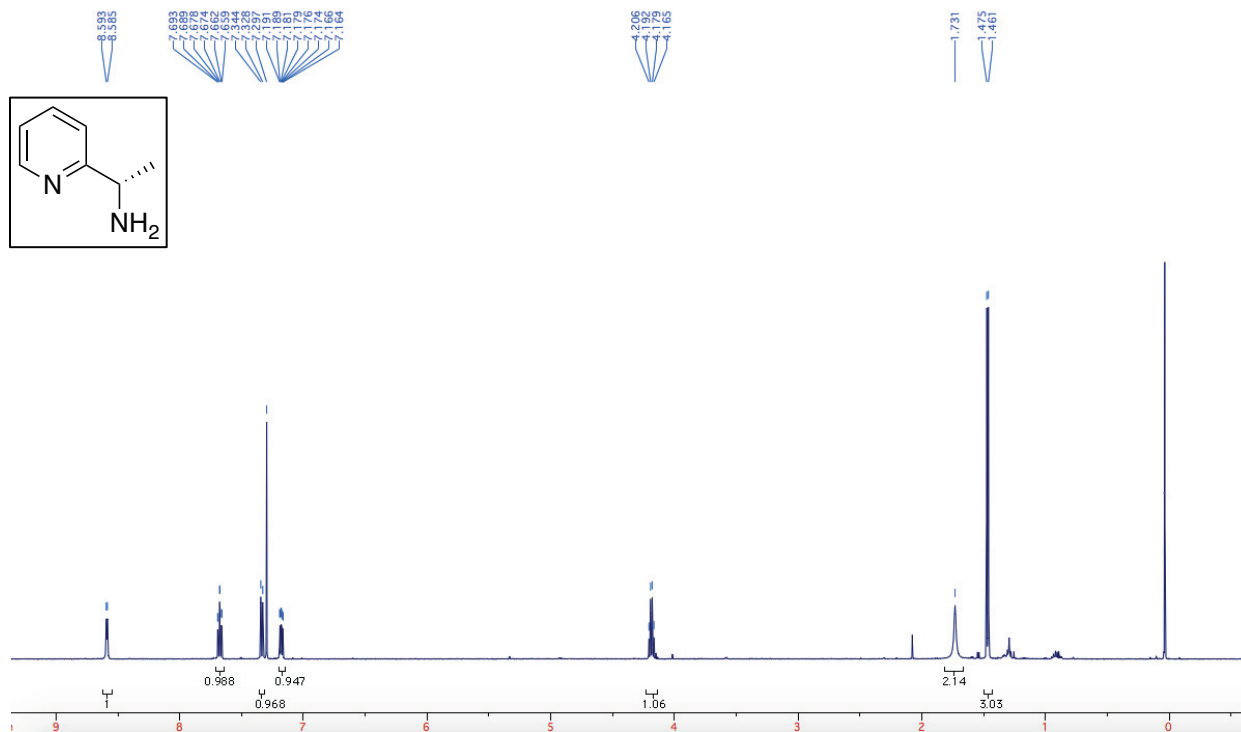
(*R*)-1-(1-Naphthyl)-(trifluoromethyl)methylamine (3.6):

3.6 (a)

3.6 (b)

244
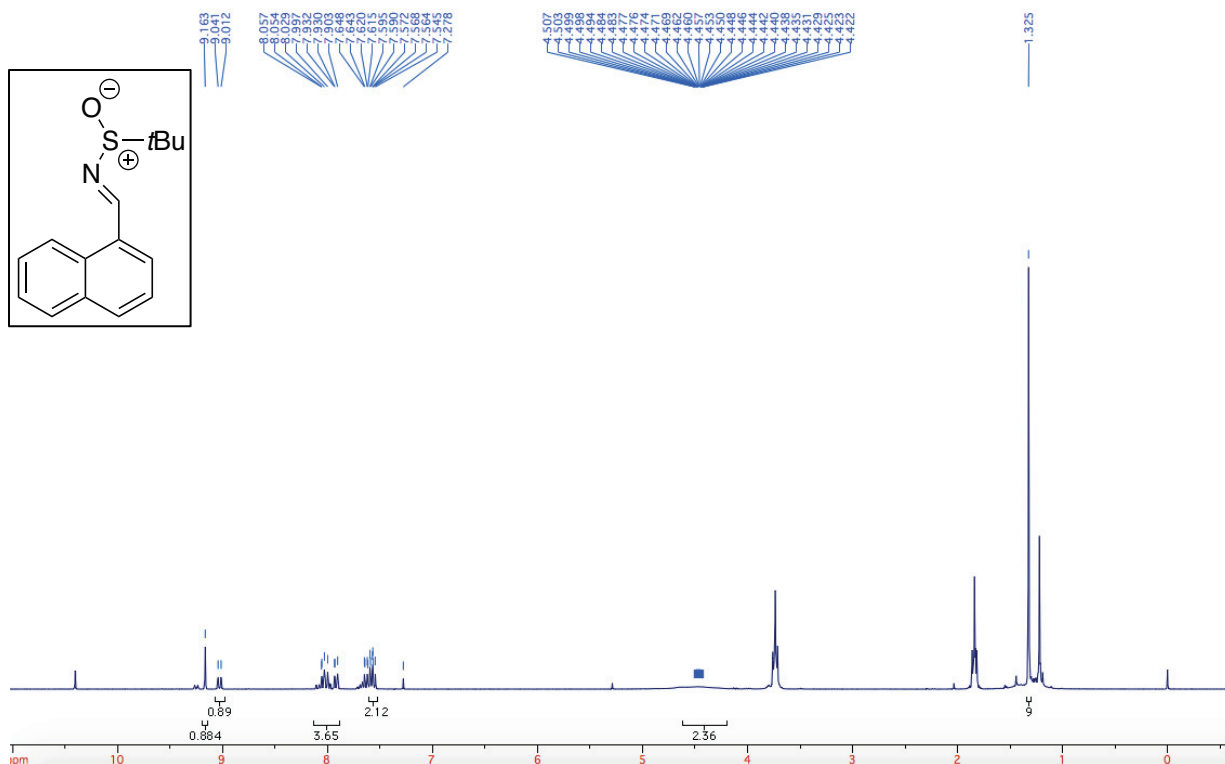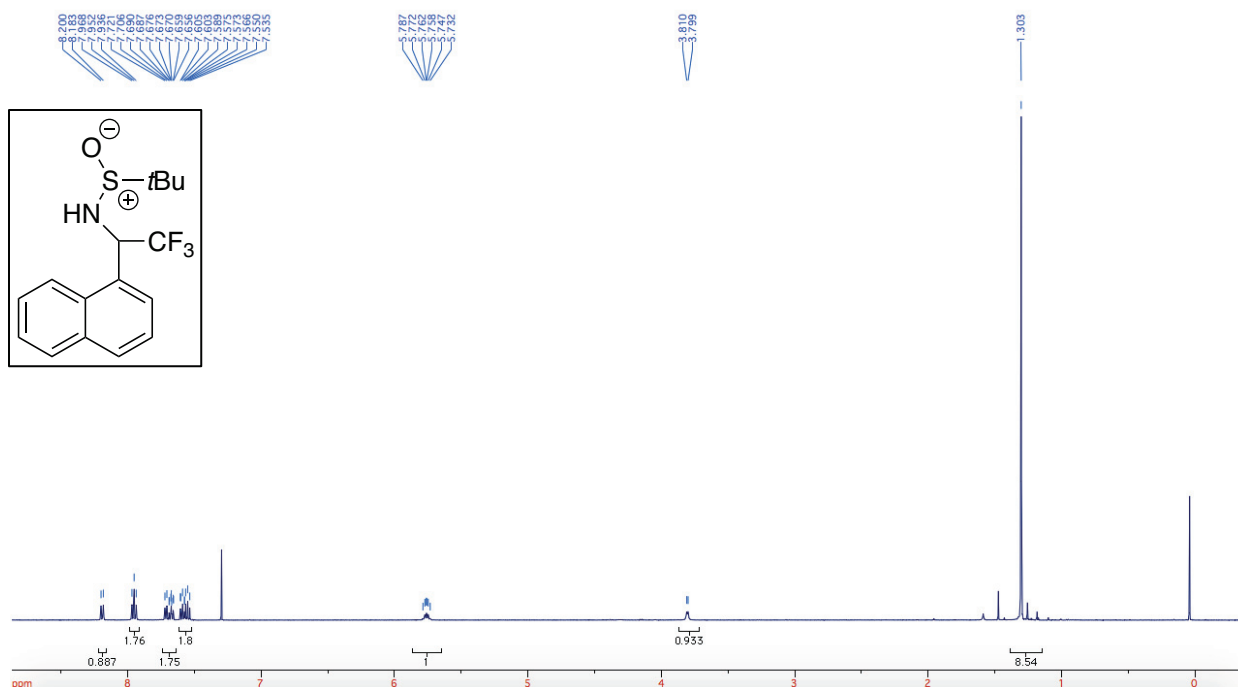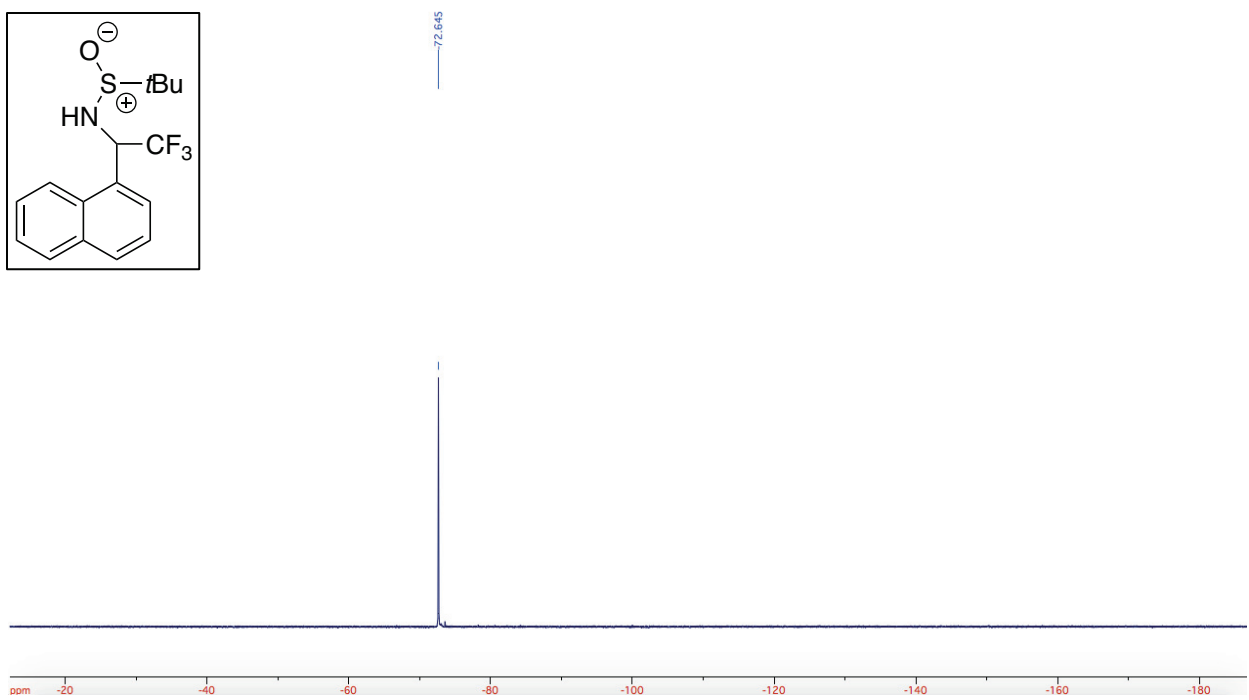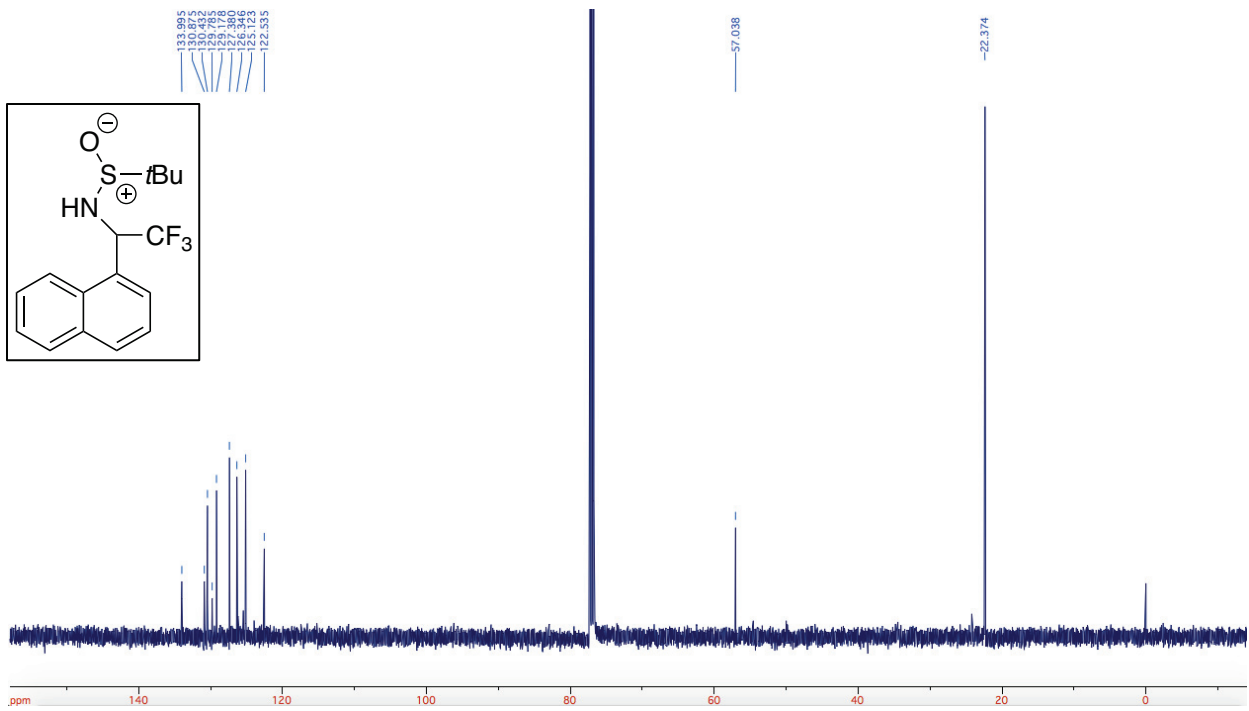
3.6 (c)
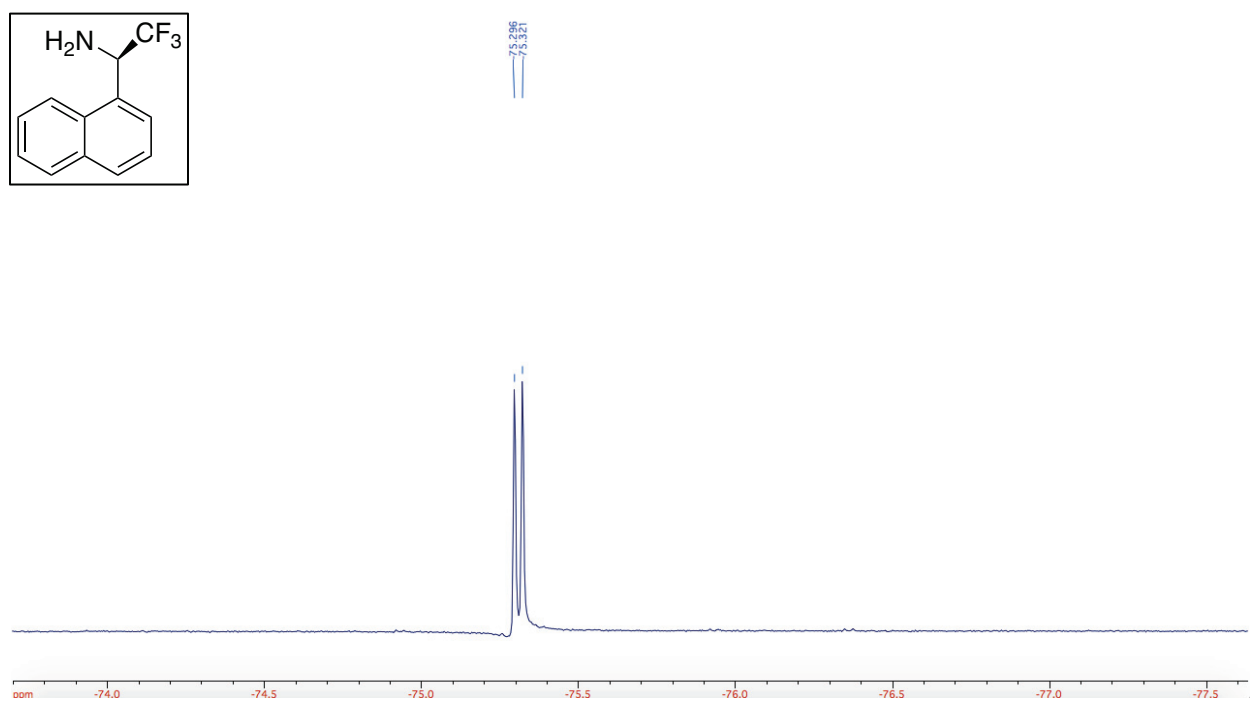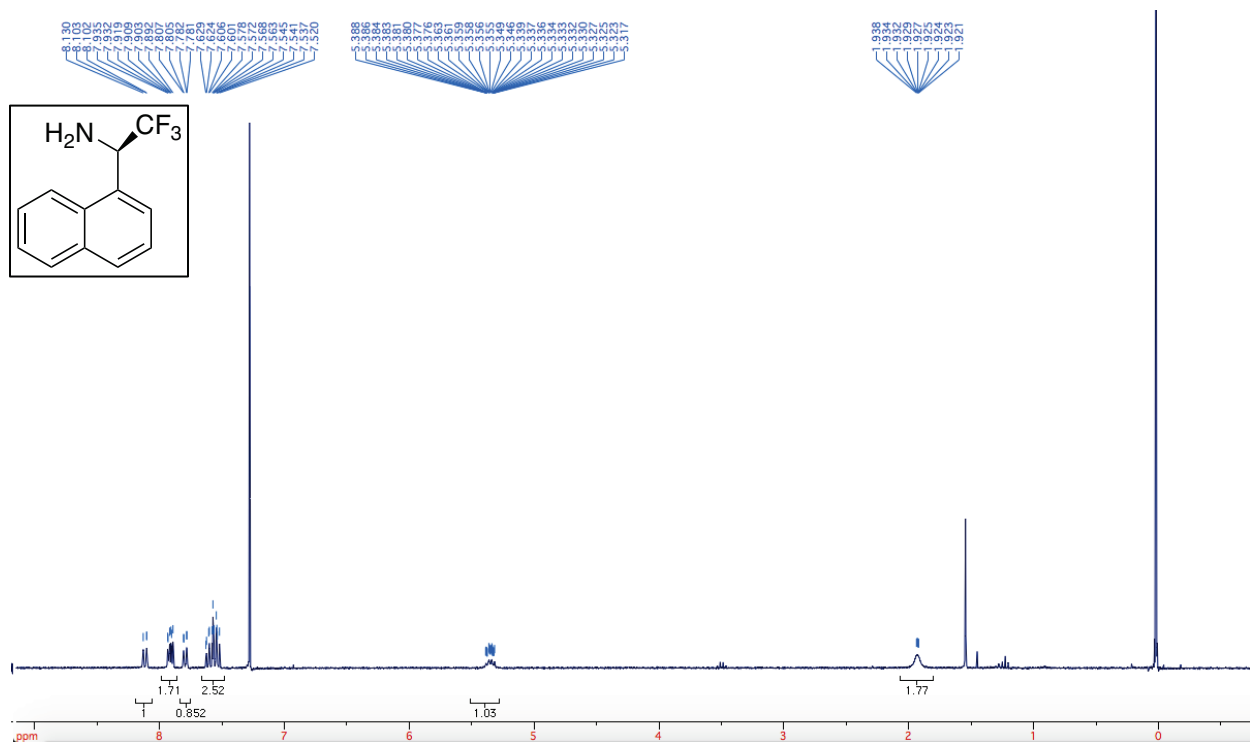
(*R*)-1-(9-Anthracyl)ethylamine (3.7):
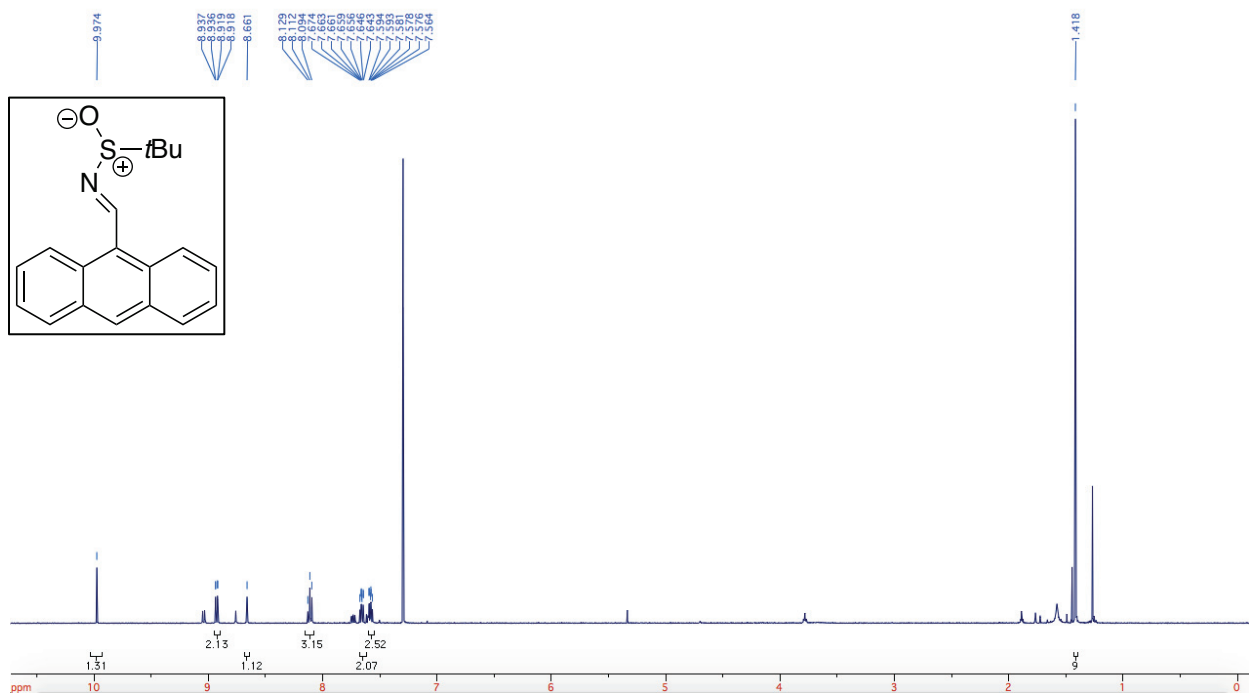
N,N'-Bis-((*R*)-2-(3,3-dimethyl)butyl)ethane-1,2-diimine (3.8):
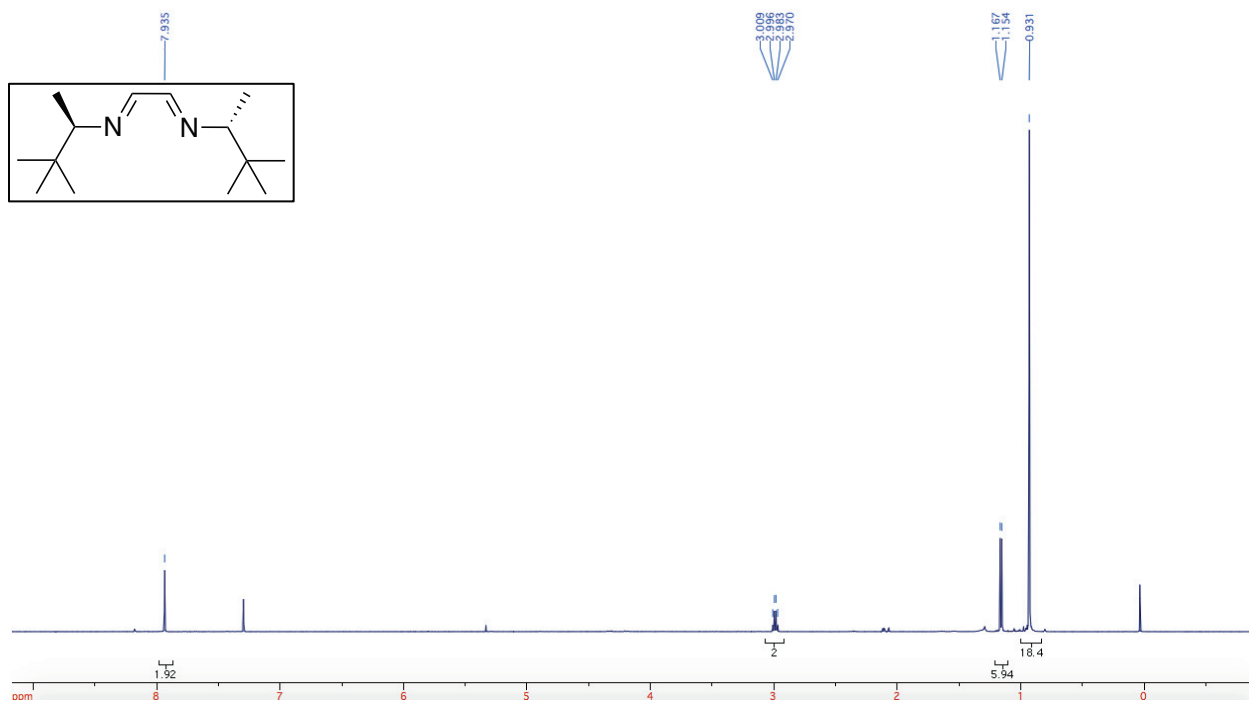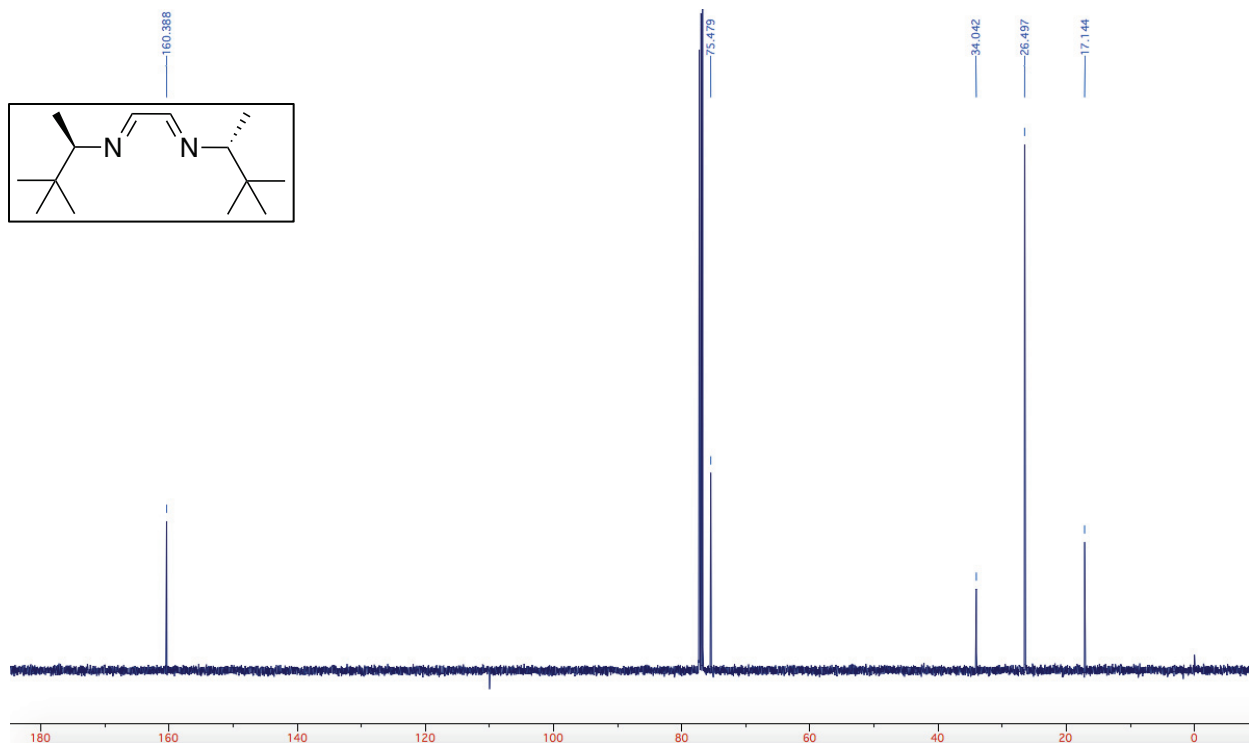
N,N'-Bis-((R)-1-phenylethyl)ethane-1,2-diimine (3.9):

N,N'-Bis-((R)-1-p-methoxyphenylethyl)ethane-1,2-diimine (3.10):

160.477
158.815
135.736
127.793
114.013
69.033
55.298
23.788

ppm 200   180   160   140   120   100   80   60   40   20   0

N,N'-*Bis*-((*R*)-1-naphthyethyl)ethane-1,2-diimine (3.11):

8.177
7.853
7.836
7.831
7.824
7.821
7.803
7.526
7.523
7.509
7.505
7.495
7.487
7.483
7.480
7.474
7.467
7.466
7.462

4.752
4.738
4.725
4.712

1.714
1.701

6.48
1.72   6.77
2
6.19
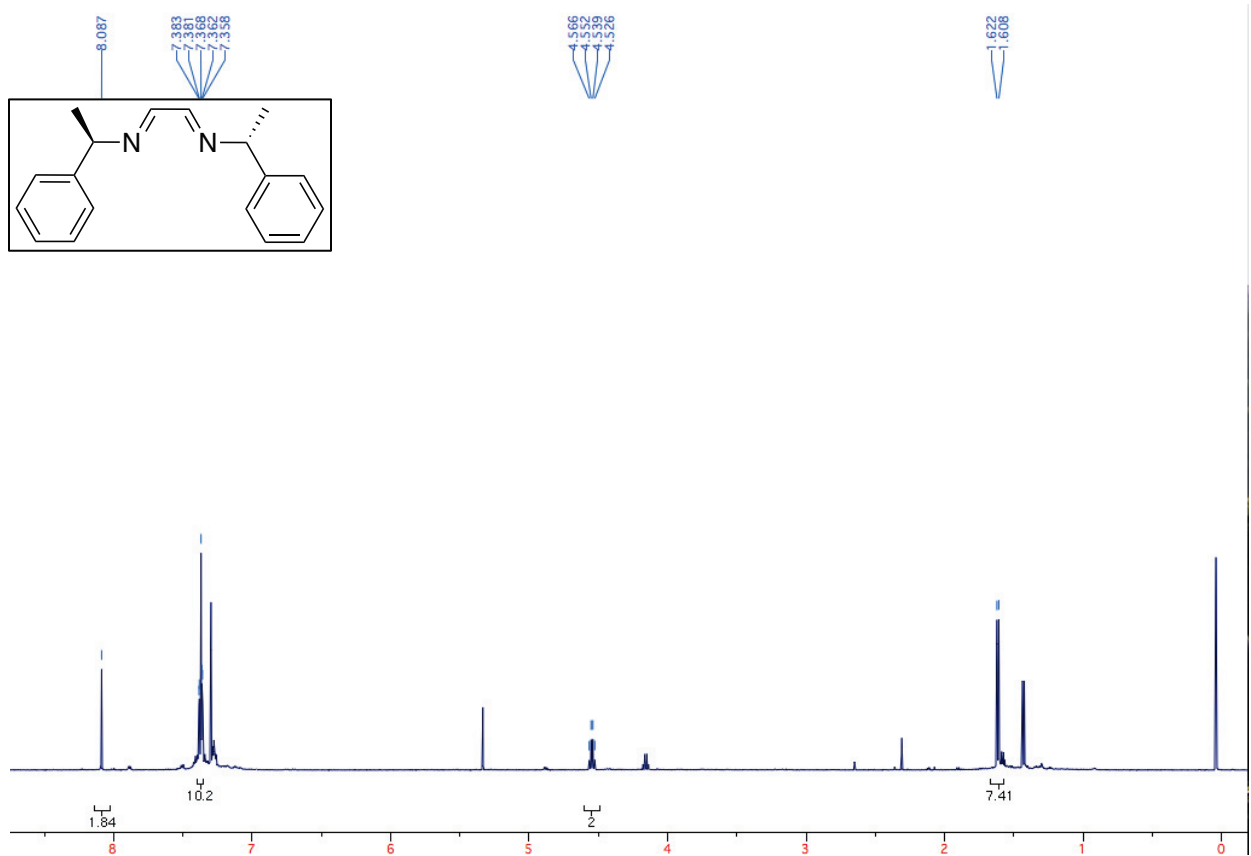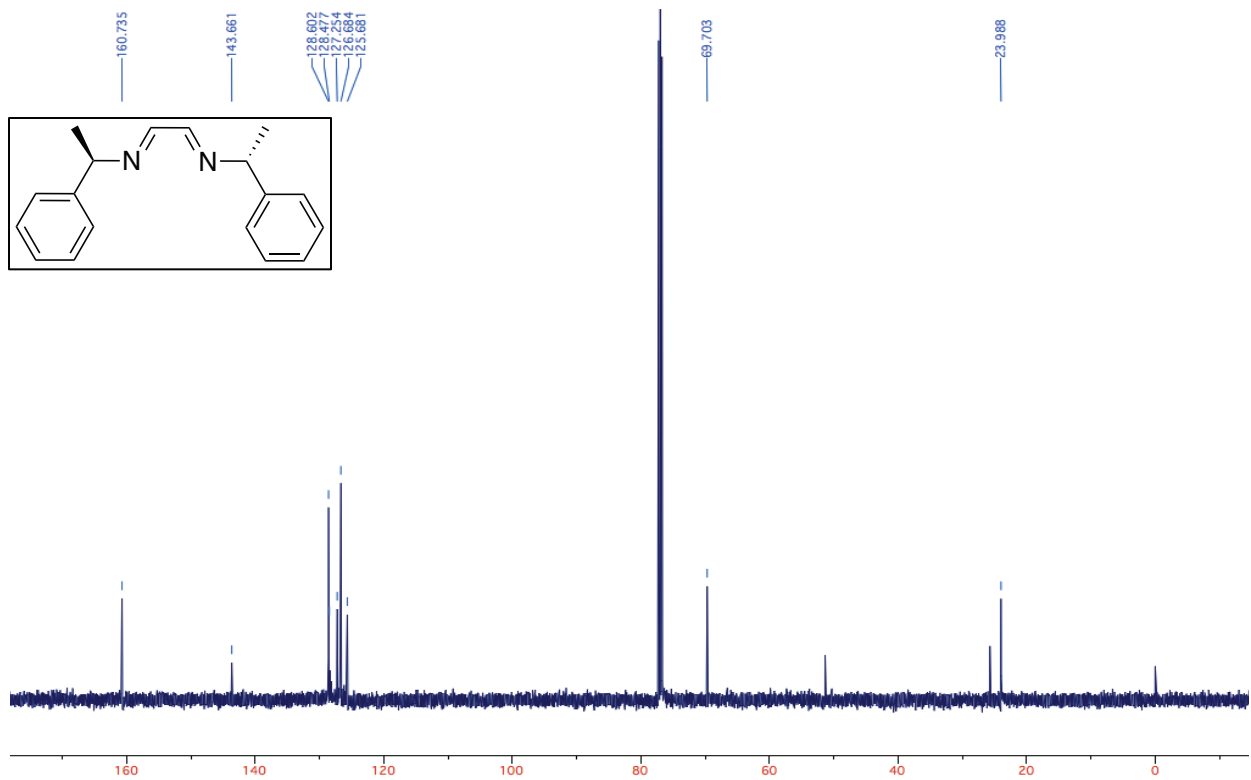
ppm   9   8   7   6   5   4   3   2   1   0
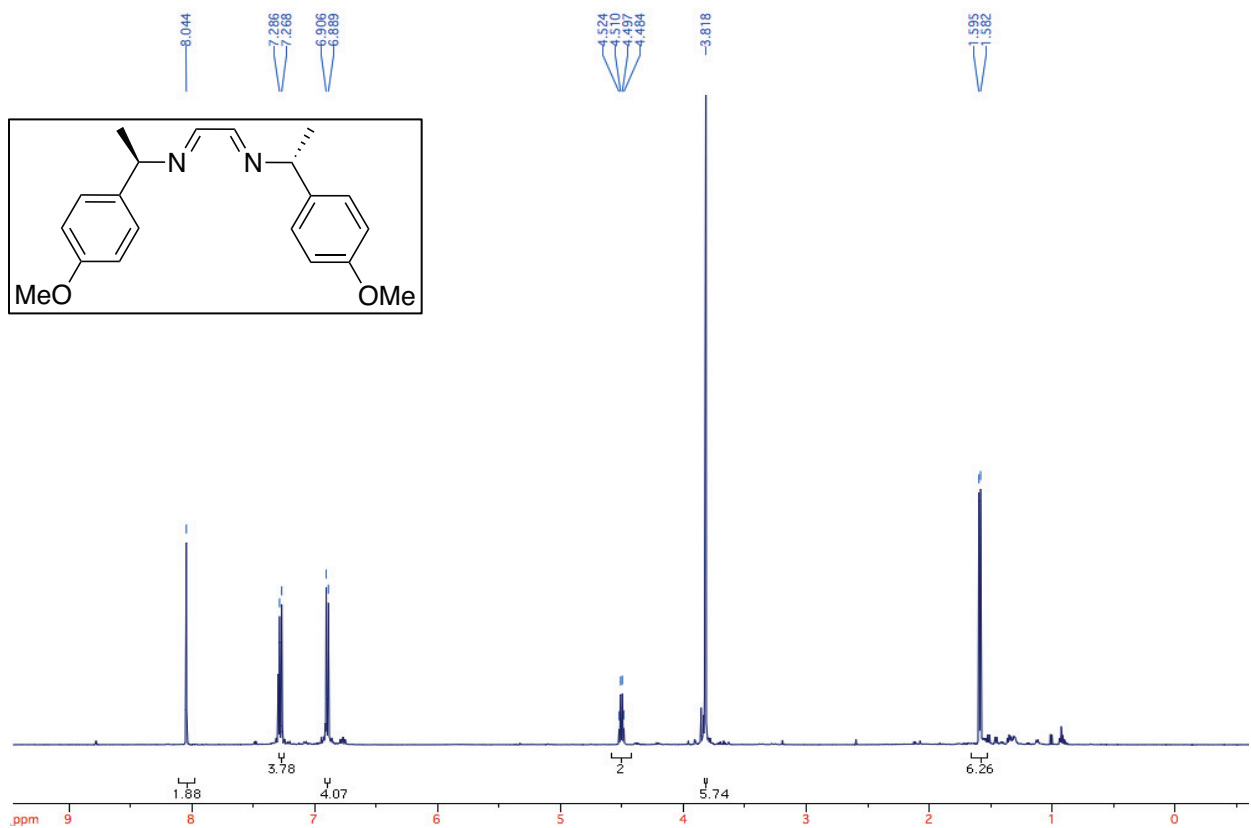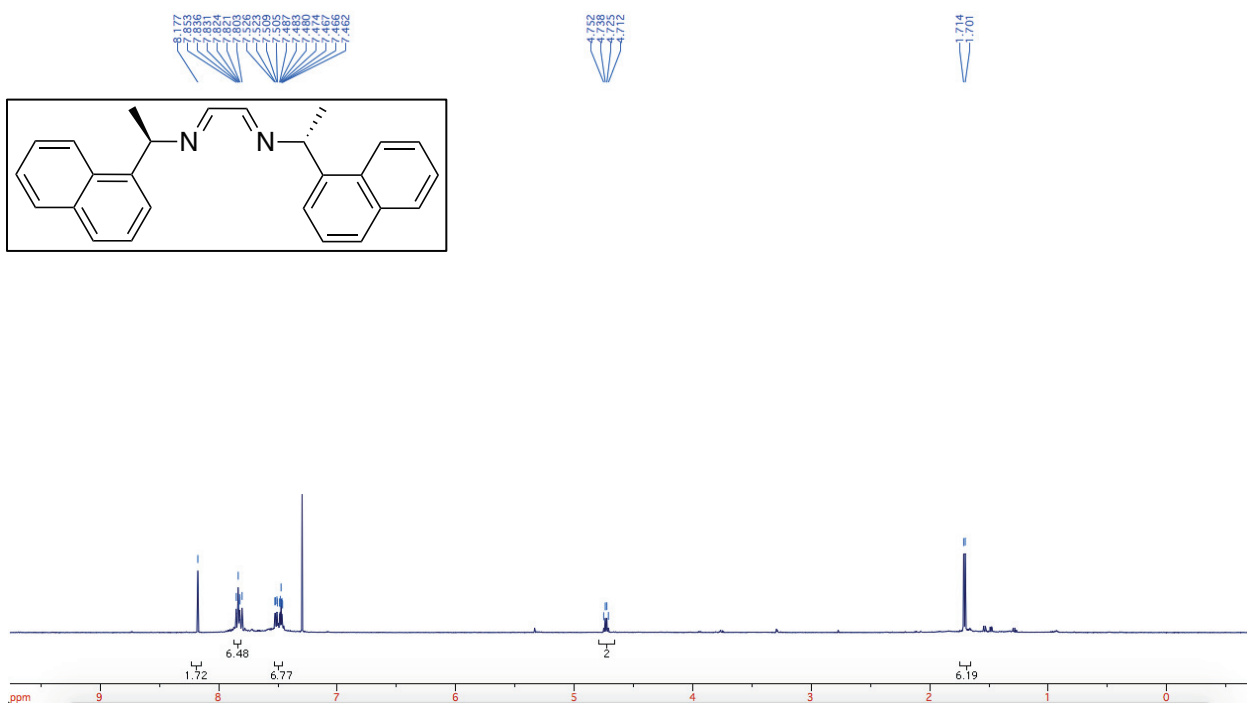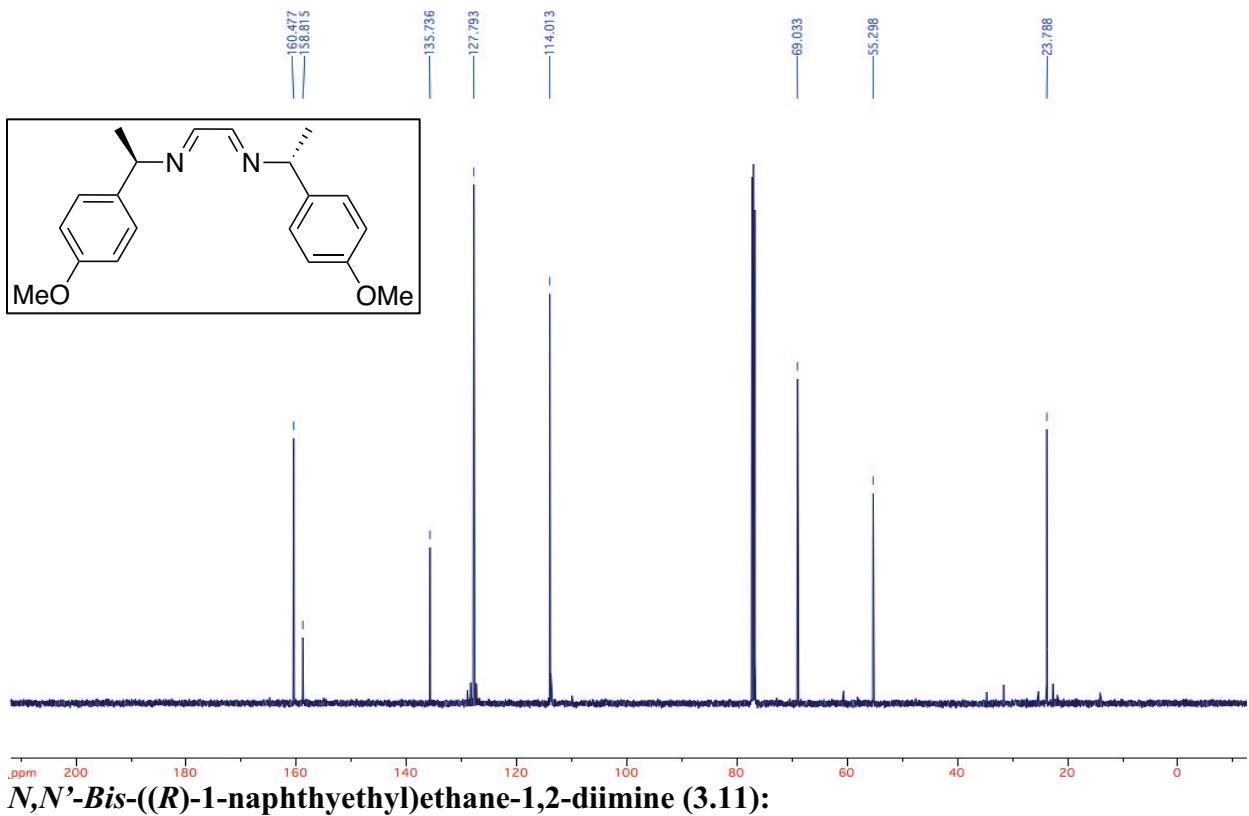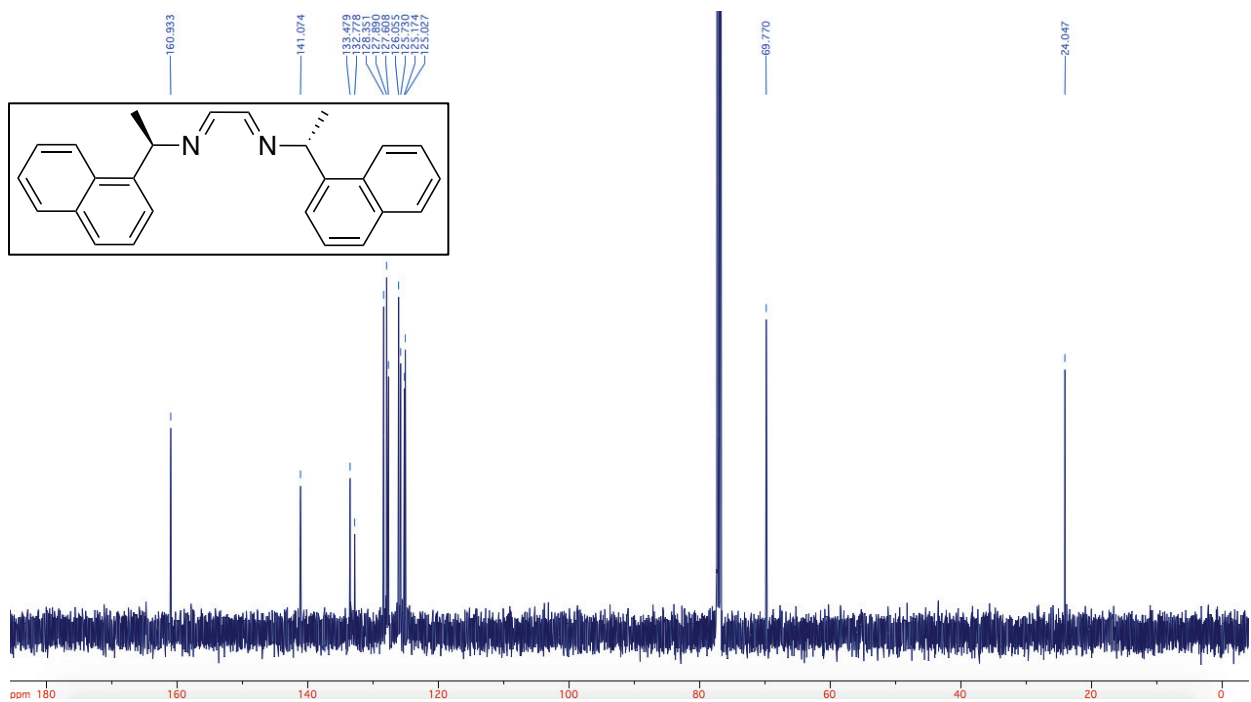
N,N'-Bis((S)-1-(naphthyl-2,2-dimethylpropyl)ethane-1,2-diimine (3.12):
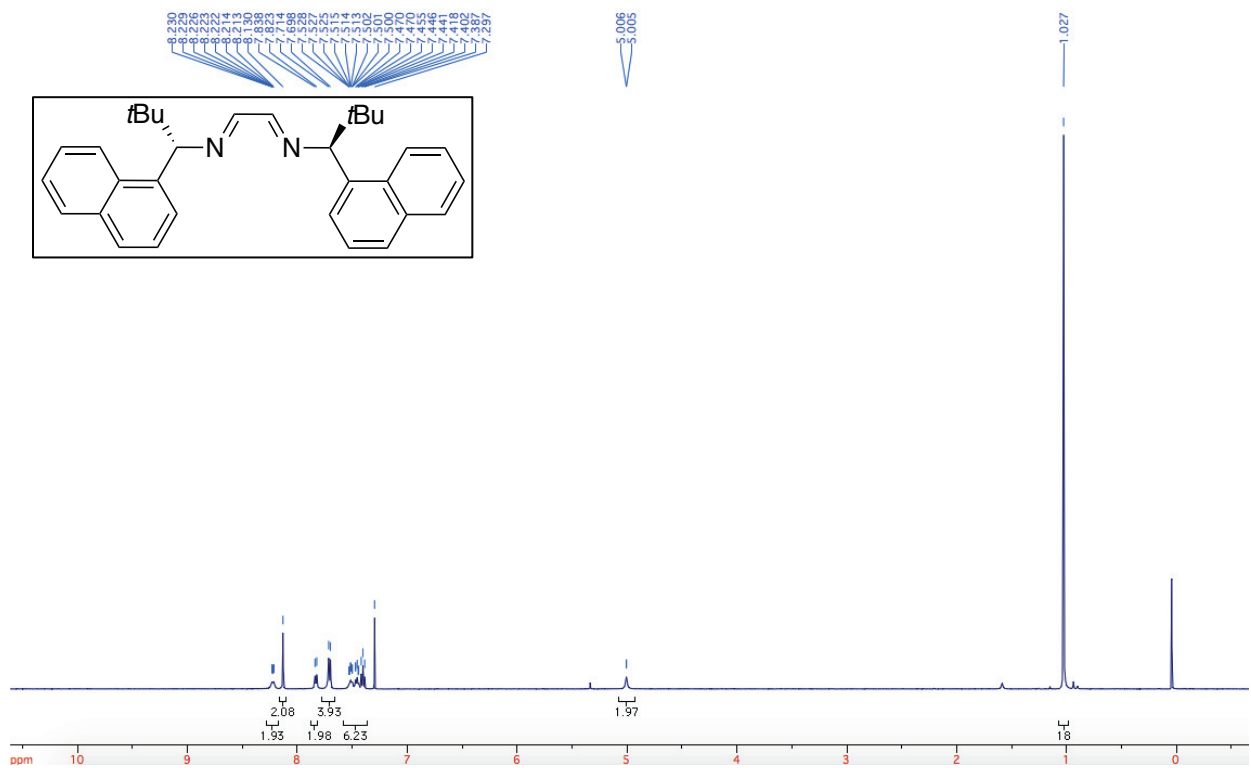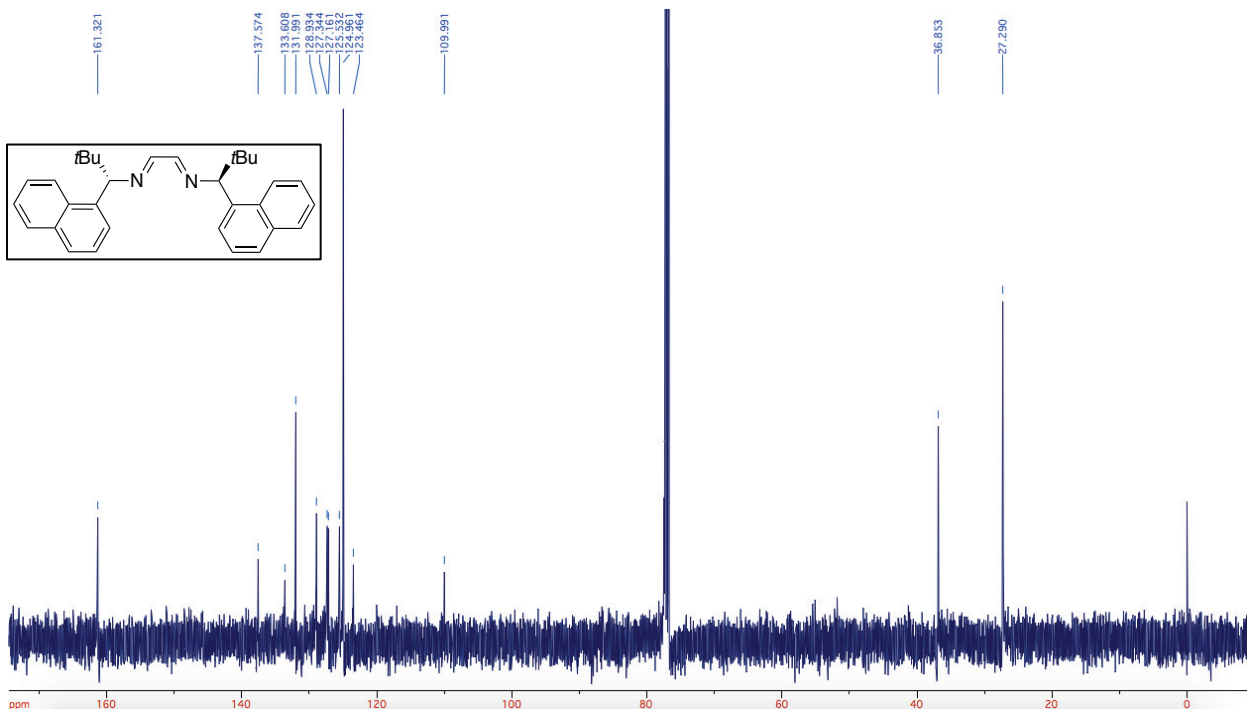
N,N'-Bis-((R)-1-napthyethyl)ethane-1,2-diimine (3.13):
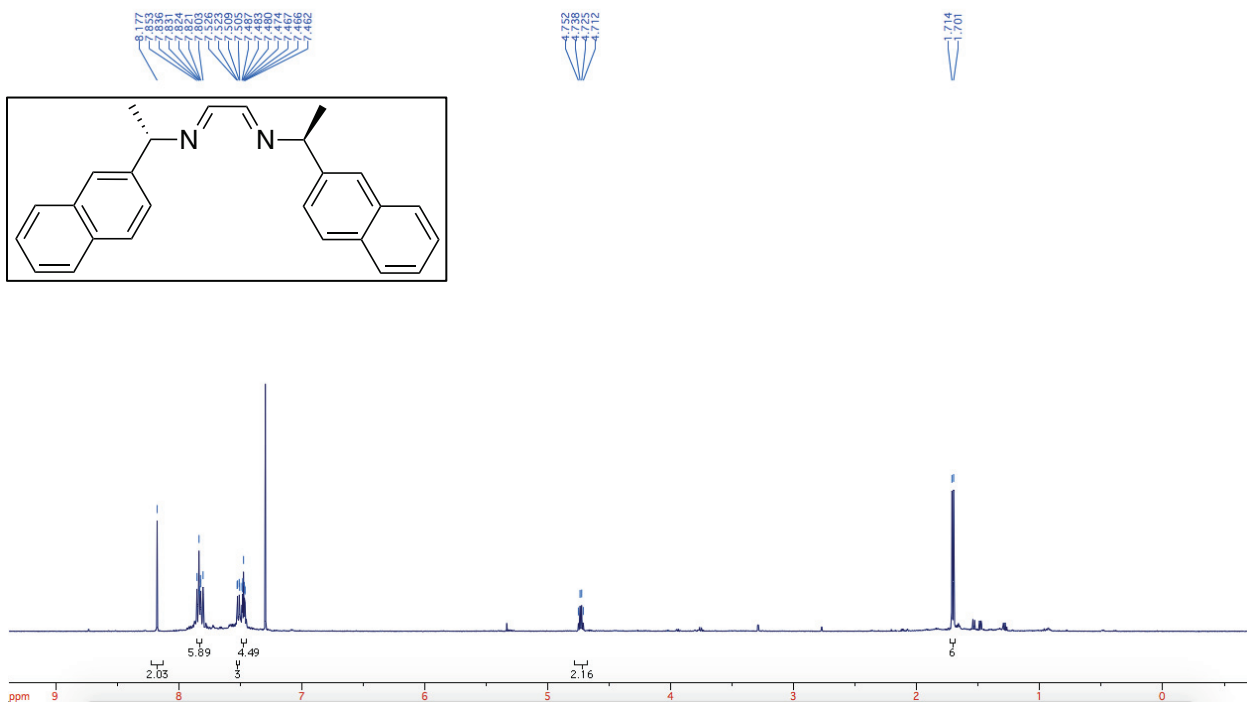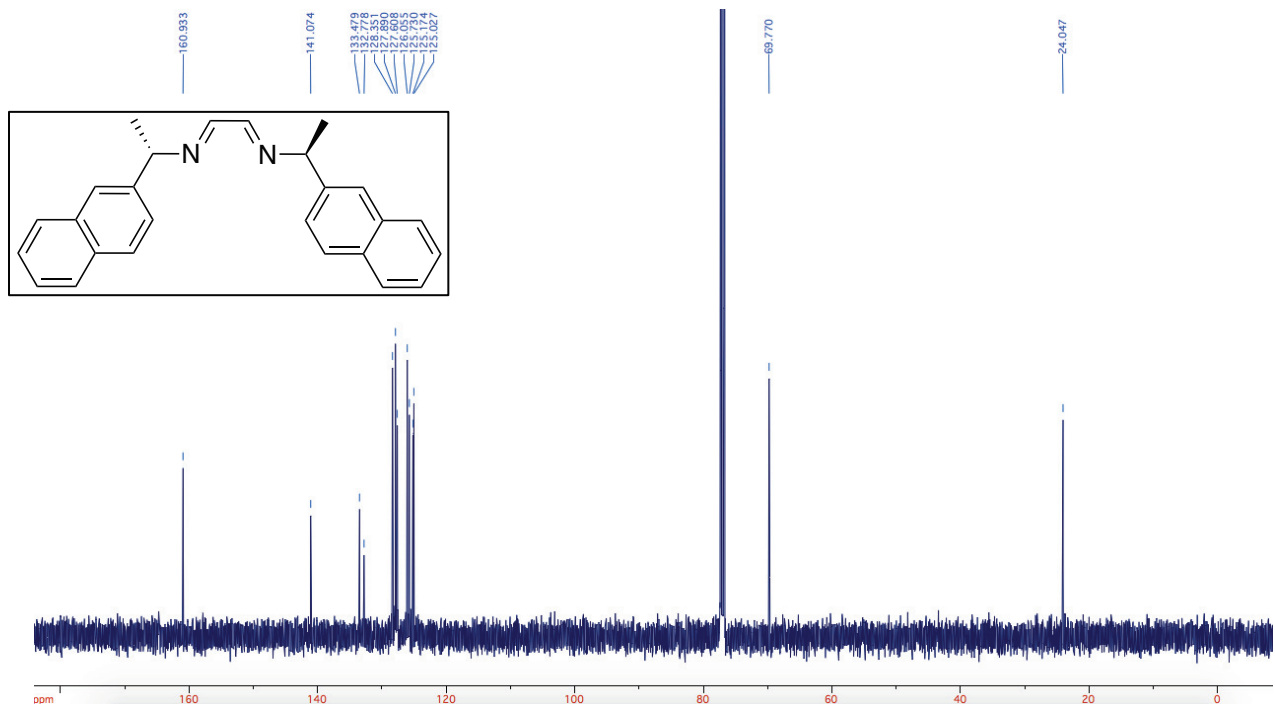
N,N'-Bis-((R)-1-naphthypropyl)ethane-1,2-diimine (3.14):
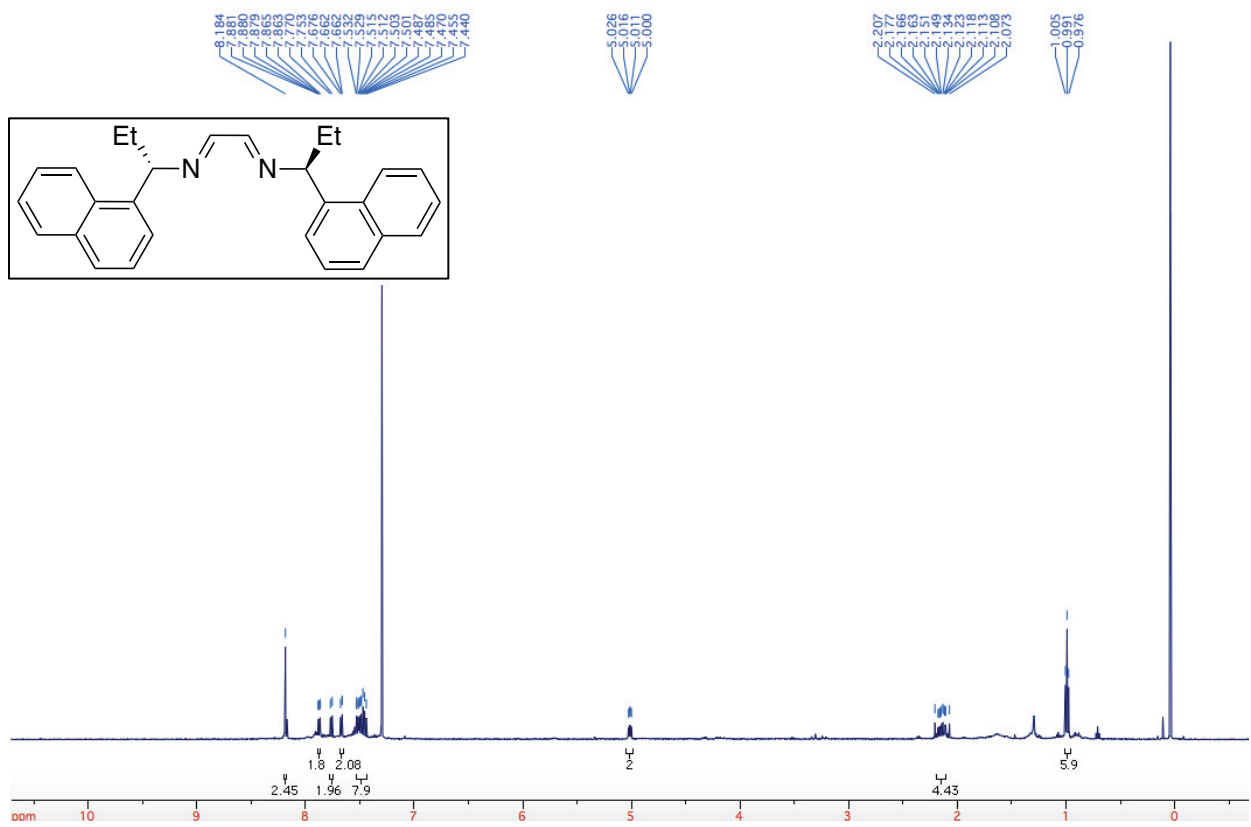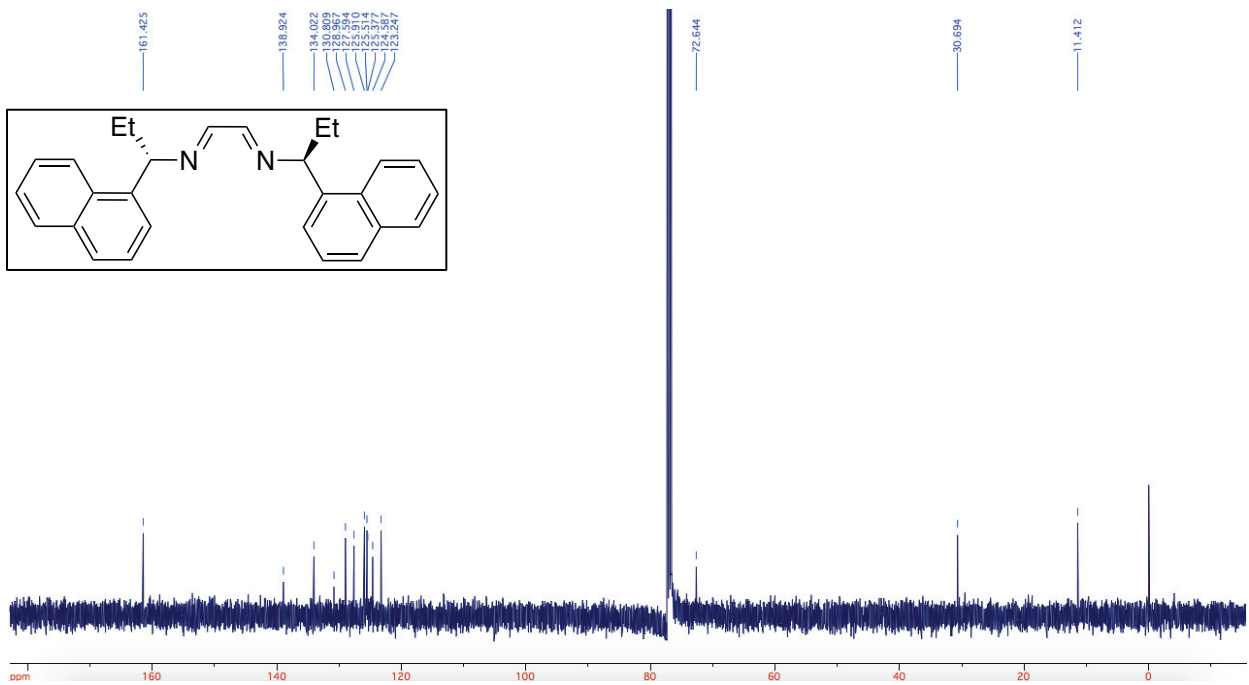
N,N'-Bis-((S)-3,5-bis(trifluoromethyl)-1-phenylethyl)ethane-1,2-diimine (3.15):
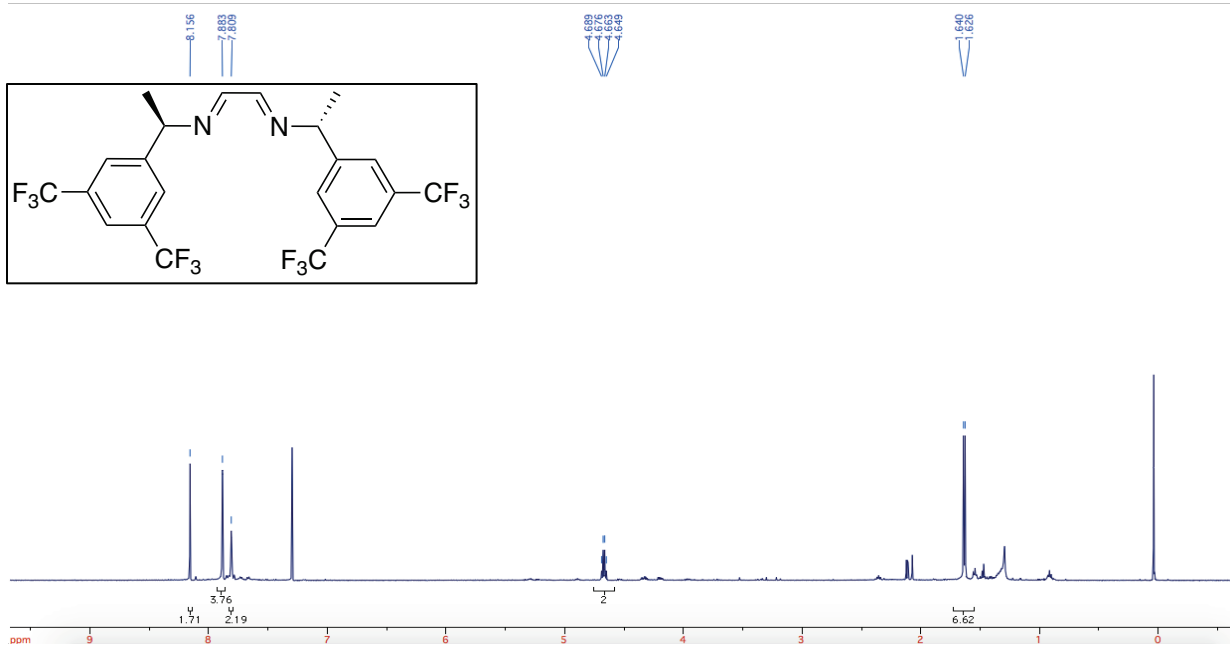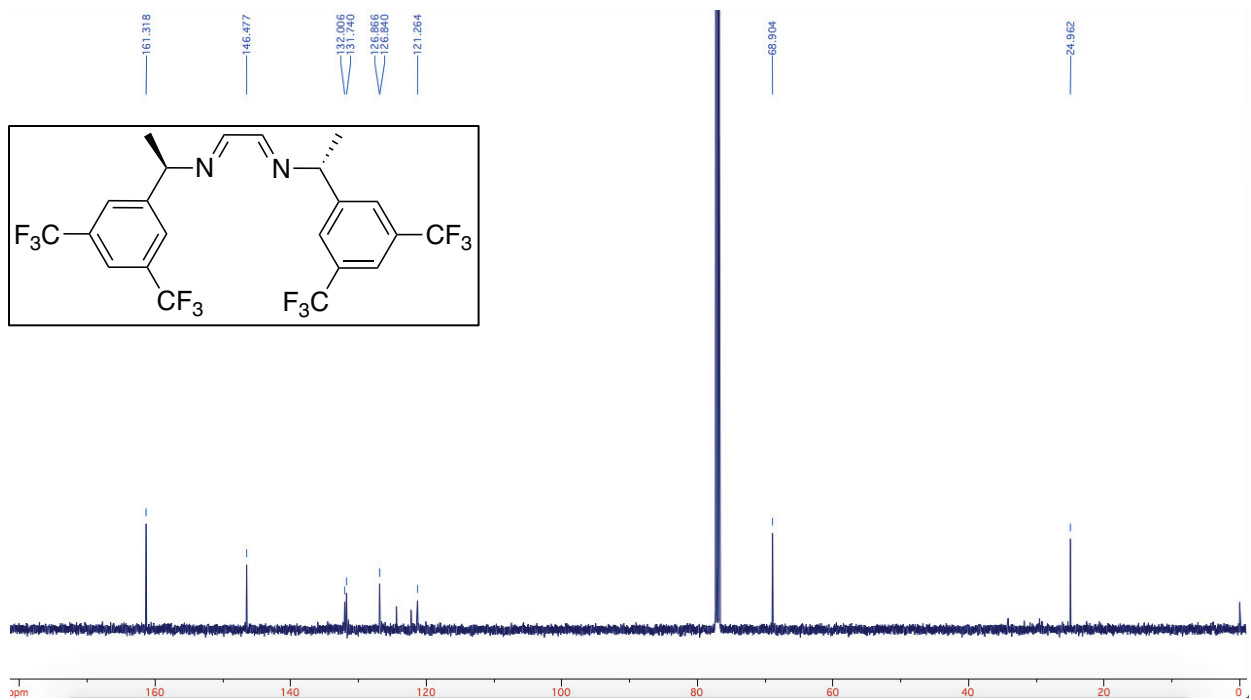
N,N'-Bis-((R)-1-naphthy-trifluoromethyl)ethane-1,2-diimine (3.17):

2-Bromo-1,3-*bis*{(*R*)2-(3,3-dimethyl)butyl}-1,3,2-diazaphosphole (3.18):

256
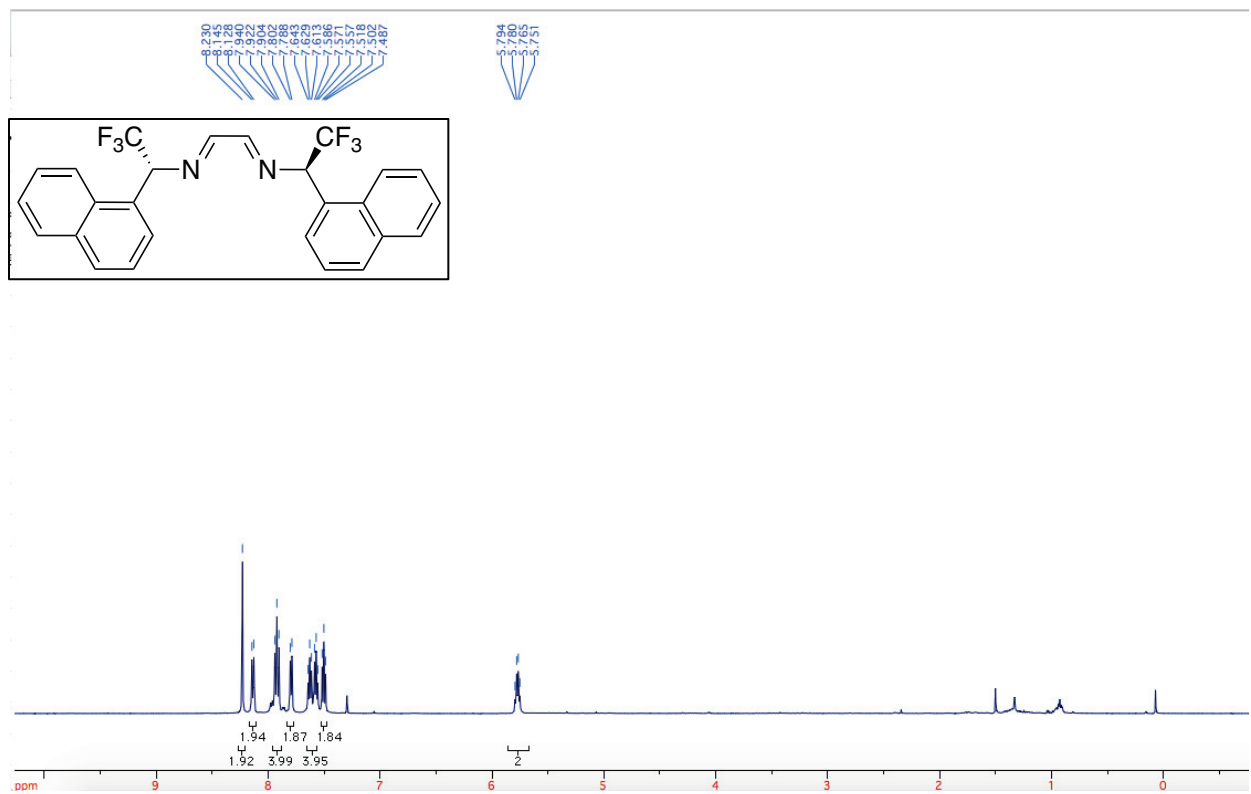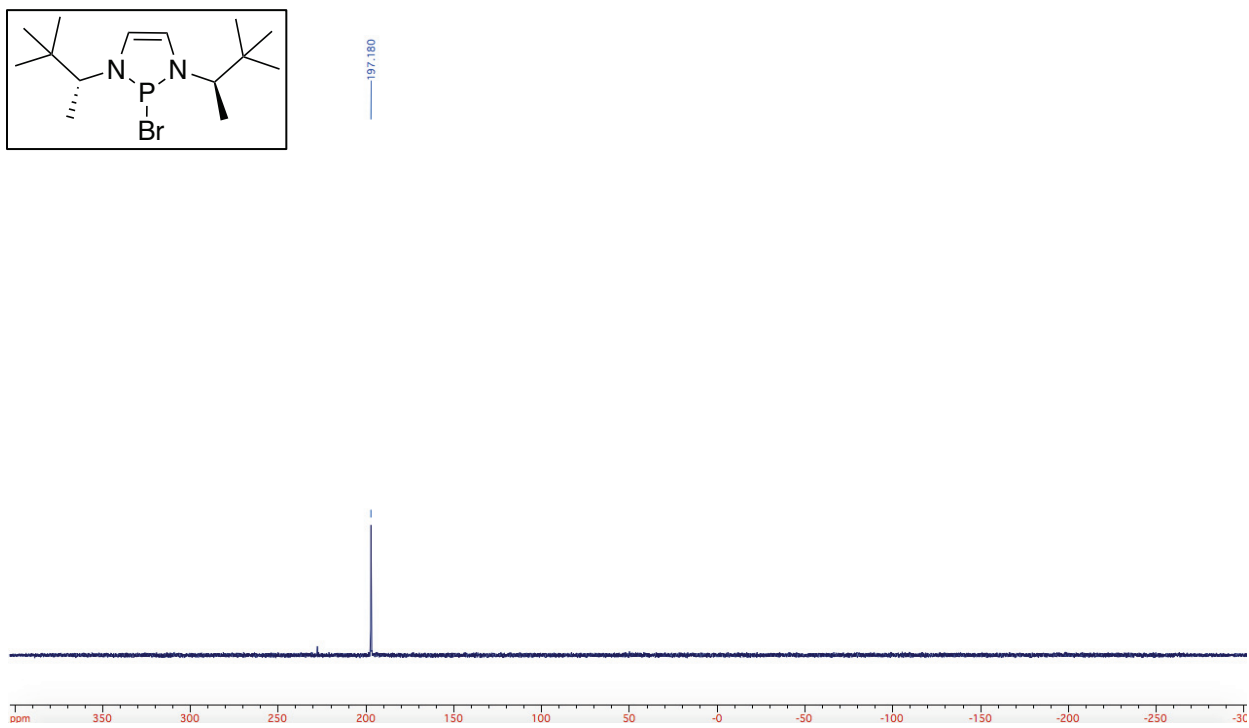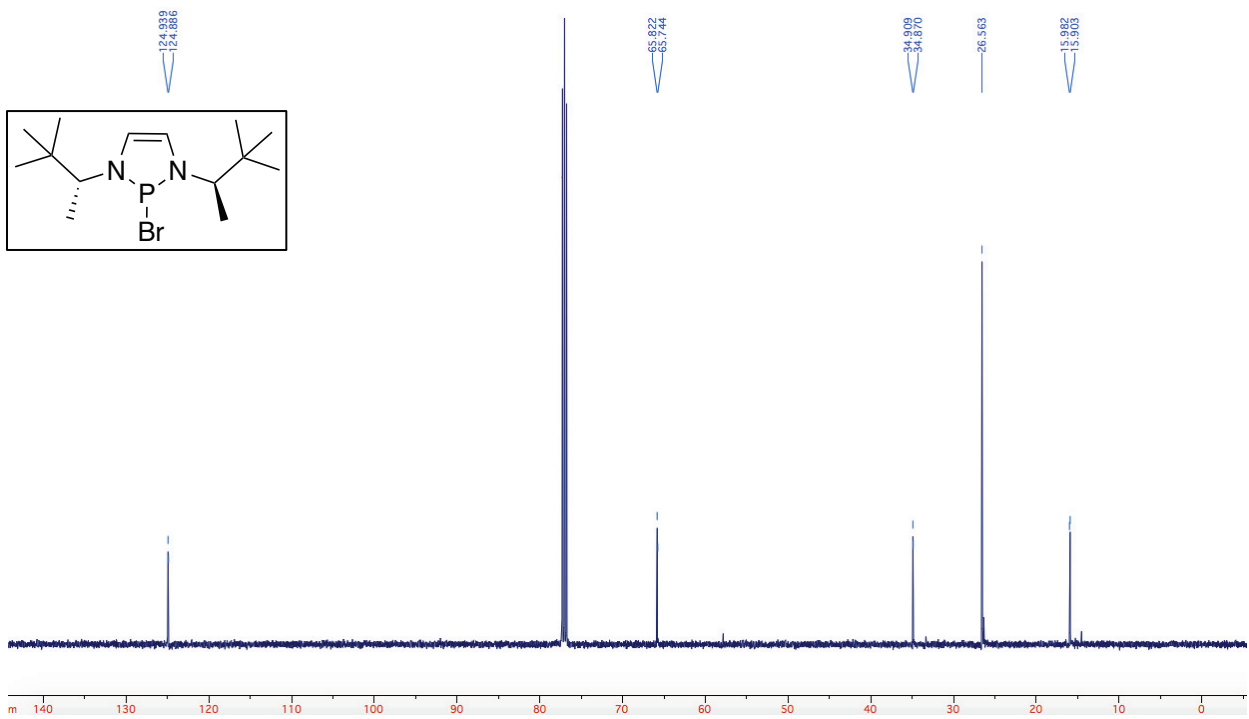
2-Bromo-1,3-*bis*{(*R*)1-phenylethyl}-1,3,2-diazaphosphole (3.19):

2-Bromo-1,3-*bis*{(*R*)1-(*p*-methoxyphenyl)ethyl}-1,3,2-diazaphosphole (3.20):

160.006

131.985
131.943
128.945
125.356
125.299

114.513

58.995
58.902
55.348

22.117
22.032

MeO

OMe

N N
P
Br

ppm 160 140 120 100 80 60 40 20 0

189.771

MeO

OMe

N N
P
Br
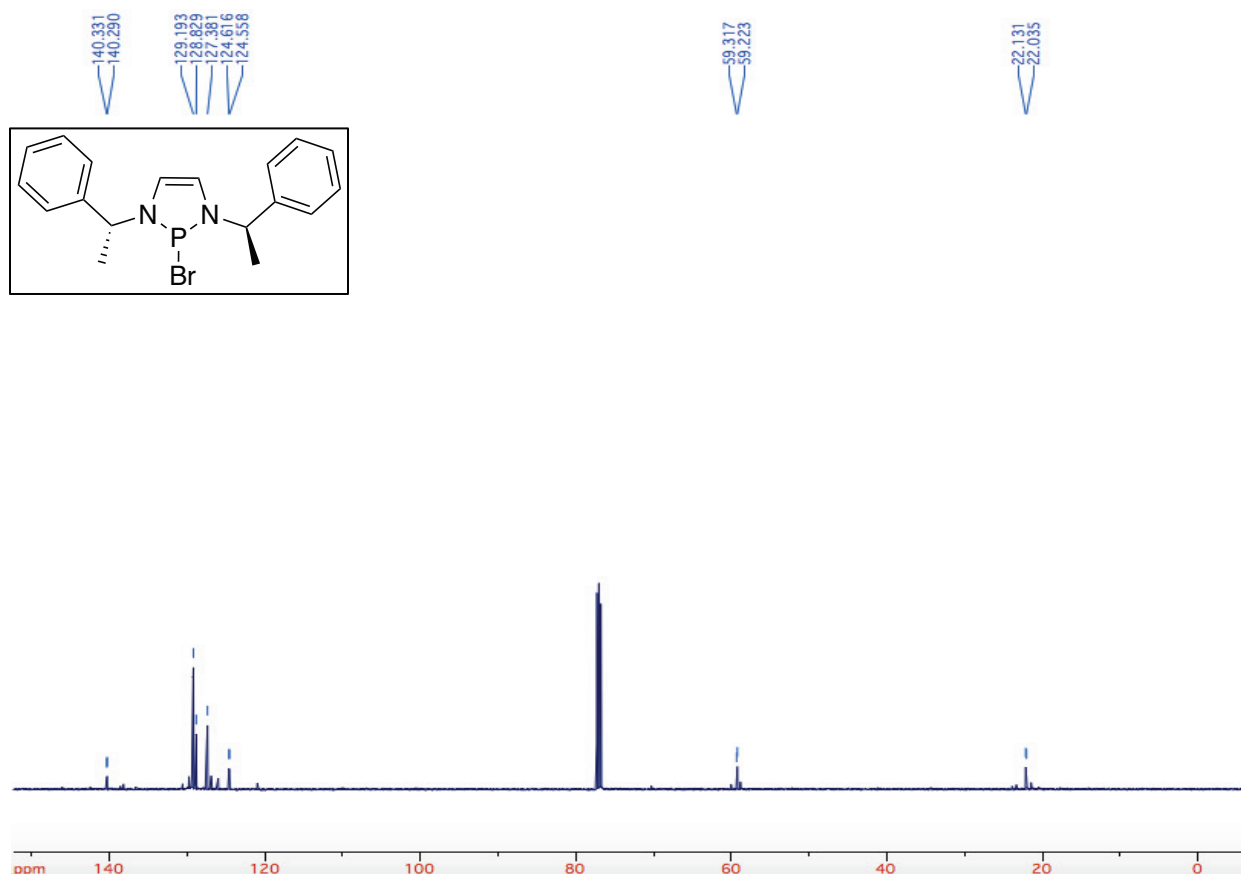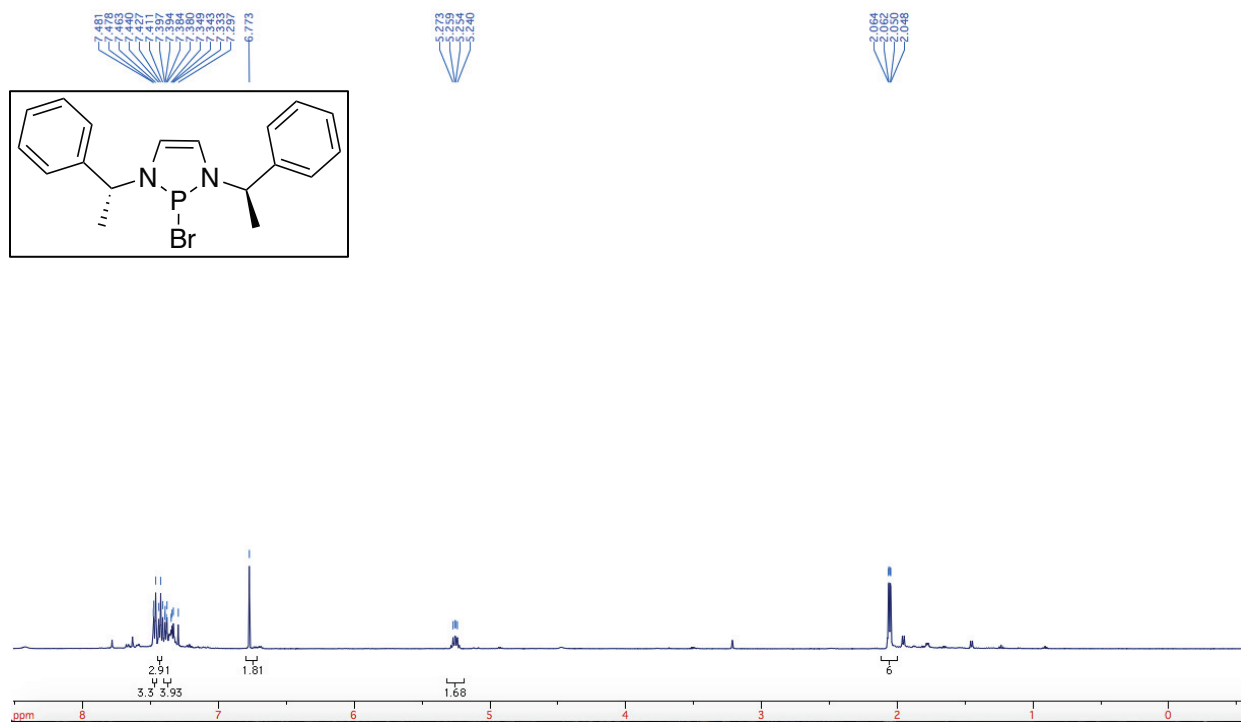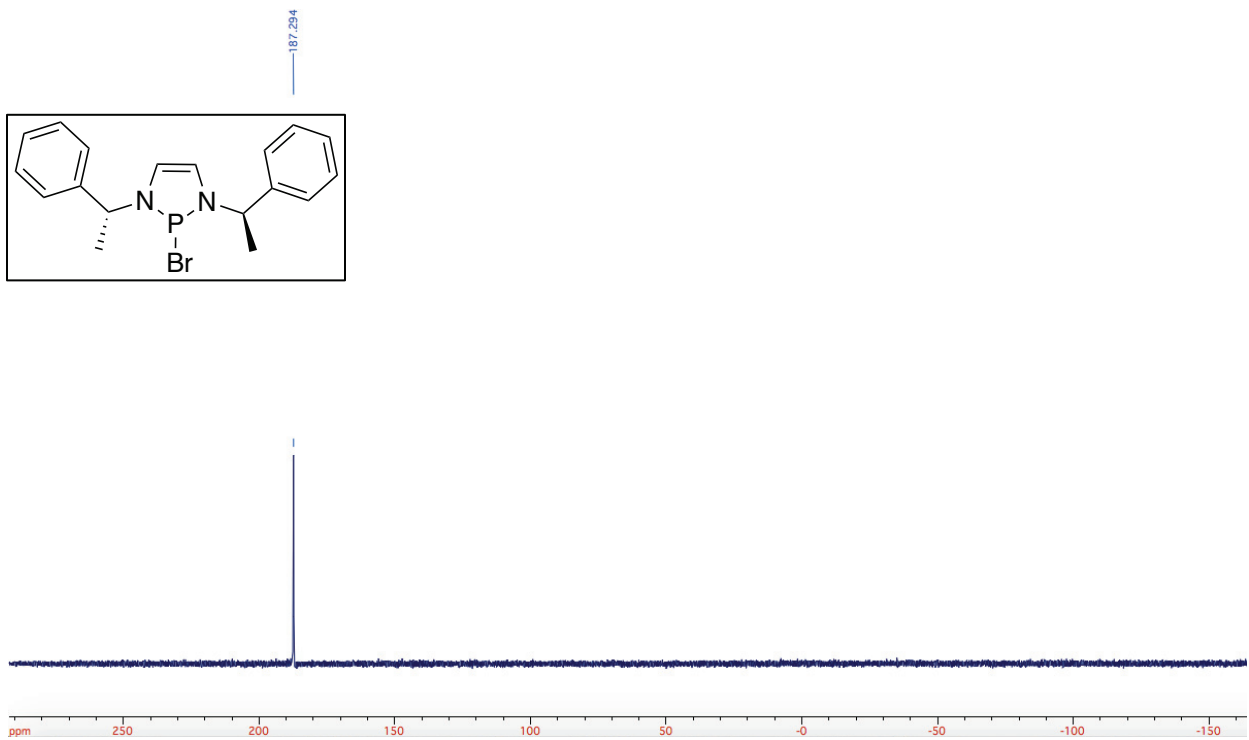
ppm 250 200 150 100 50 -0 -50 -100 -150
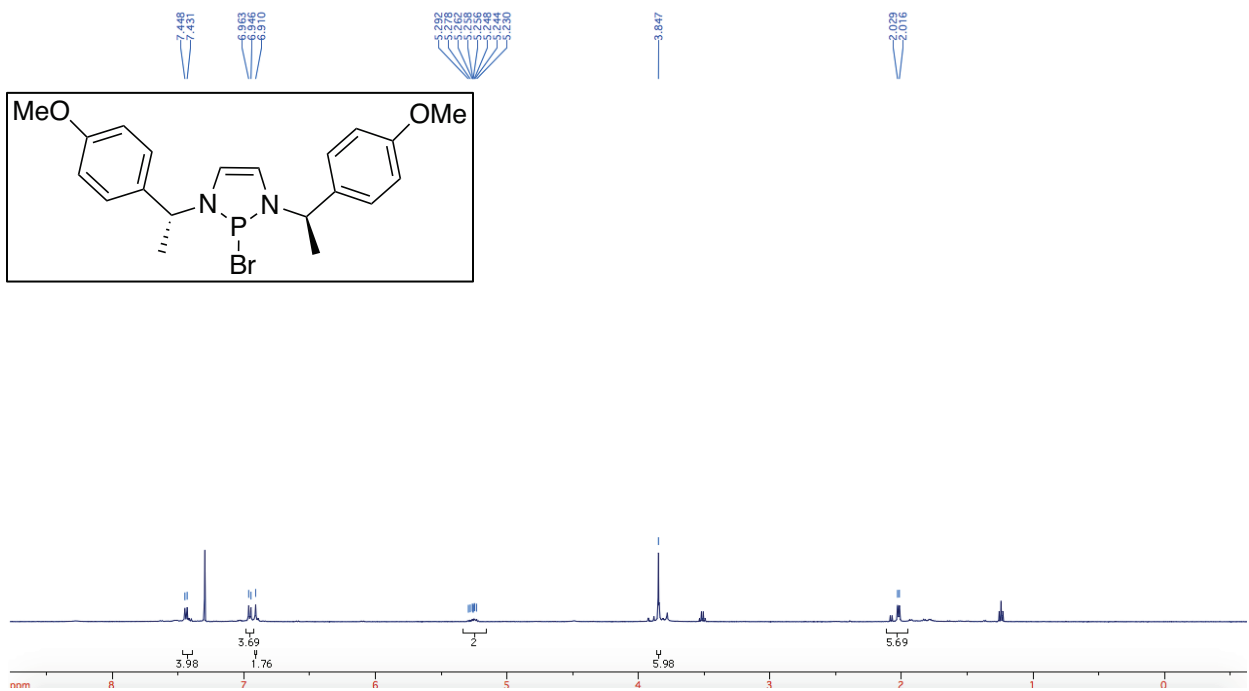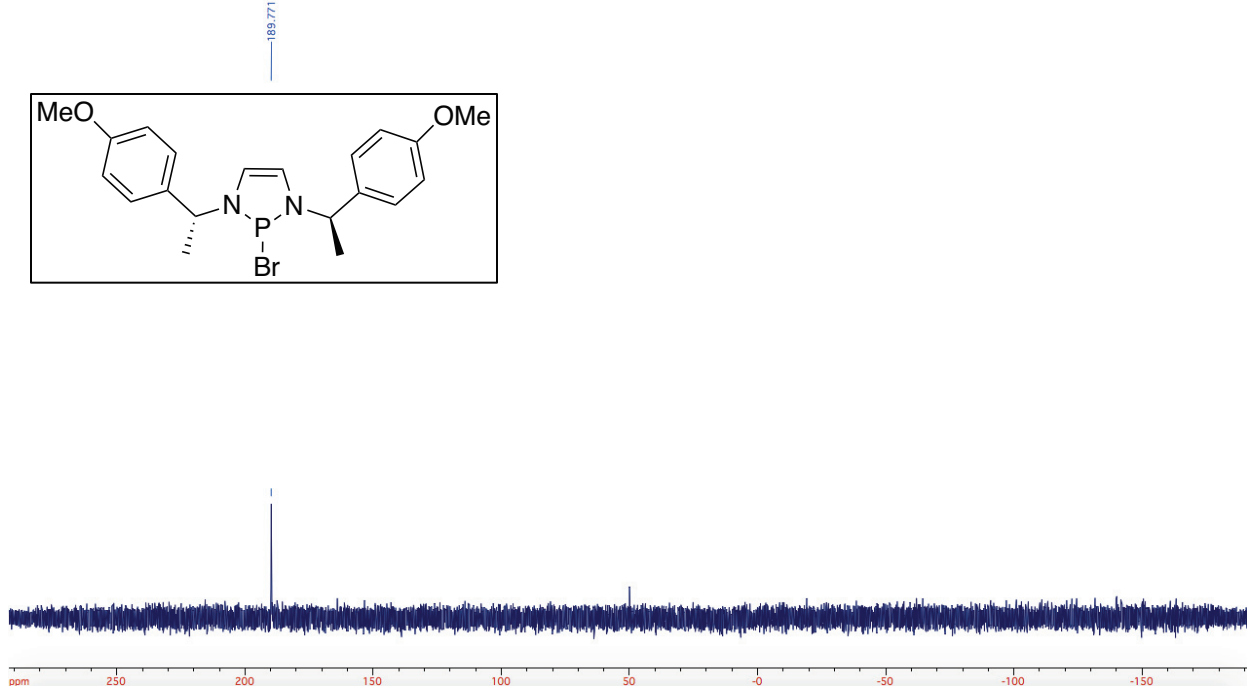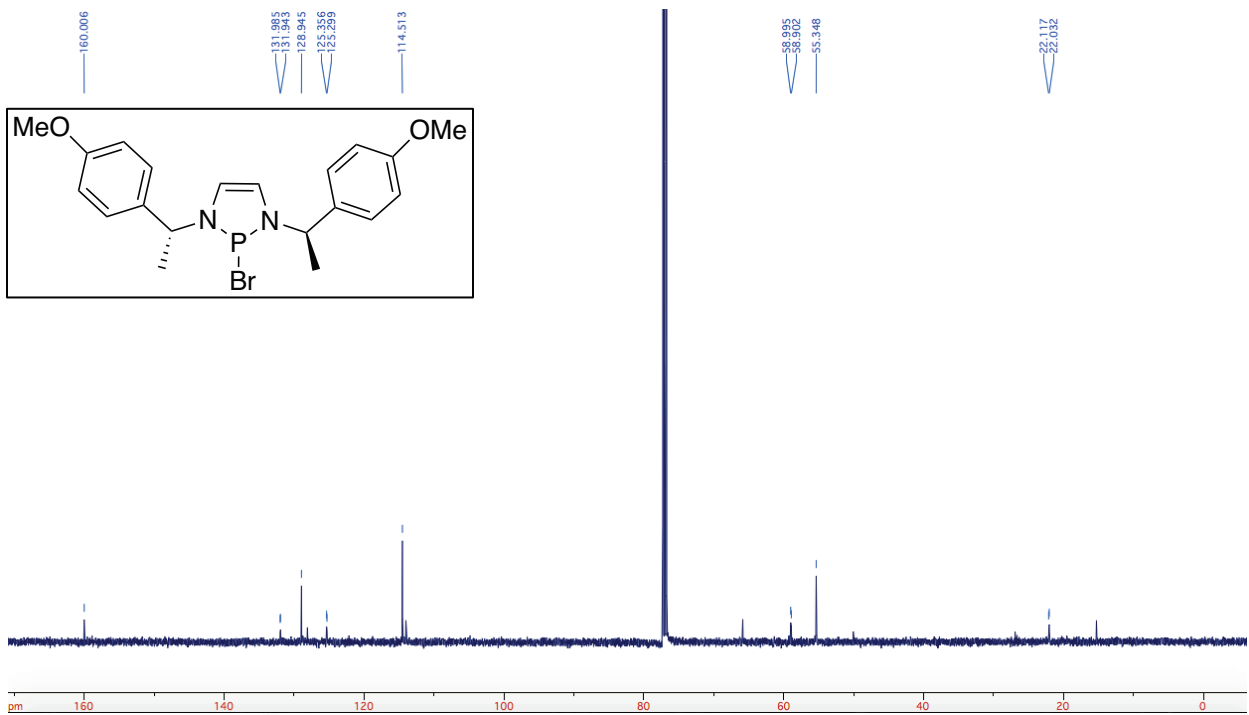
2-Bromo-1,3-*bis*{(*R*)1-(naphthalen-1-yl)ethyl}-1,3,2-diazaphosphole (3.21):
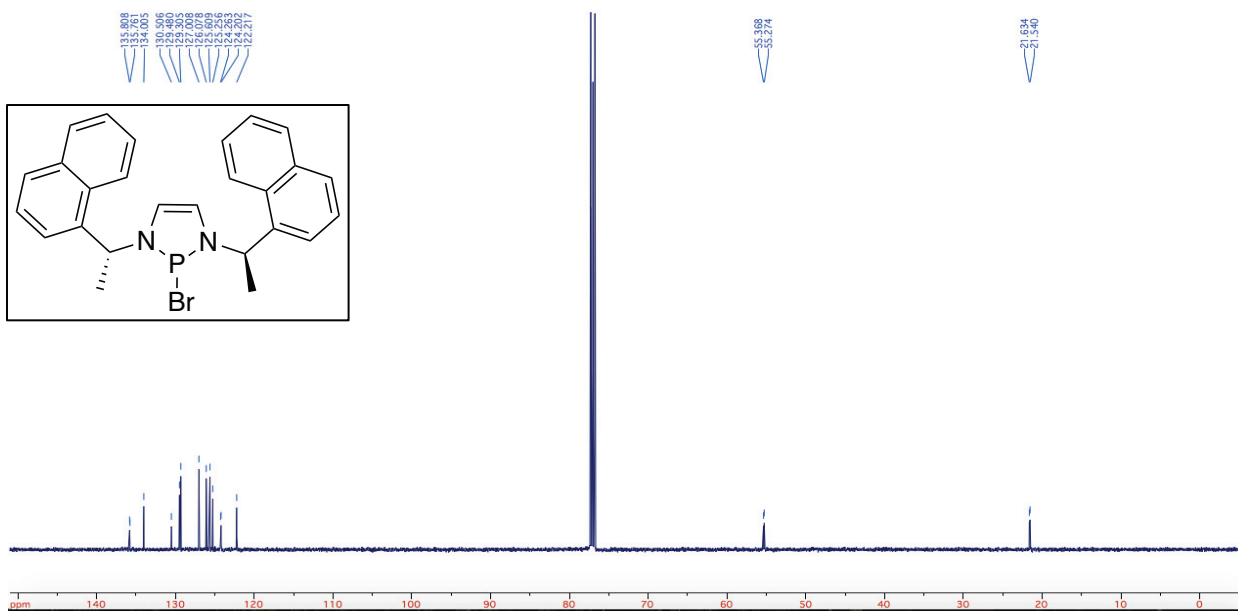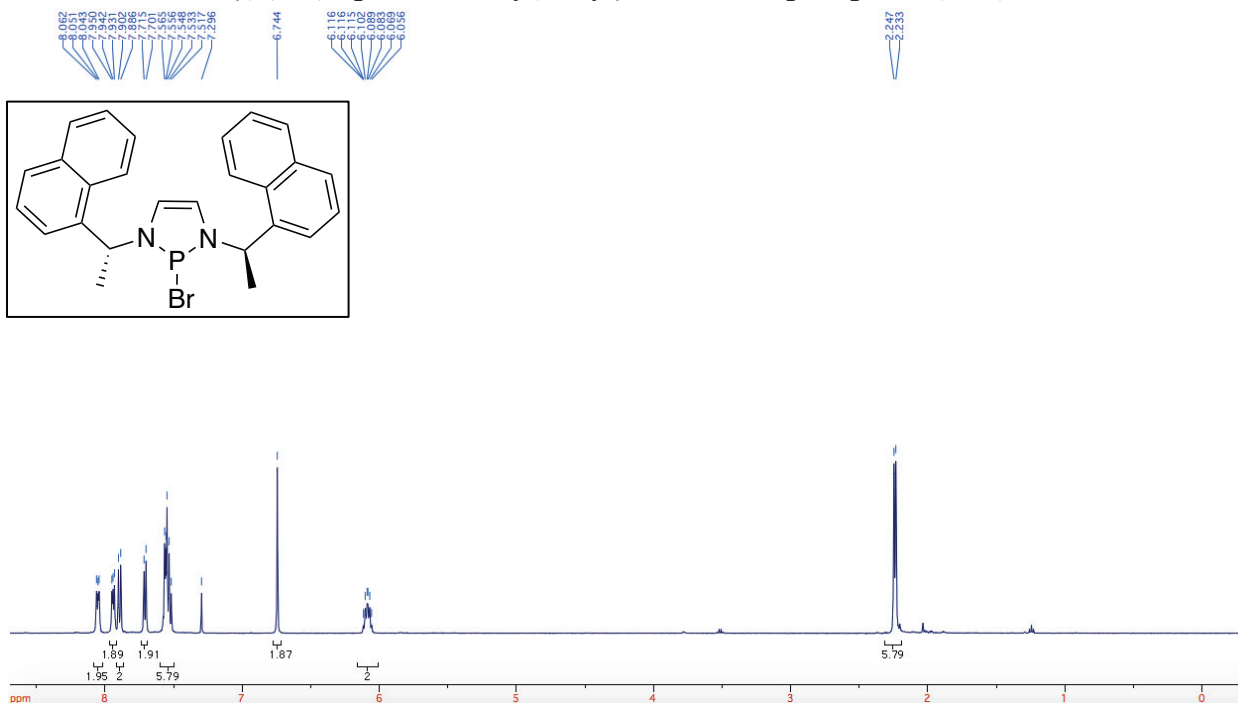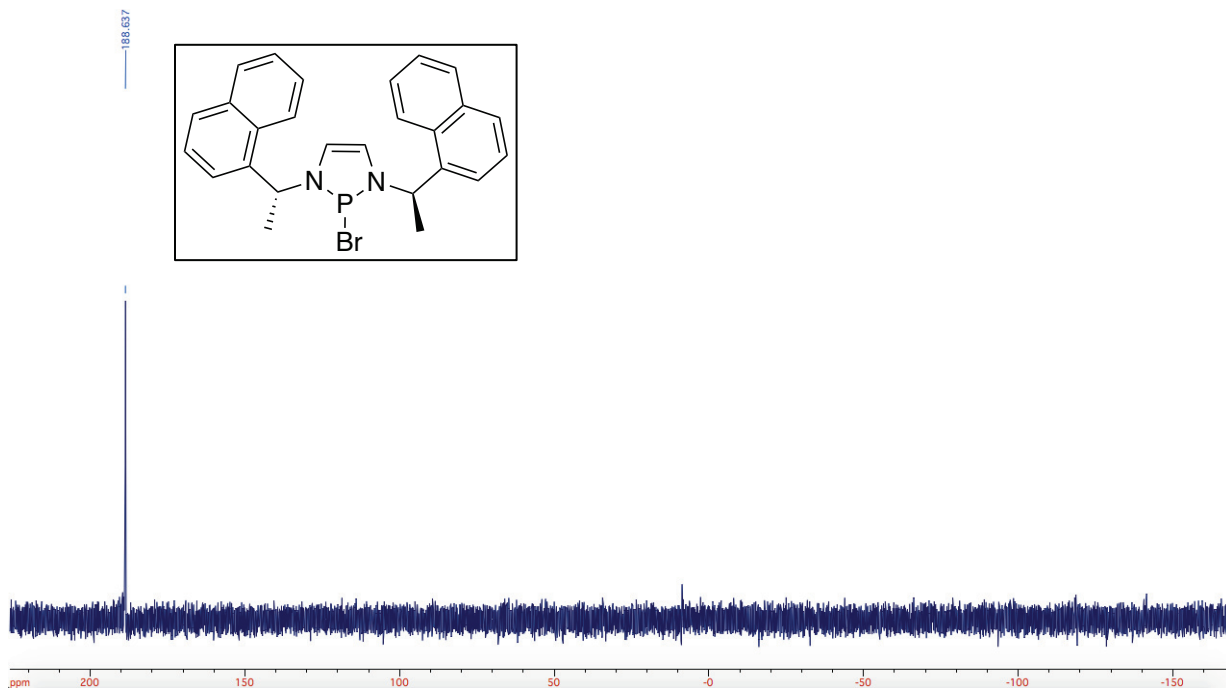
2-Bromo-1,3-*bis*{(*R*)1-(naphthalen-1-yl)ethyl}-1,3,2-diazaphosphole (3.23):
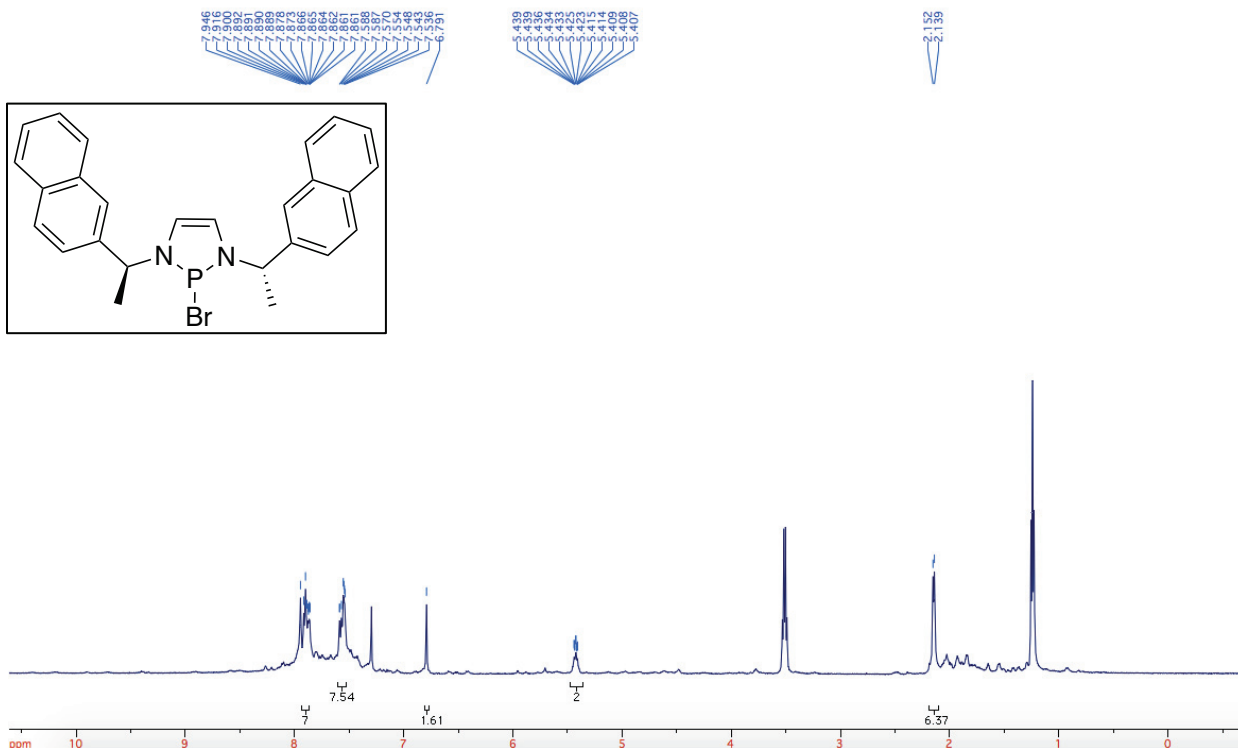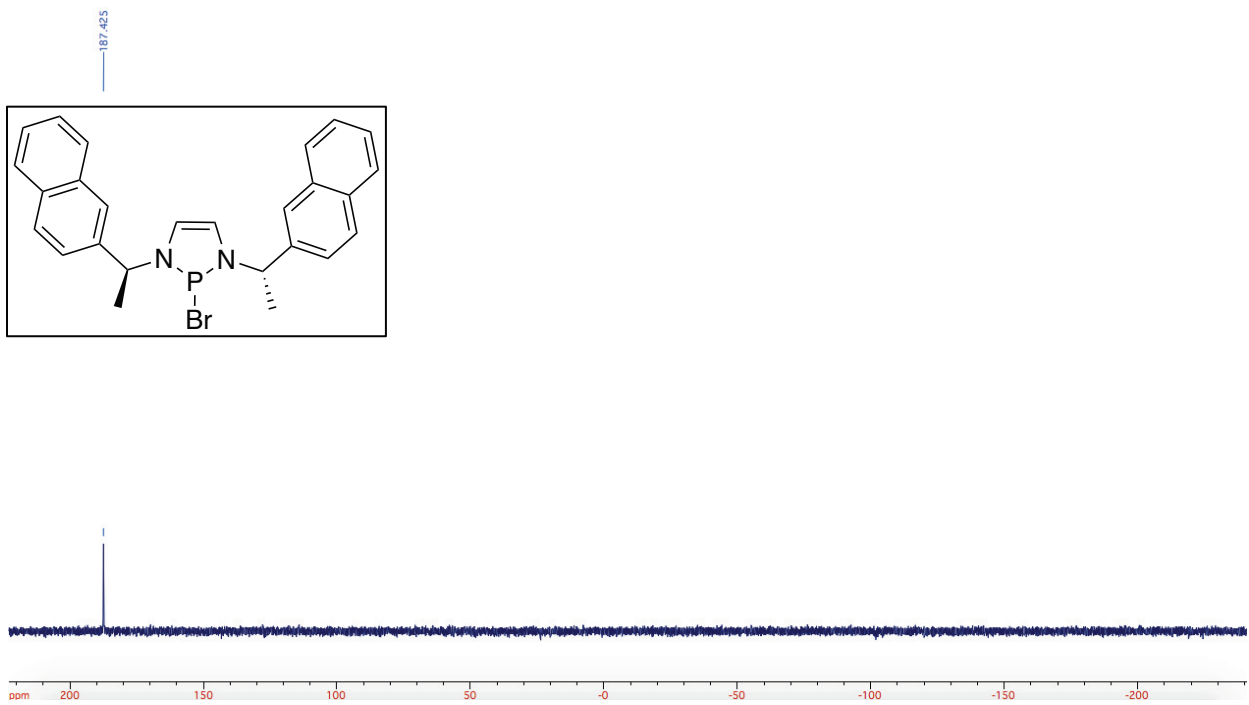
2-Bromo-1,3-*bis*{(*R*)1-(naphthalen-1-yl)propyl}-1,3,2-diazaphosphole (3.24):
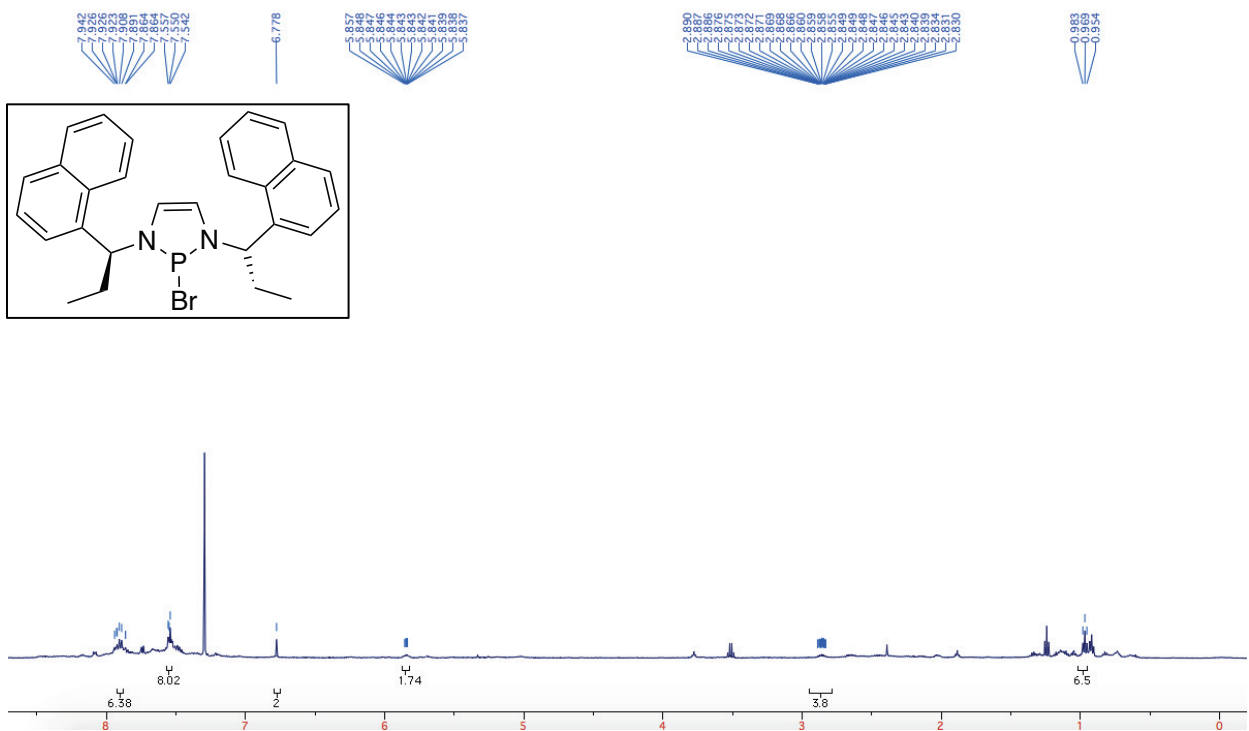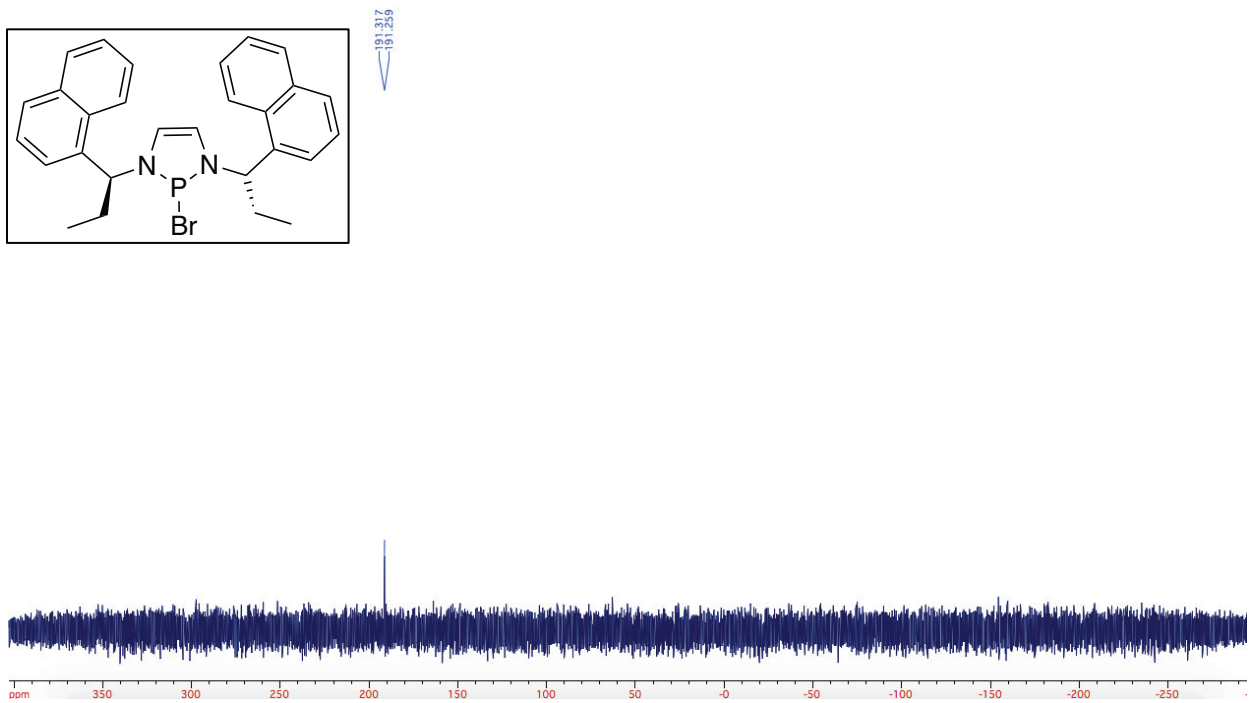
1,3-*Bis*{(*S*)1-(naphthalen-1-yl)-(2,2-dimethl)propyl}-1,3,2-diazaphosphole (3.27):
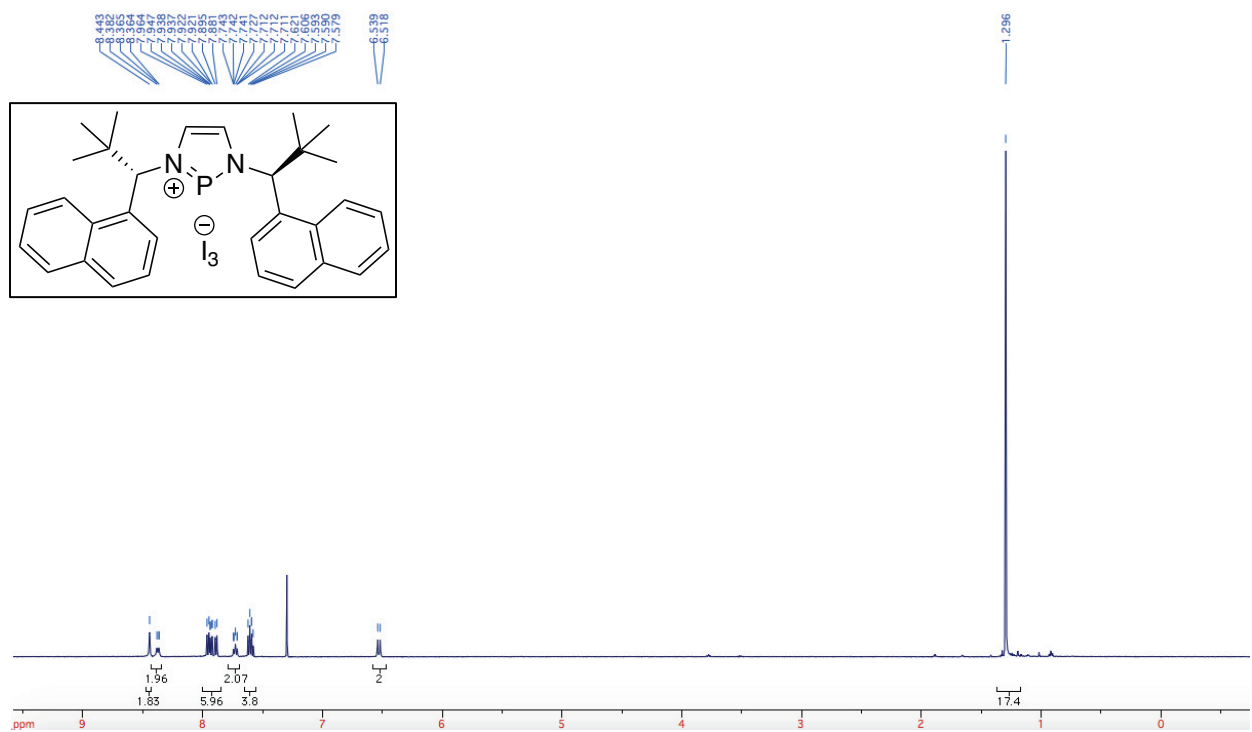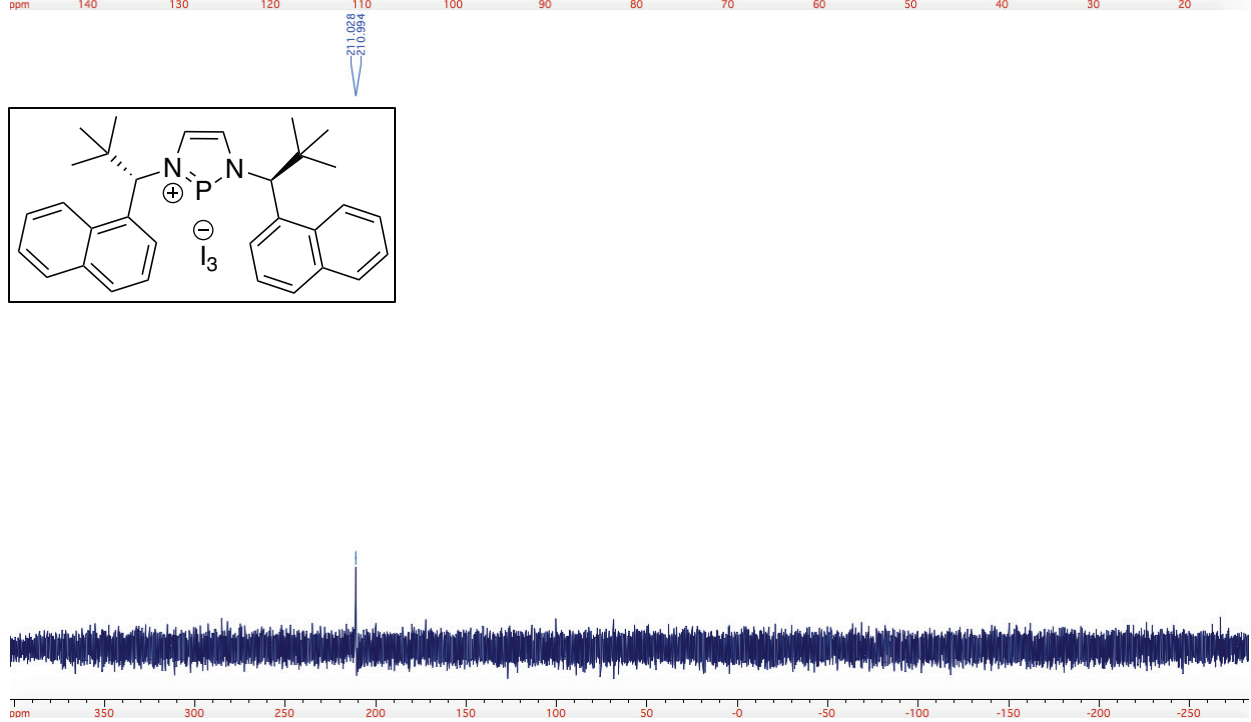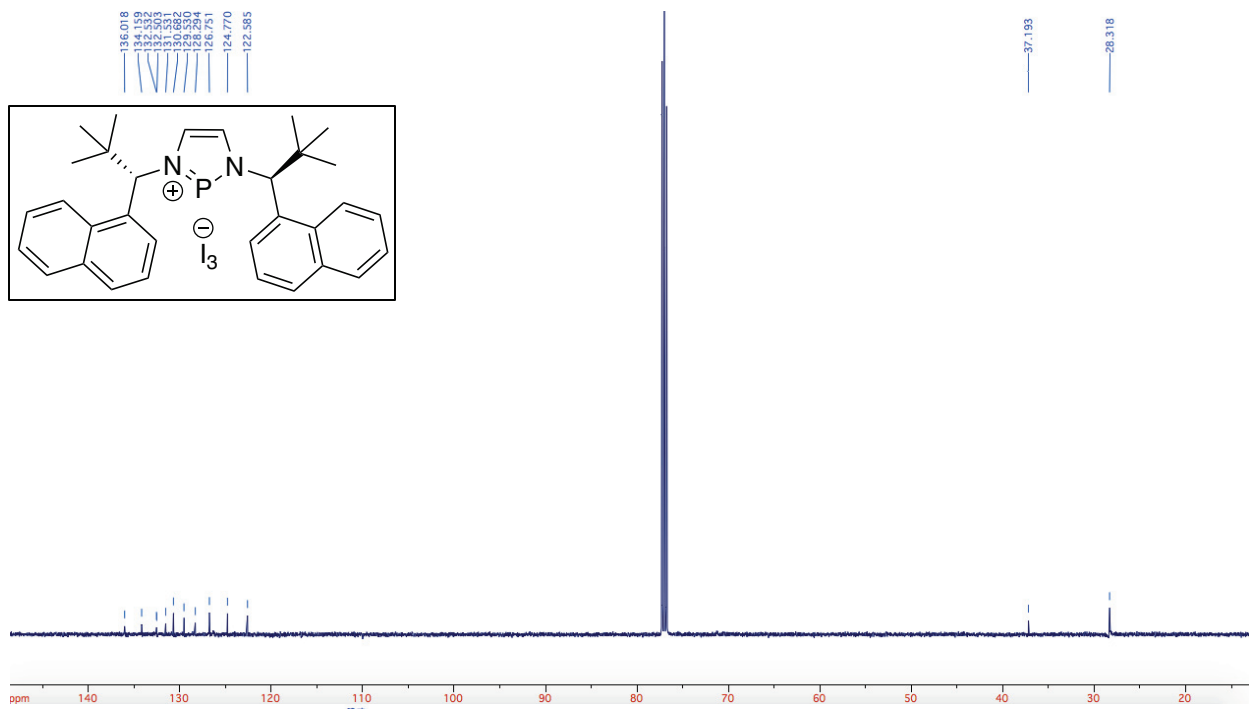
2-Iodo-1,3-*bis*{(*S*)1-(naphthalen-1-yl)-(2,2-dimethl)propyl}-1,3,2-diazaphosphole
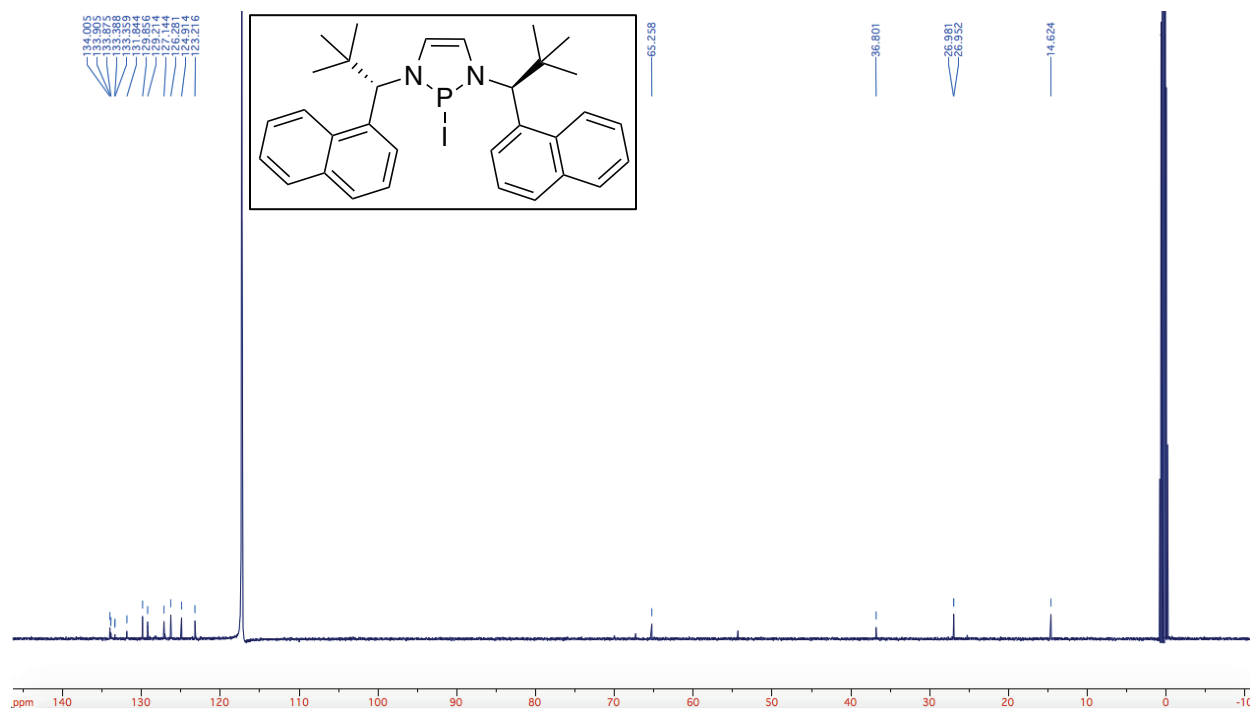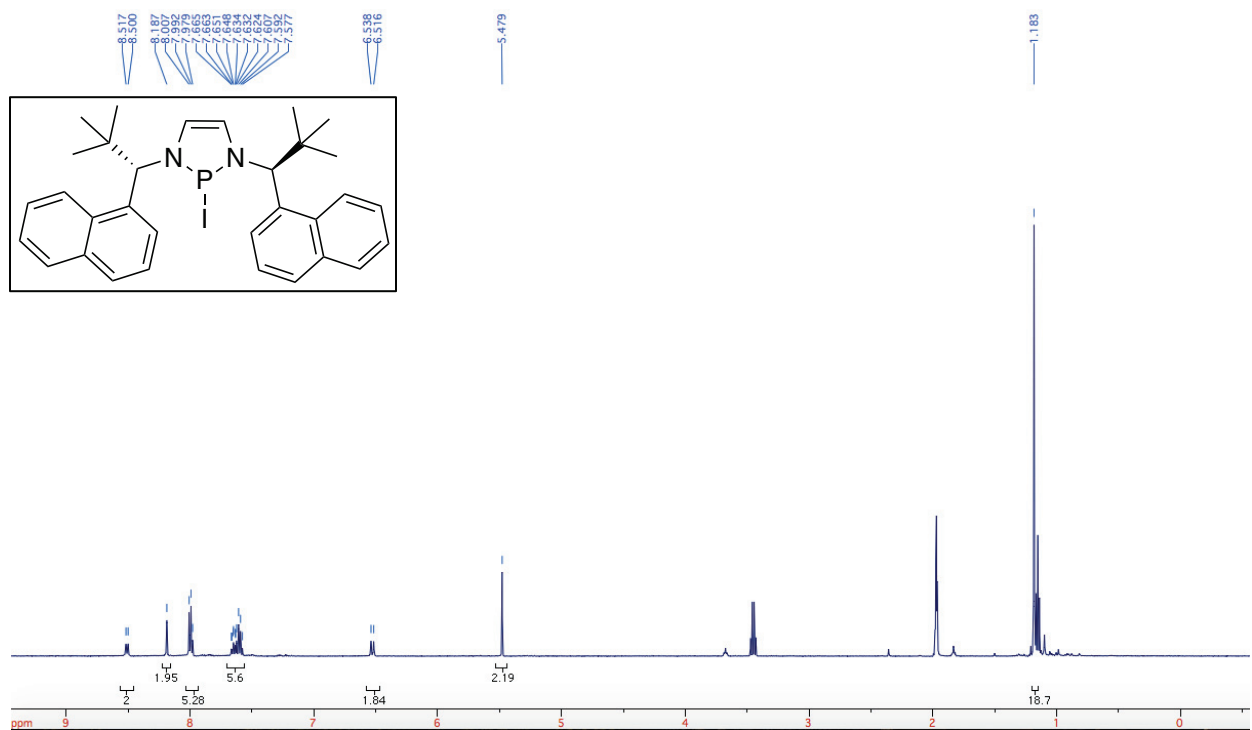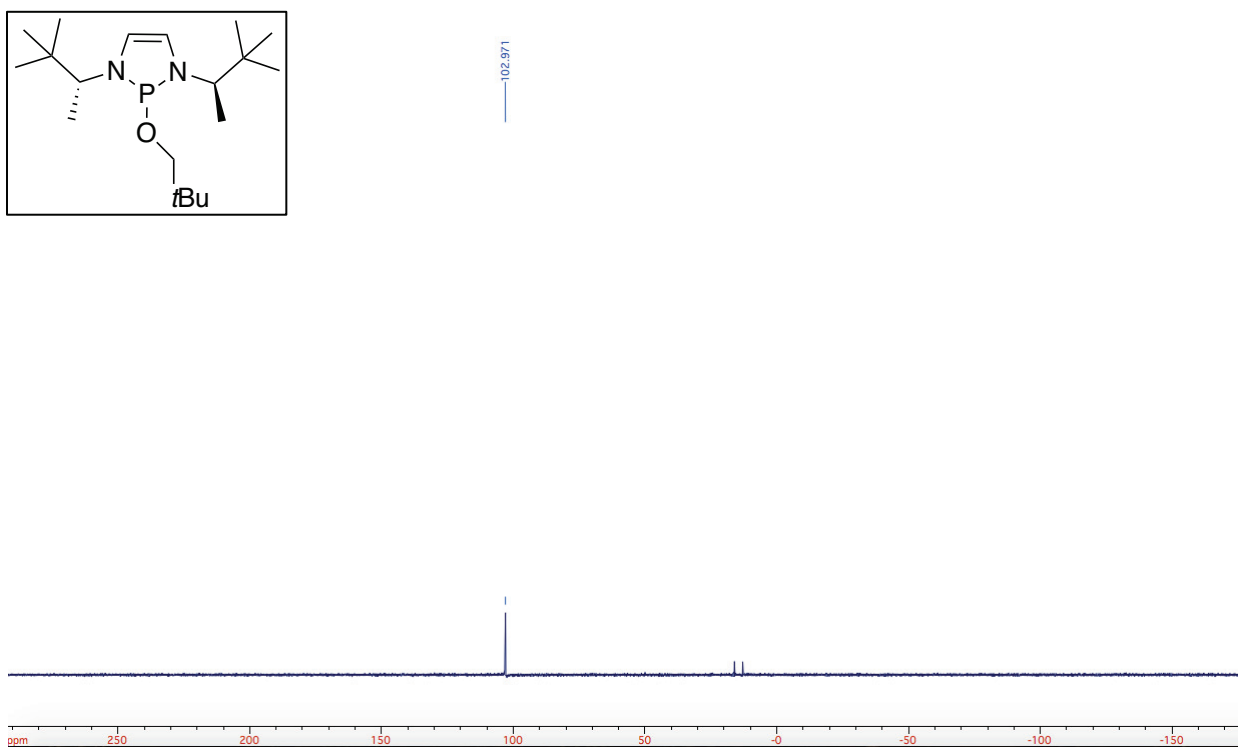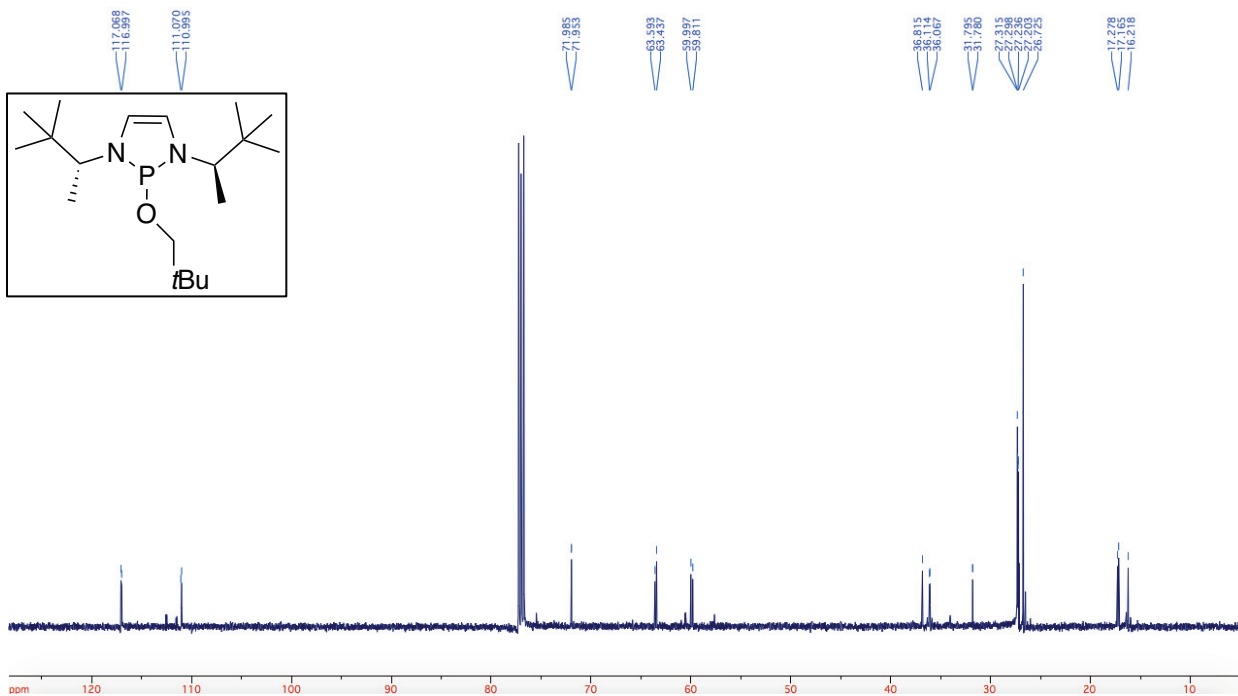
(3.28):

2-Neopentoxy-1,3-*bis*{(*R*)2-(3,3-dimethyl)butyl}-1,3,2-diazaphosphole (3.29):
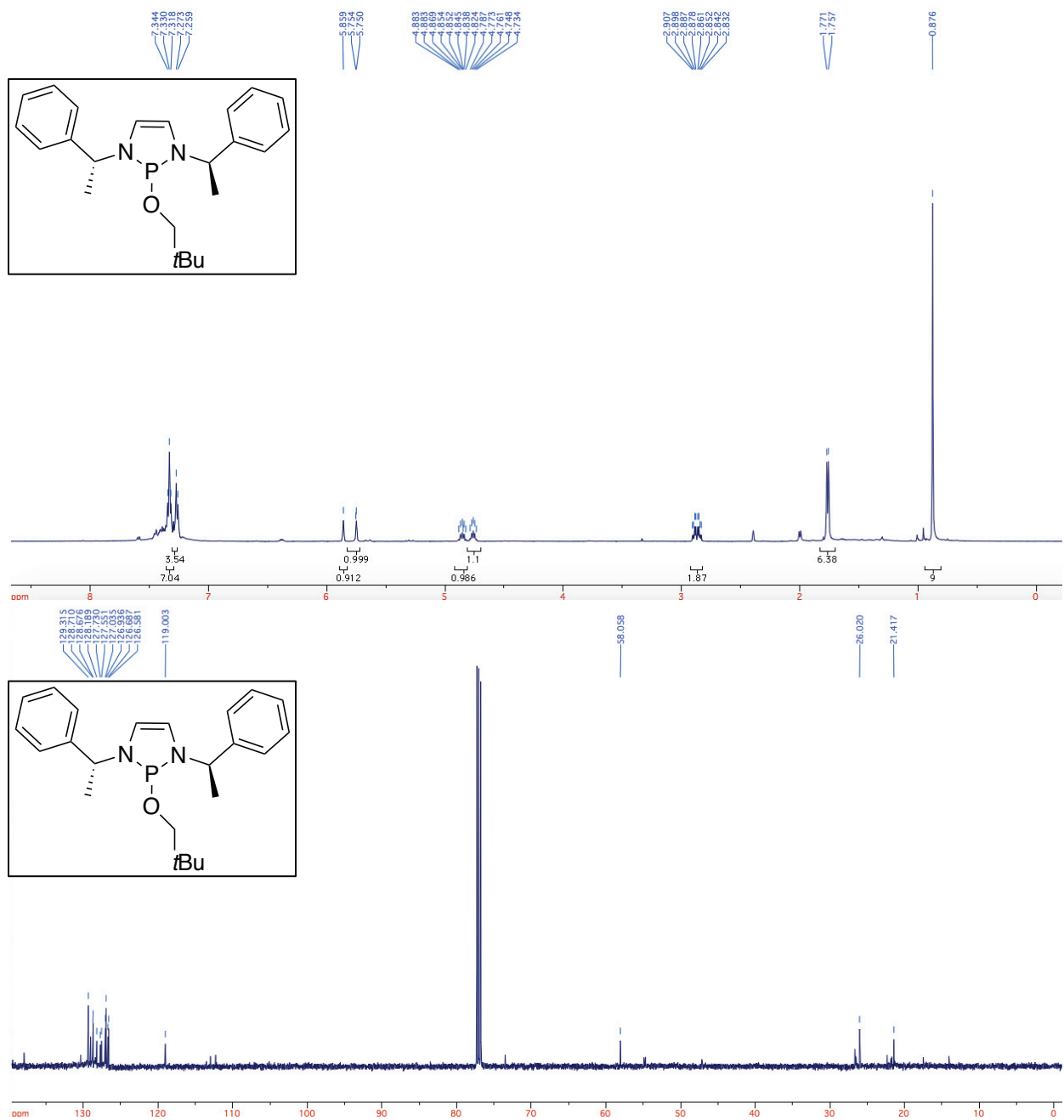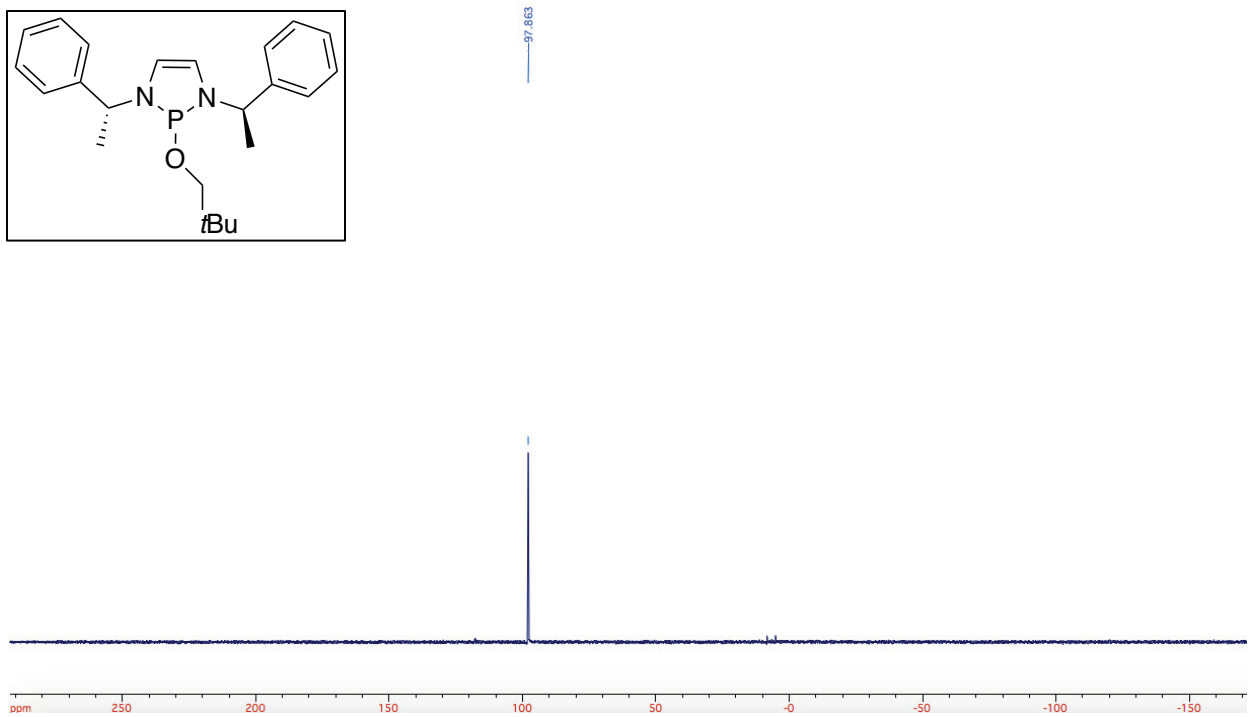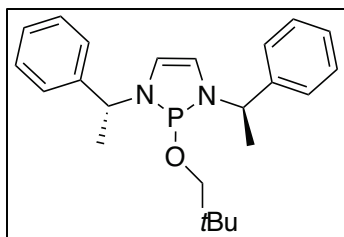
2-Neopentoxy-1,3-*bis*{(*R*)1-phenylethyl}-1,3,2-diazaphosphole (3.30):

97.863

2-Neopentoxy-1,3-*bis*{(R)1-(*p*-methoxyphenyl)ethyl}-1,3,2-diazaphosphole (3.31):

2-Neopentoxy-1,3-*bis*{(*R*)1-(naphthalen-1-yl)ethyl}-1,3,2-diazaphosphole (3.32):
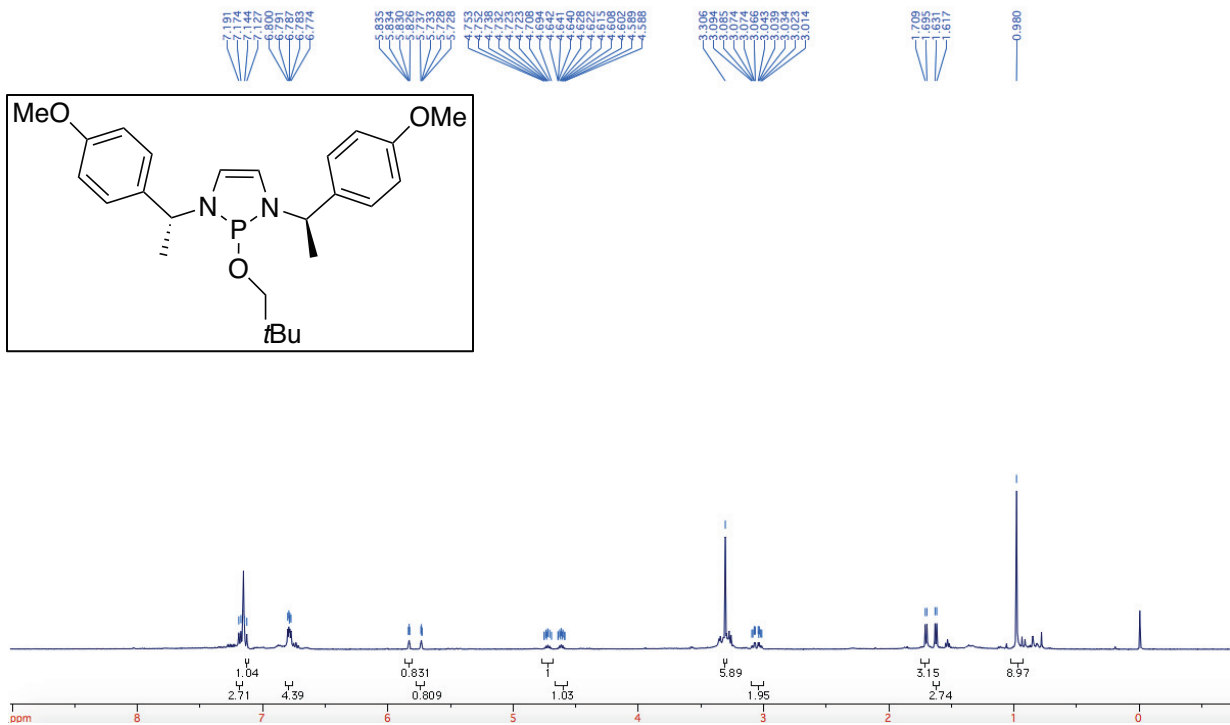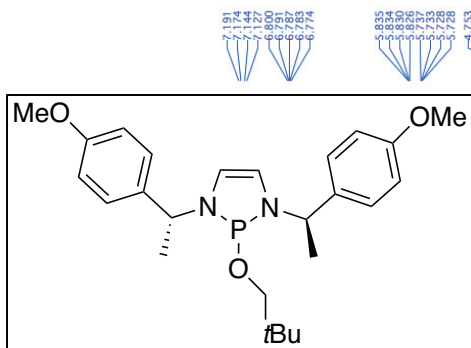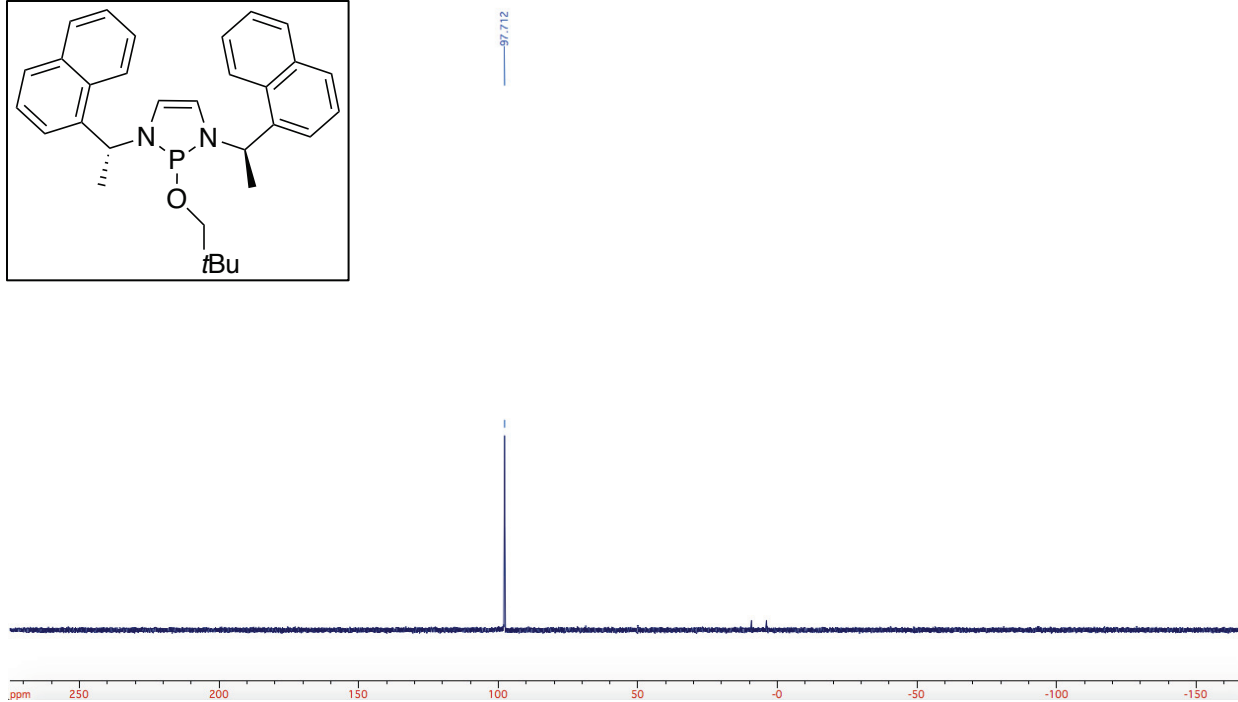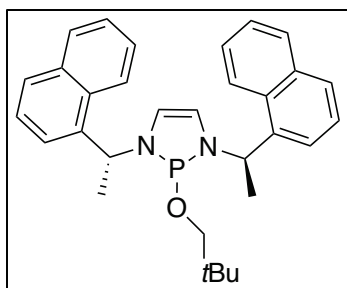
2-Hydro-1,3-*bis*{(*R*)1-(naphthalen-1-yl)ethyl}-1,3,2-diazaphosphole (3.32'):

5 minutes:

272

2 hours:

5 hours:

2-Neopentoxy-1,3-*bis*{(*S*)1-(naphthalen-1-yl)-(2,2-dimethl)propyl}-1,3,2-
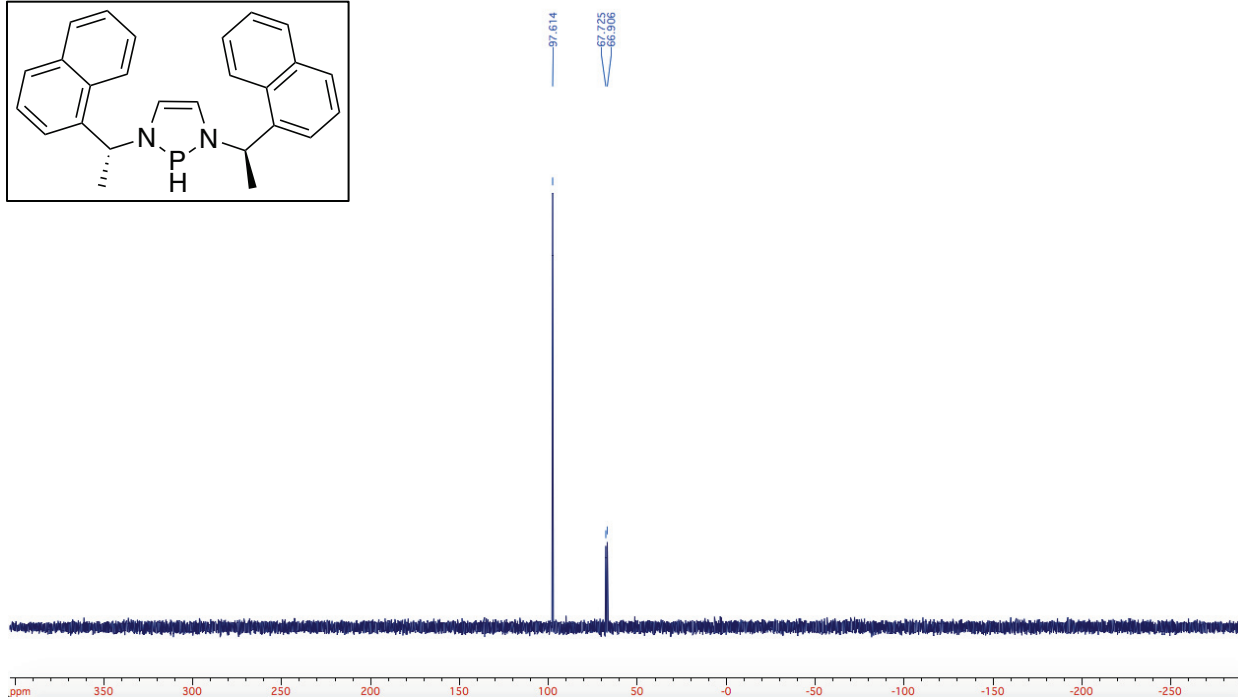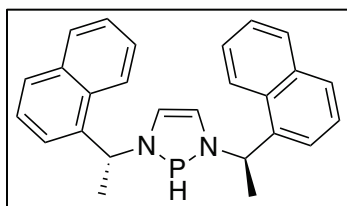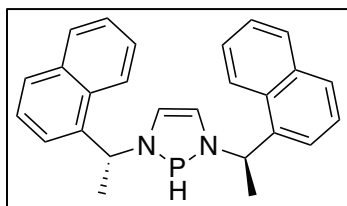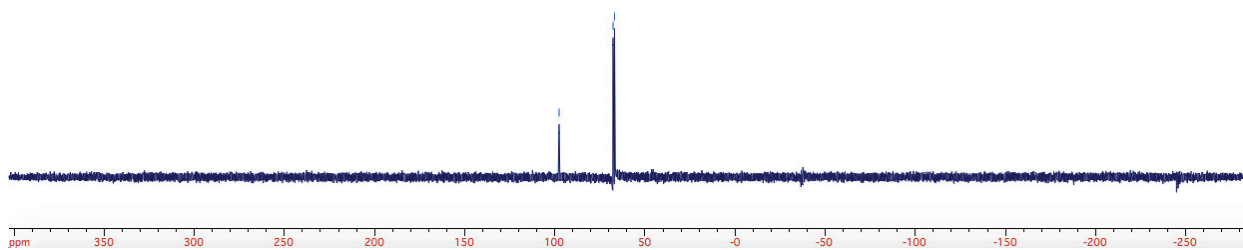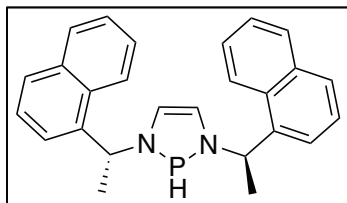
diazaphosphole (3.33):
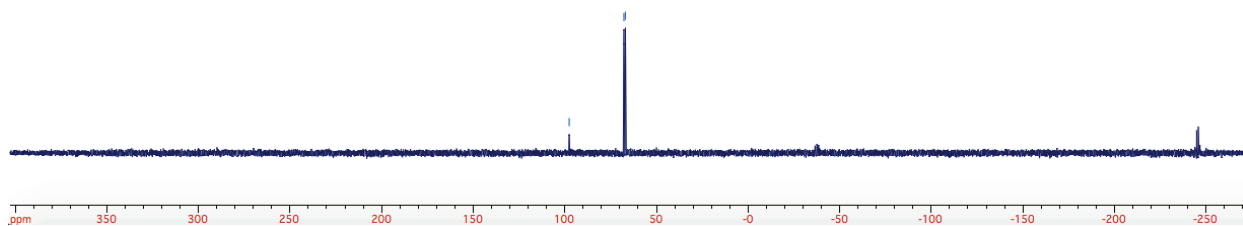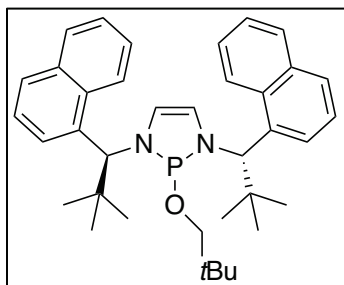
103.236
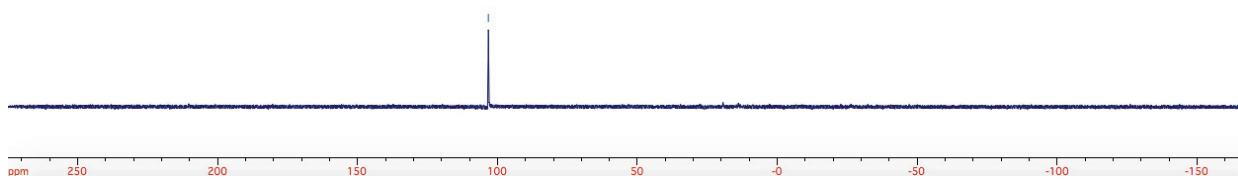
2-Neopentoxy-1,3-*bis*{(*R*)1-(naphthalen-2-yl)ethyl}-1,3,2-diazaphosphole (3.34):
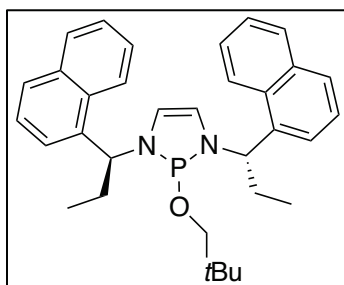
97.877
97.850
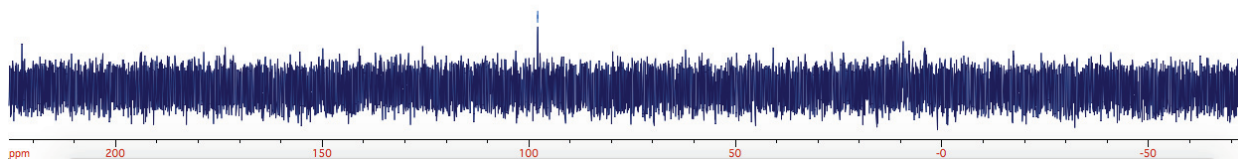
2,3-Butanedione-(2,6-diisopropylphenyl)imine (3.39):
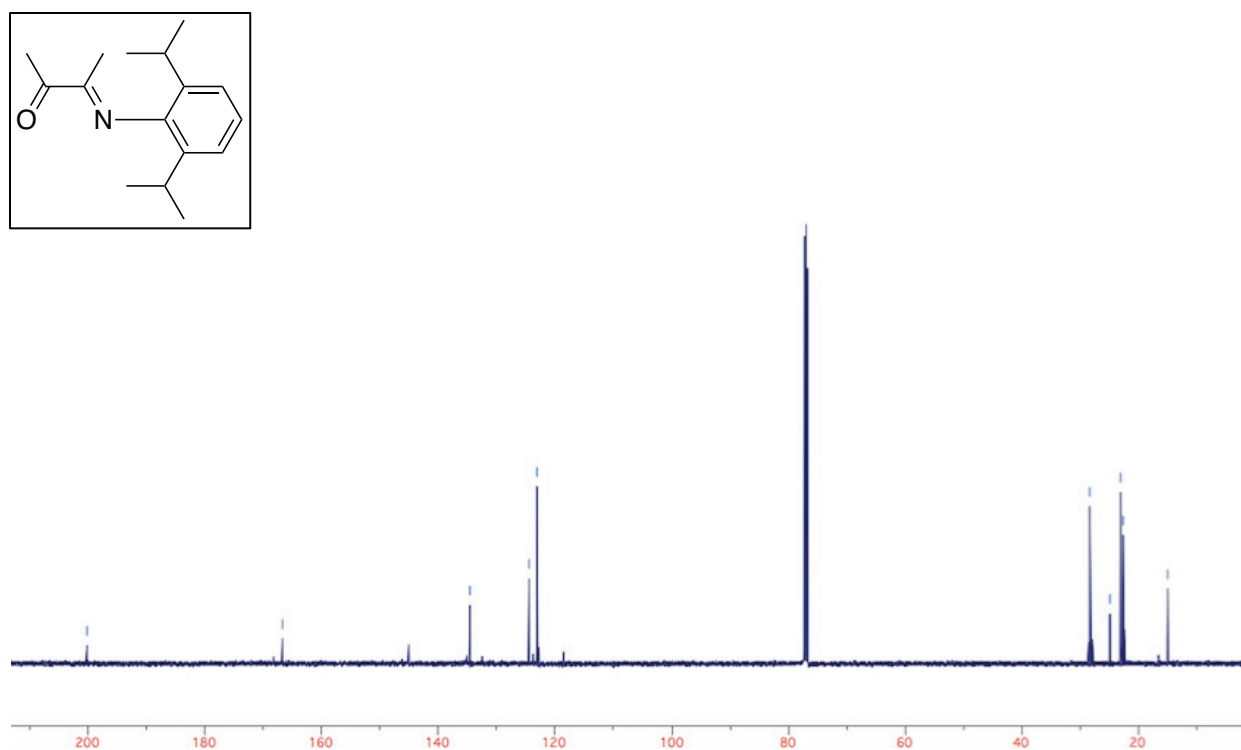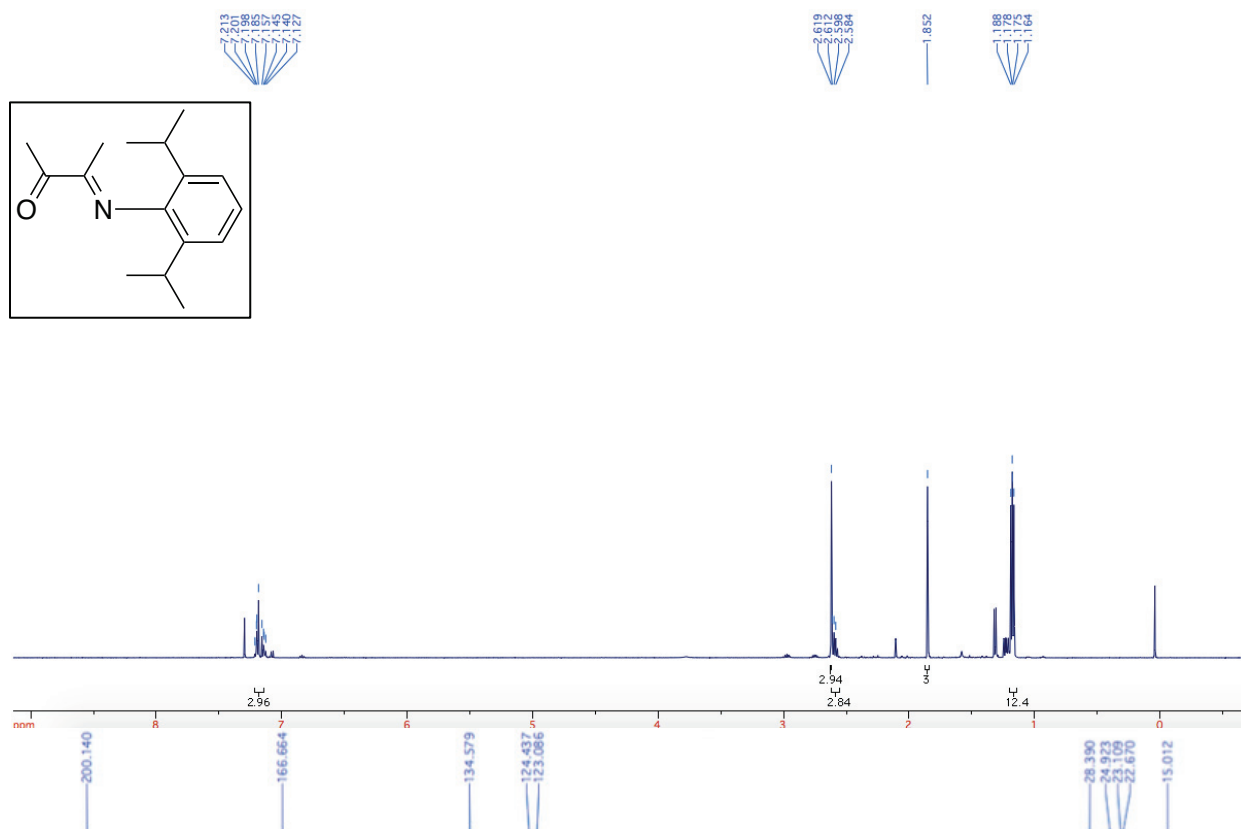
_N_-(2,6-Diisopropylphenyl)-_N_'-((_R_)-1-naphthyethyl)ethane)-1,2-diimine (3.40):
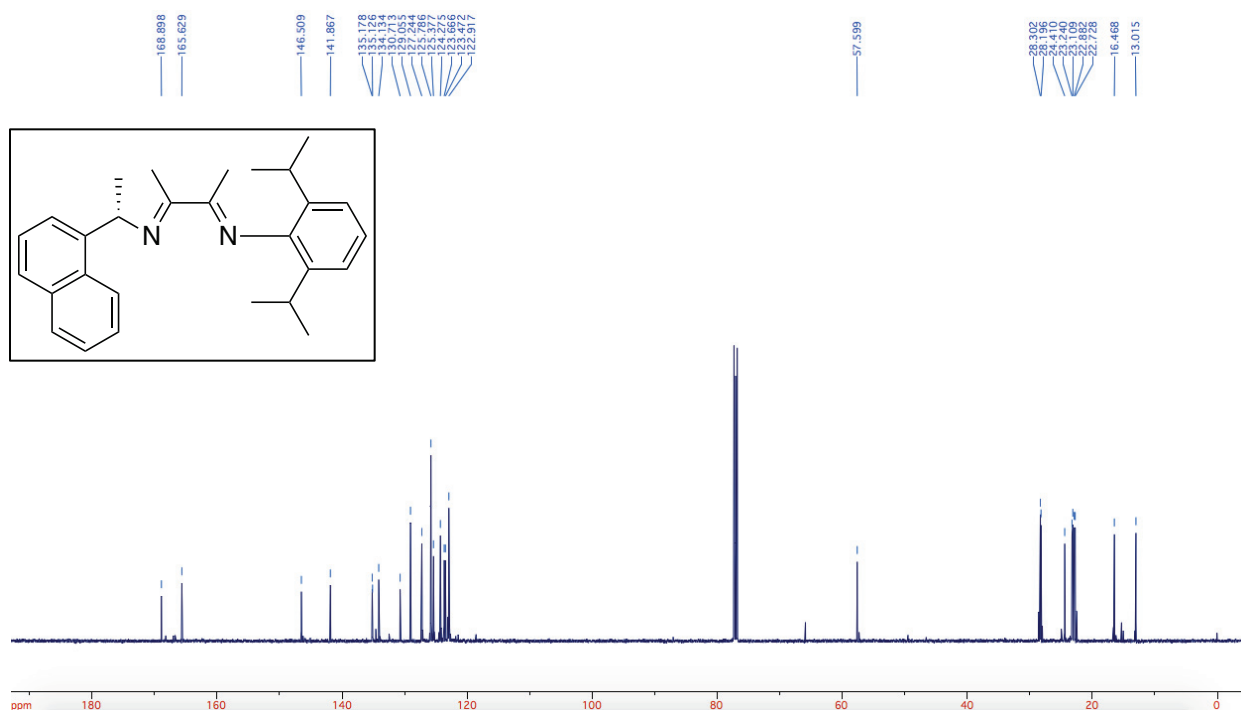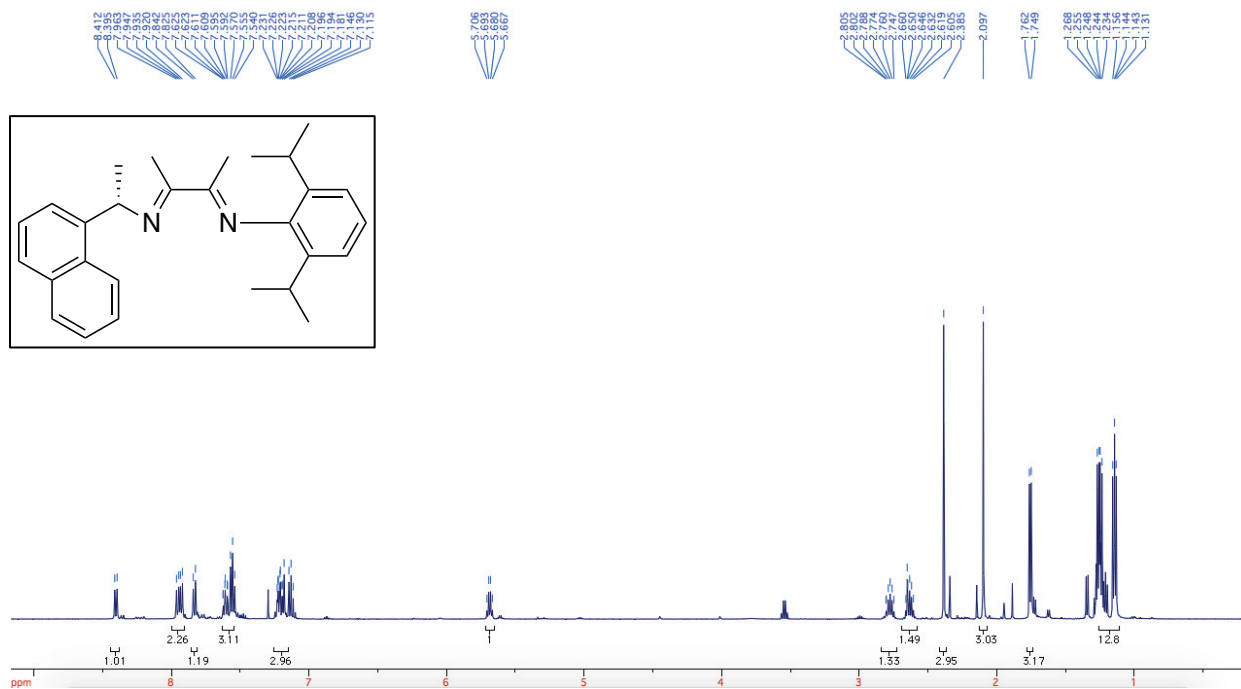
***N*-(1-((*R*)1-Naphthalenyl)ethyl)-benzamide (3.42):**
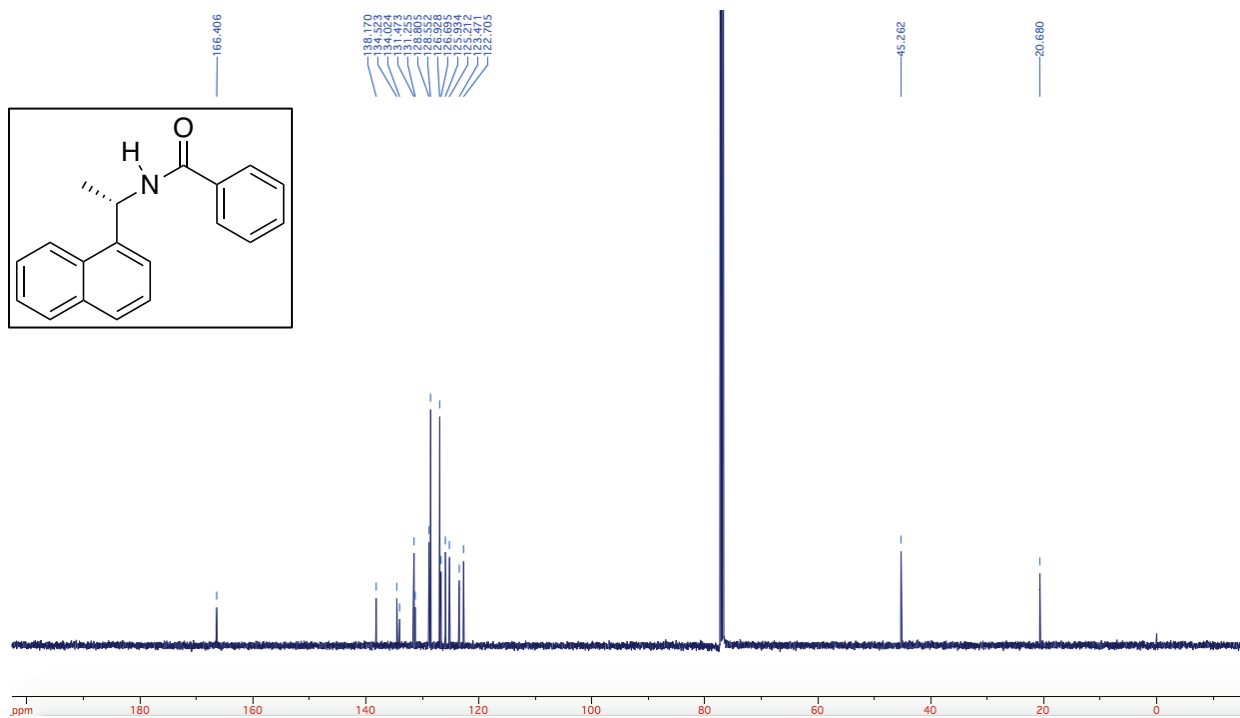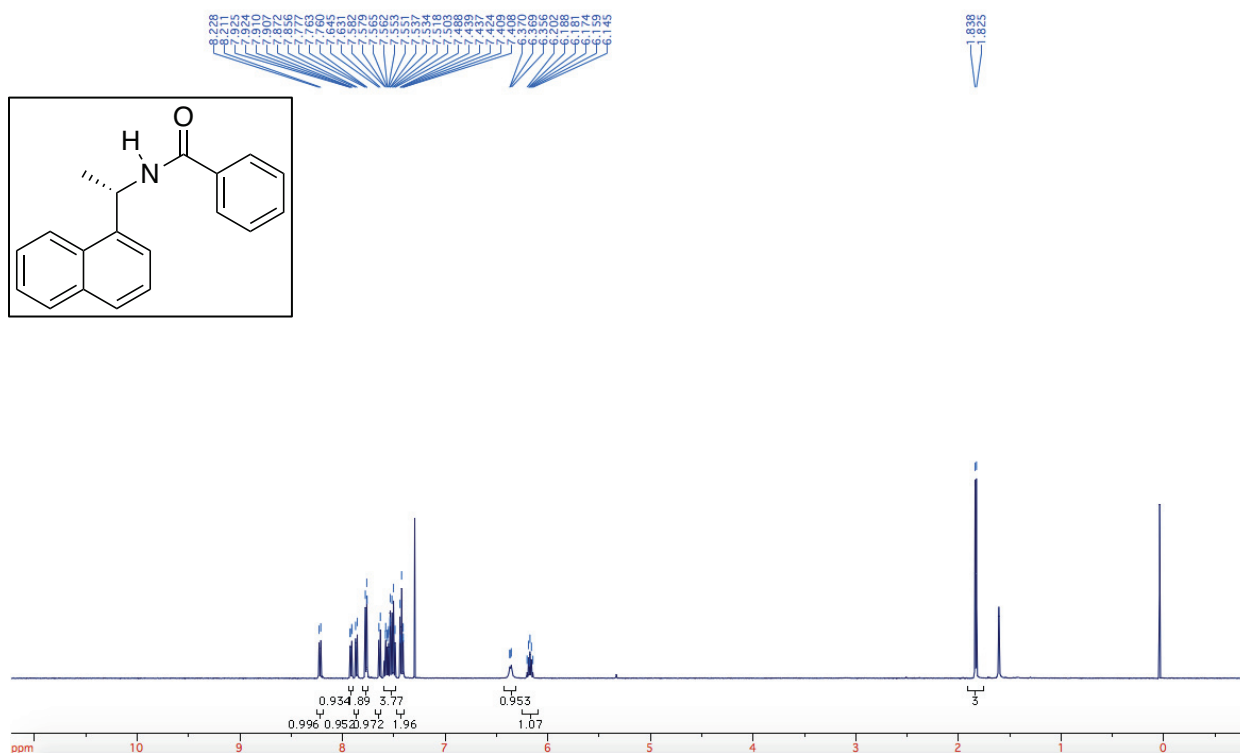
_N_-((_R_)-1-Naphthethyl)phenyl-imidoyl chloride (3.43):
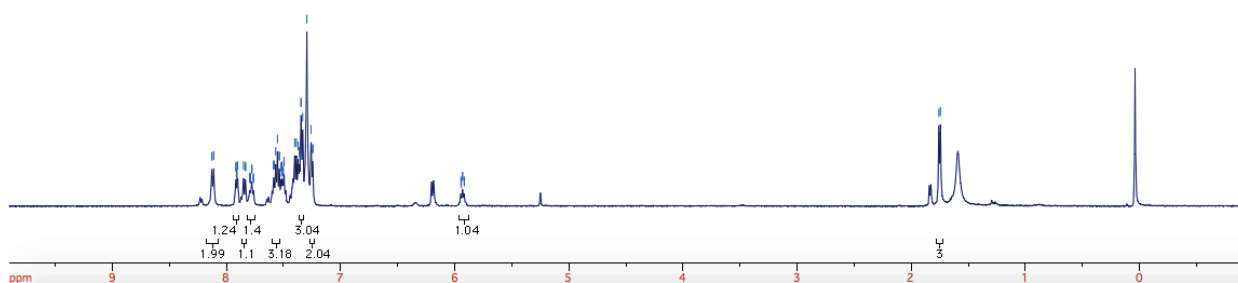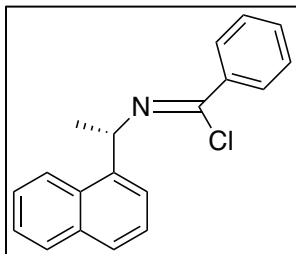
_N_-((_R_)-1-Naphthethyl)phenyl-imidoyl diphenylmethanamine (3.44):
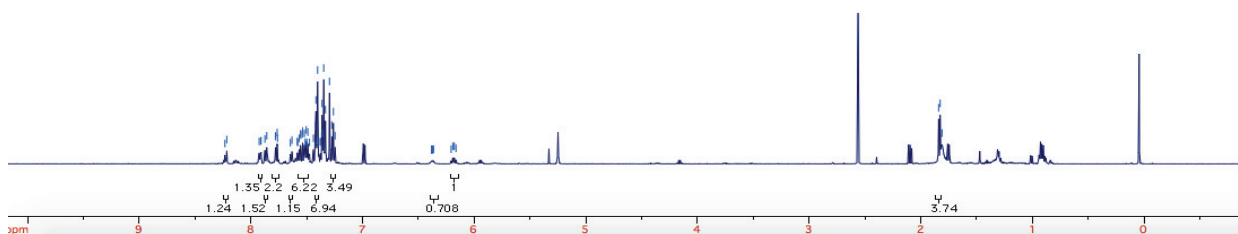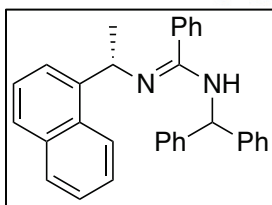
(*S*)-*N*-(Prop-2-ynyl)-2,3-dihydro-1*H*-inden-1-amine (3.46):
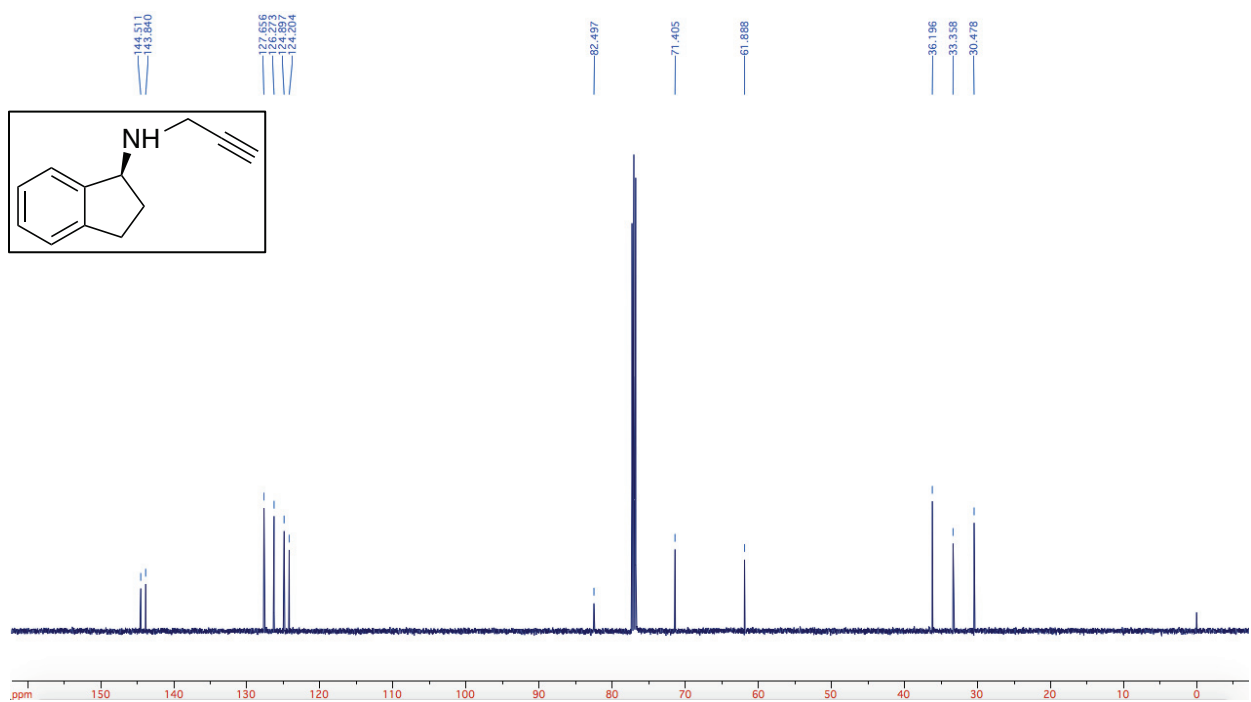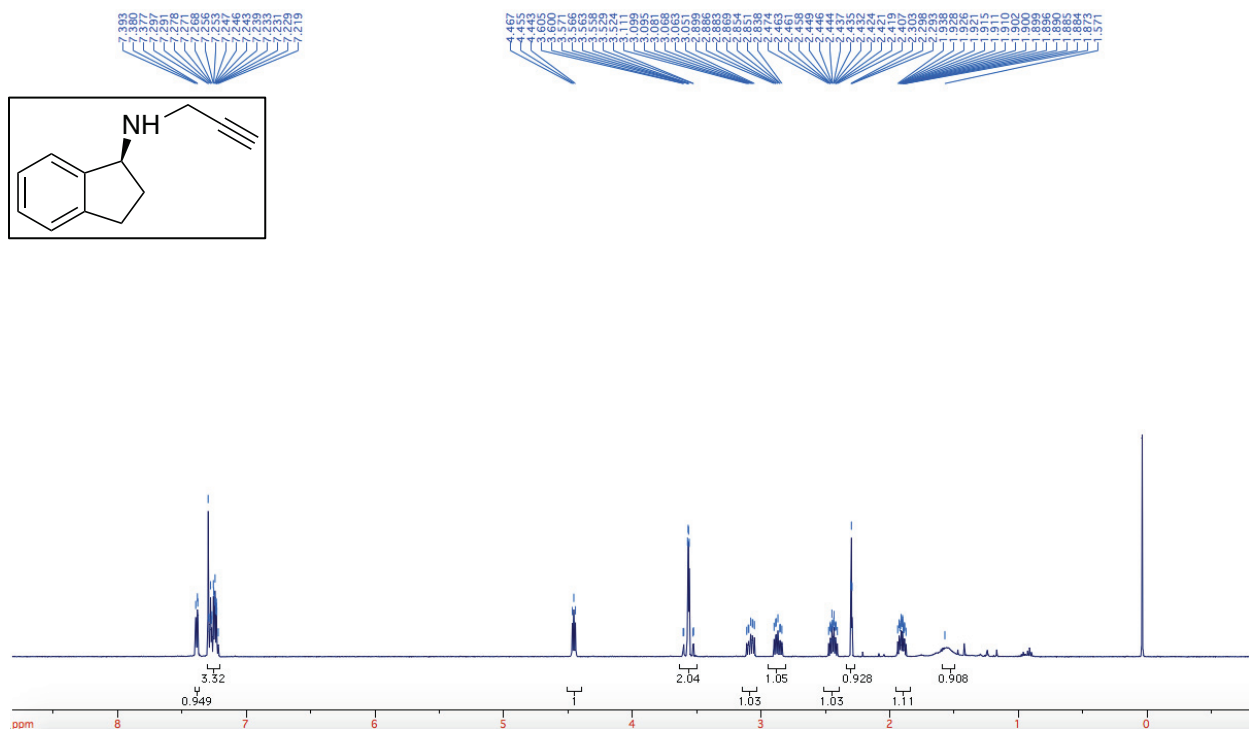
(*S*)-*N*-Benzyl-2,3-dihydro-1*H*-inden-1-amine (3.47):
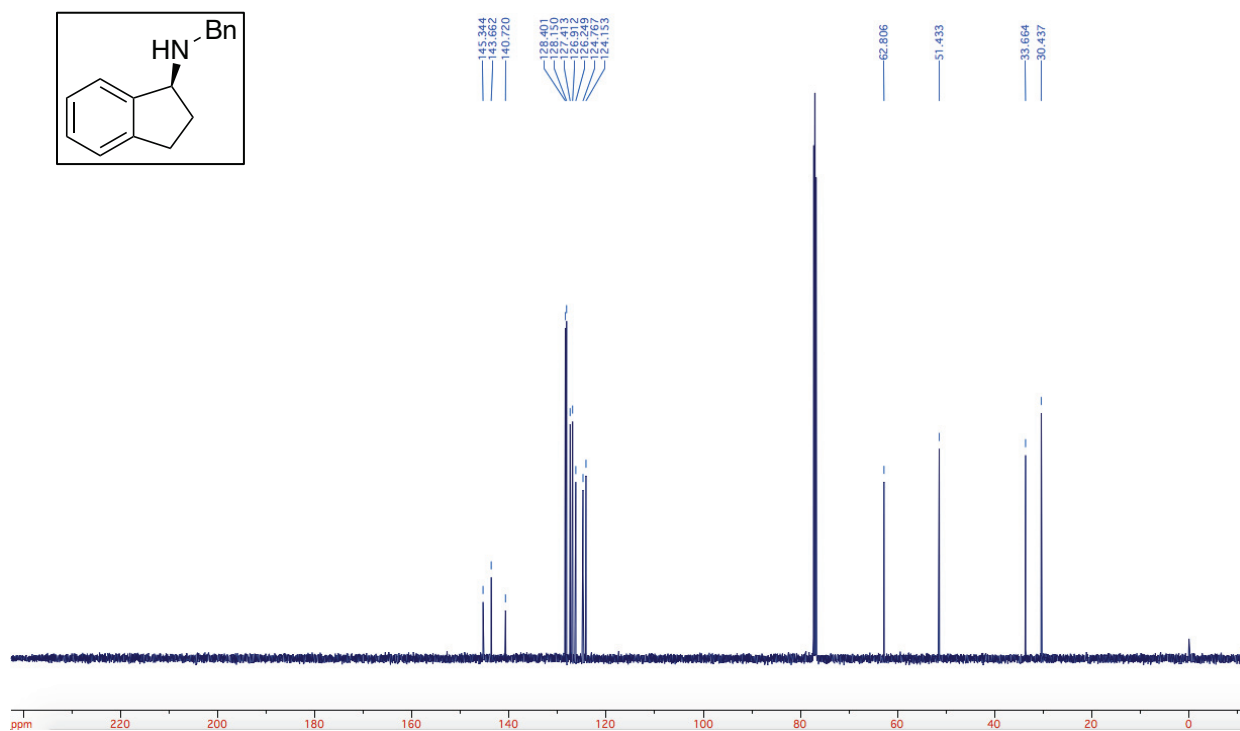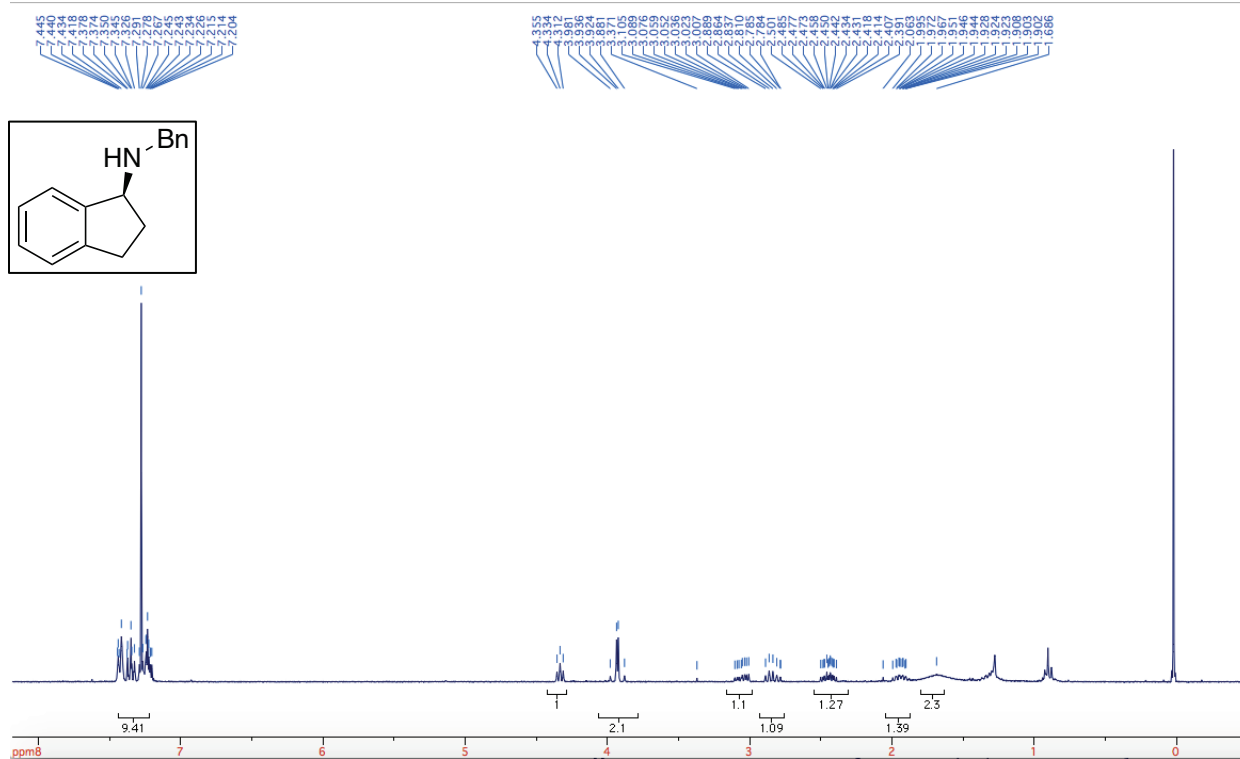
(*S*)-*N*-Benzyl-*N'*-(*tert*-butyloxycarbonyl)-2,3-dihydro-1*H*-inden-1-amine (3.47):
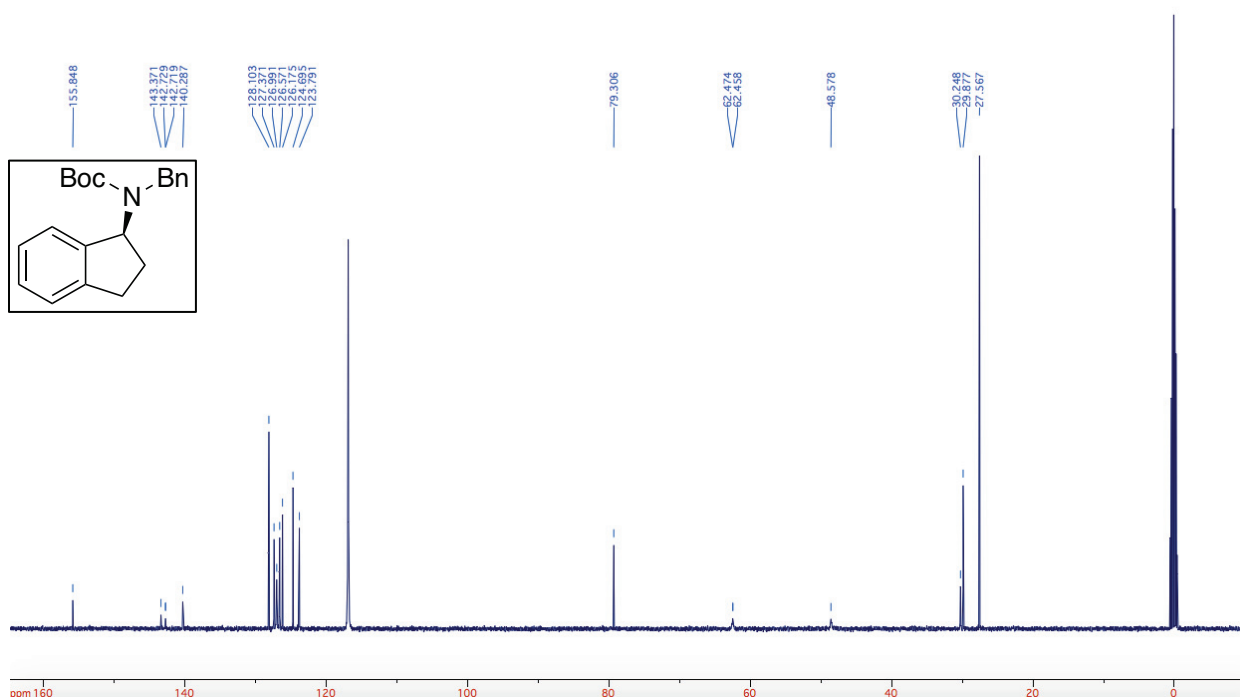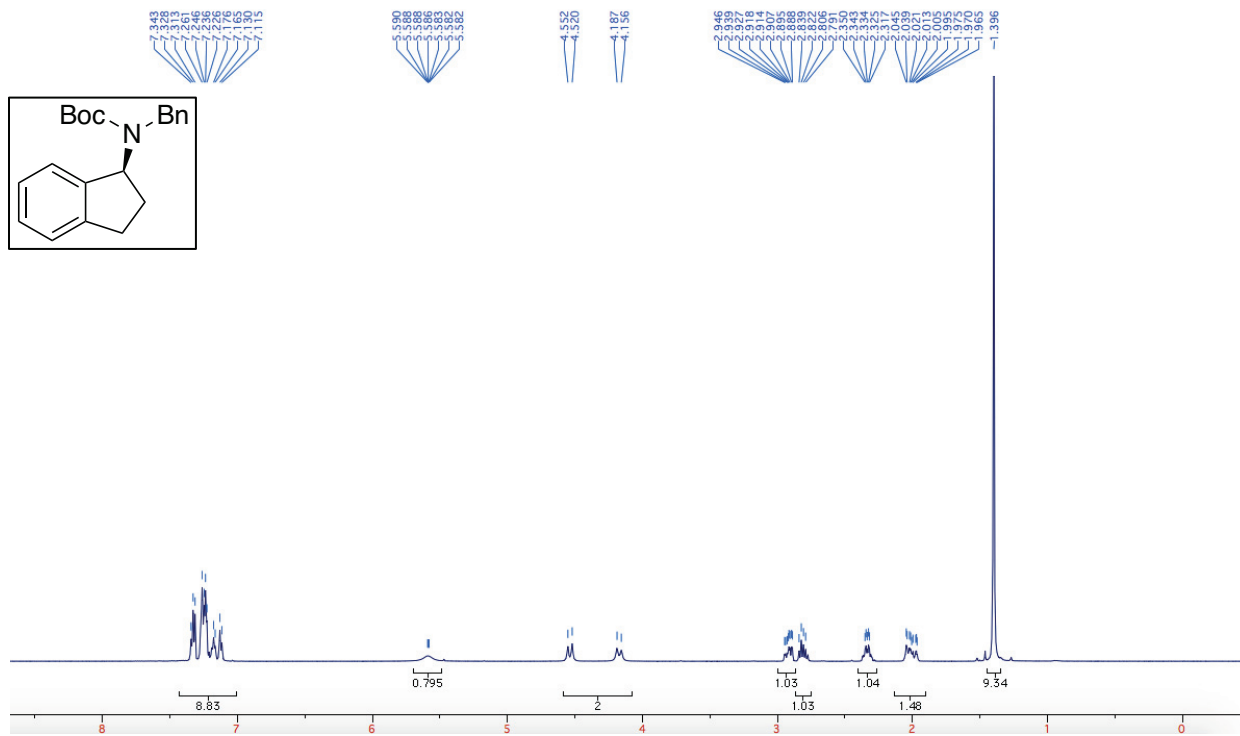
(*S*)-*N*-(4-Methoxybenzyl)-1-phenylethanamine (3.48):
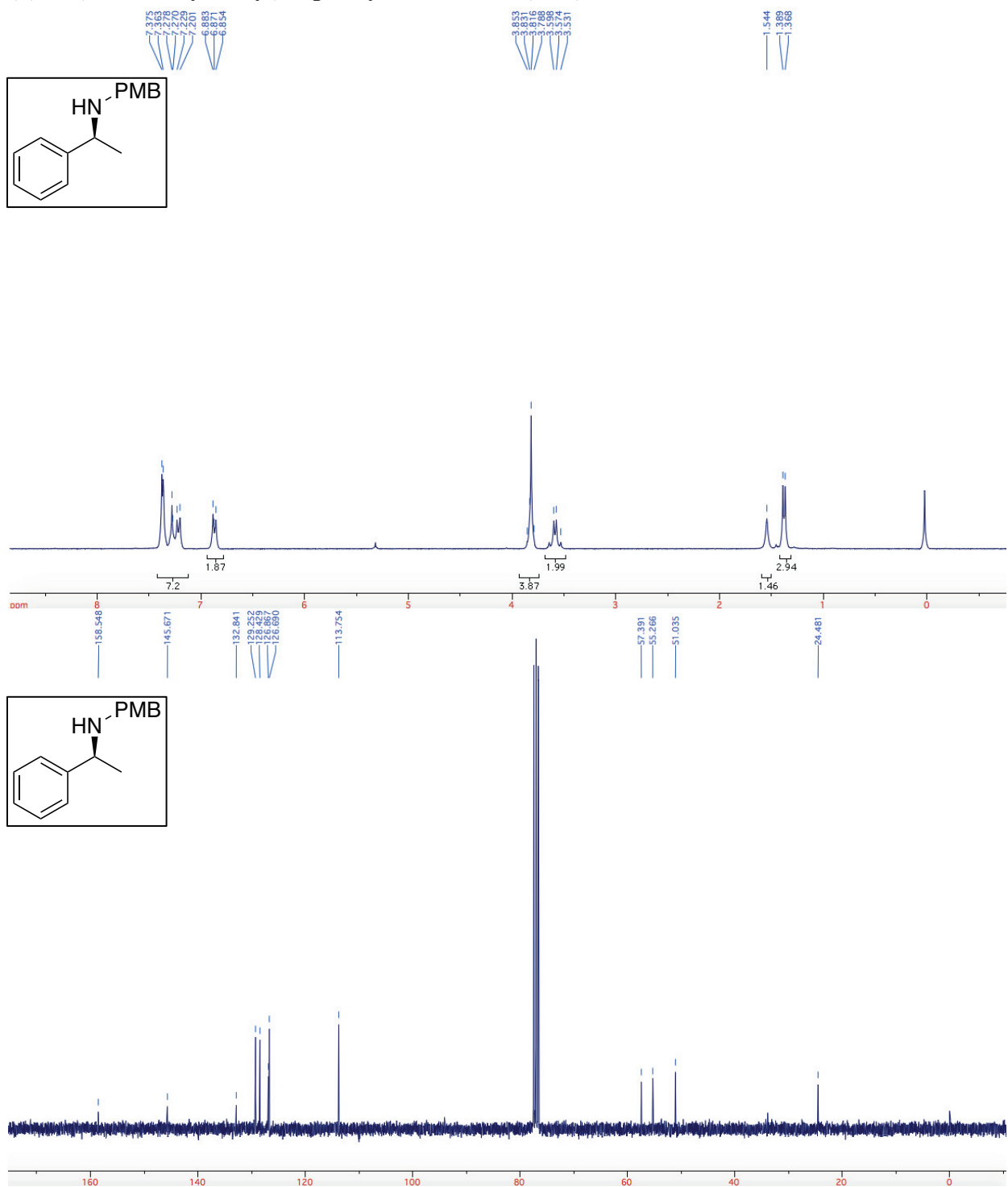
(*S*)-*N*-Benzyl-1-(4'-cyanophenyl)ethylamine (3.49):
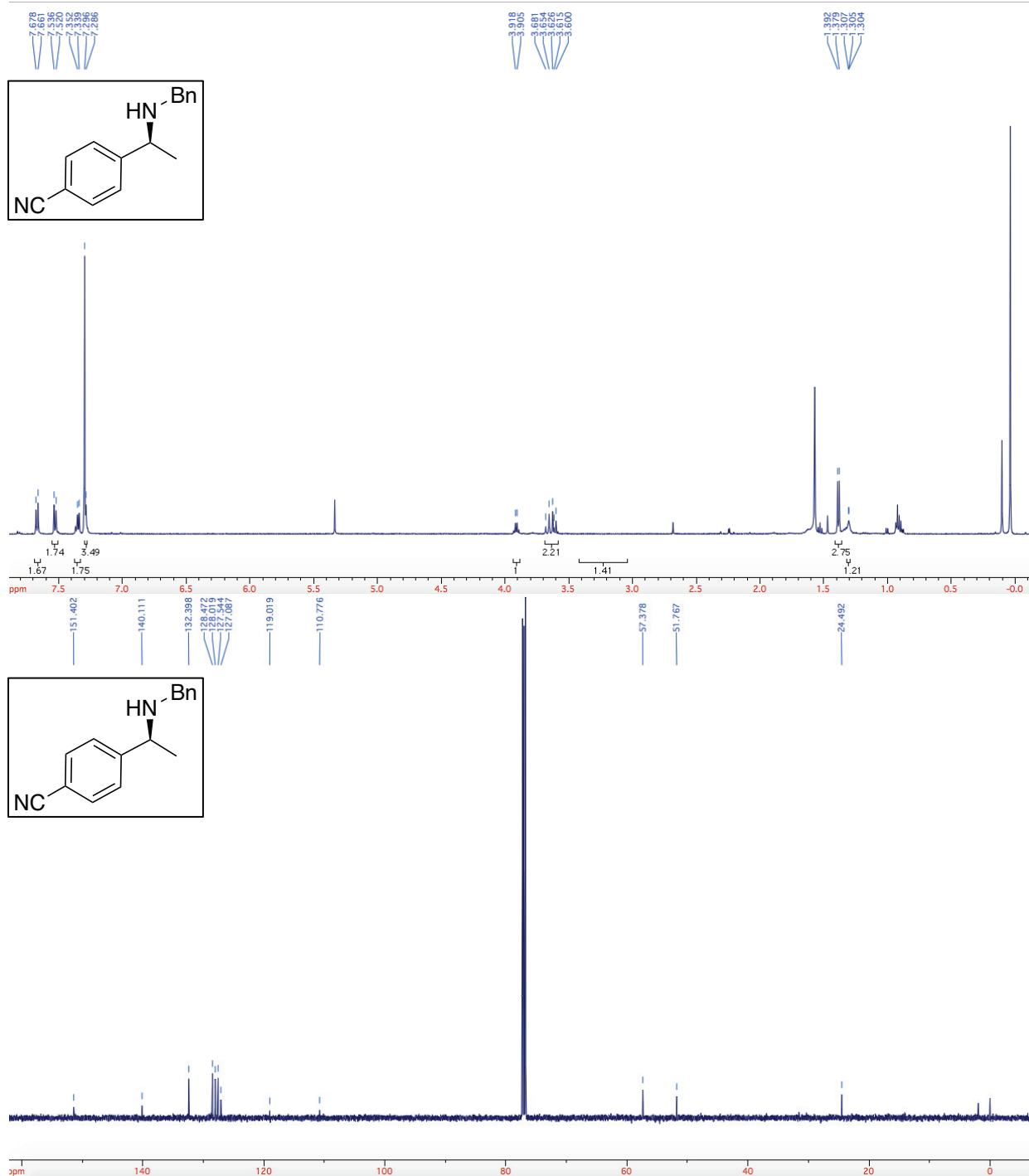
(*S*)- *N*-Benzyl-1-(4'-methoxy)phenylethylamine (3.50):
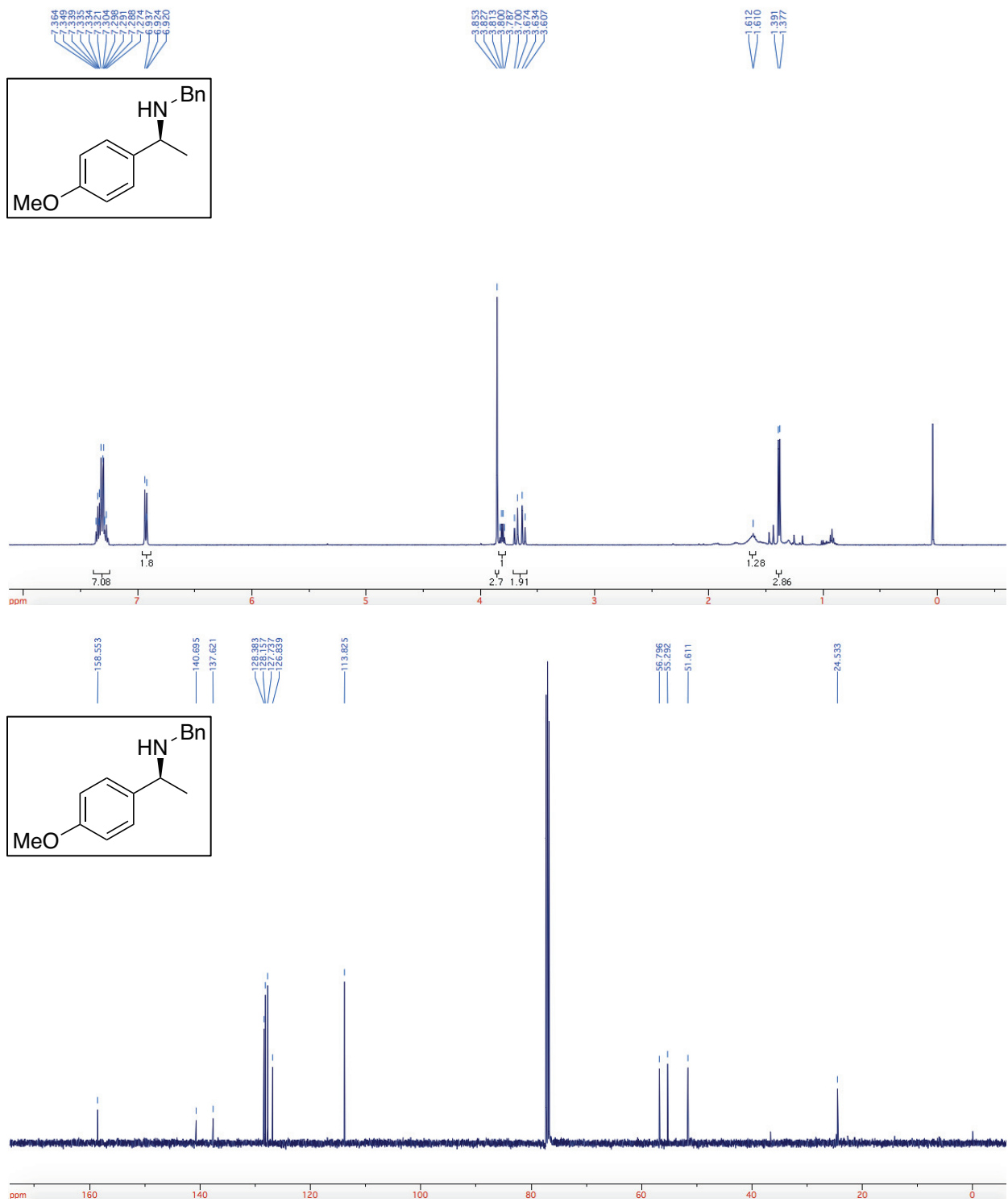
(*S*)-*N*-(4-Methoxybenzyl)-1-4-methoxyphenylethanamine (3.51):
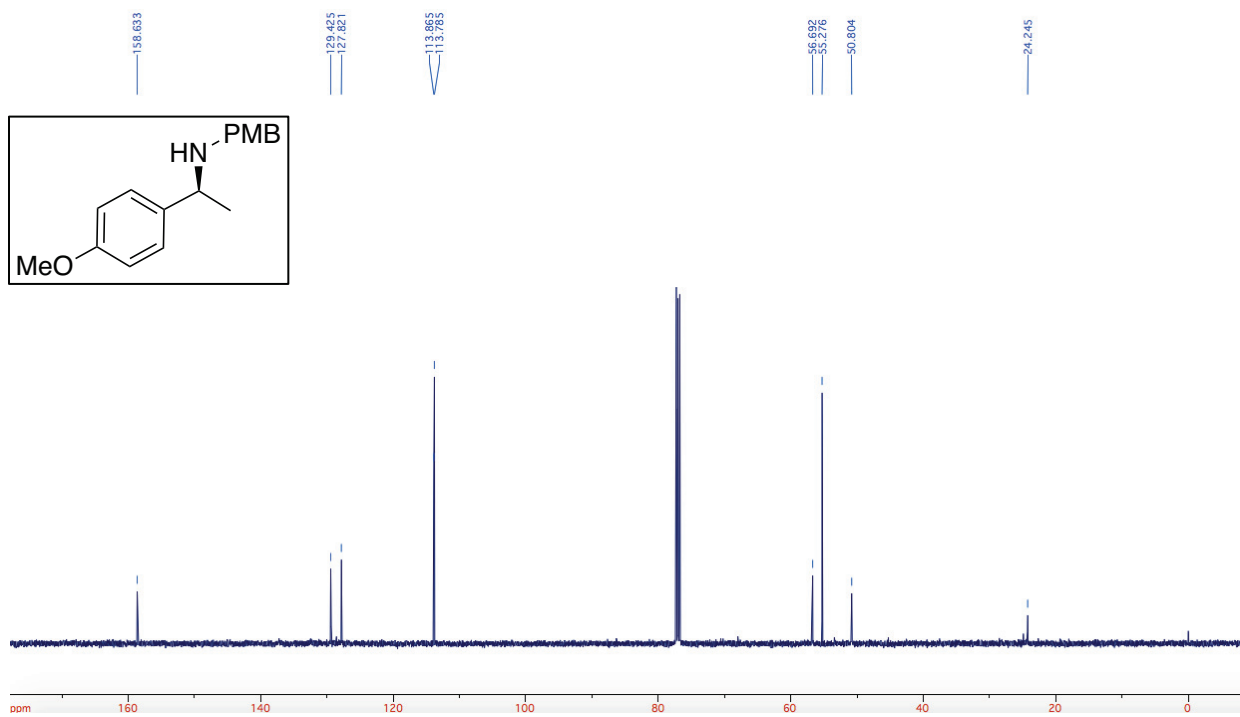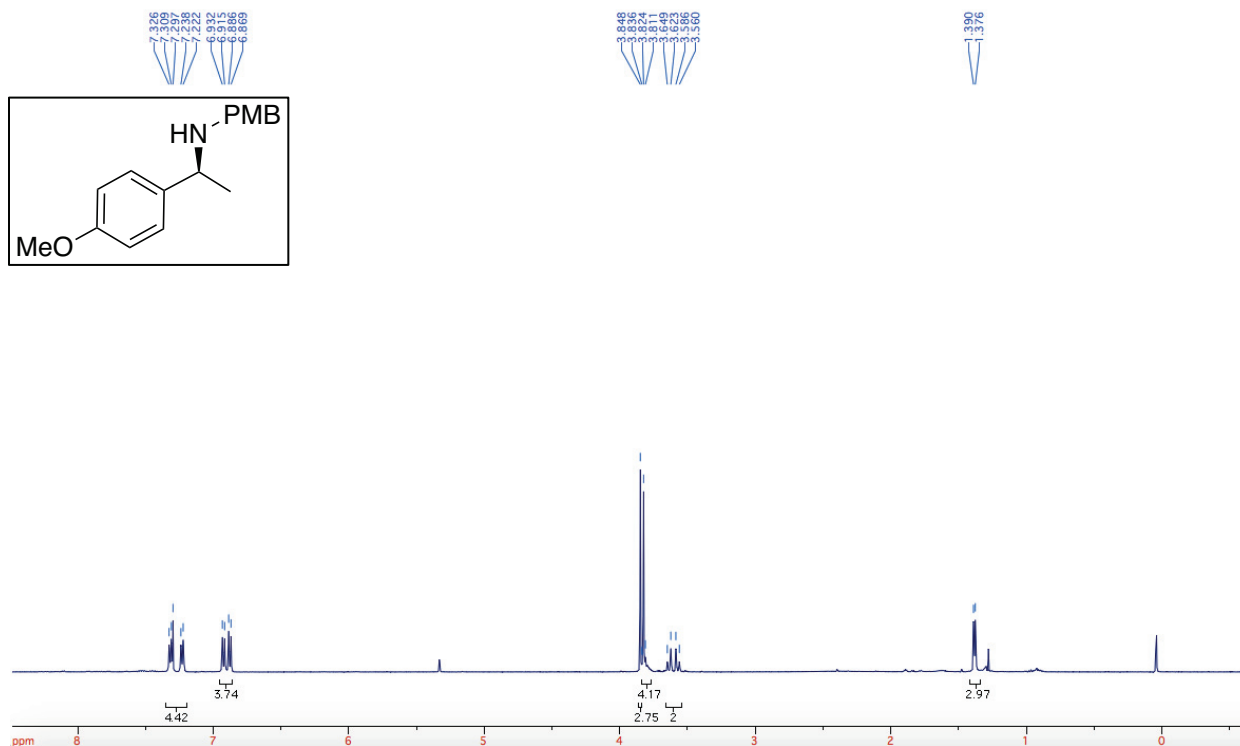
(*S*)-*N*-Benzyl-1-(2-napthyl)ethylamine (3.52):
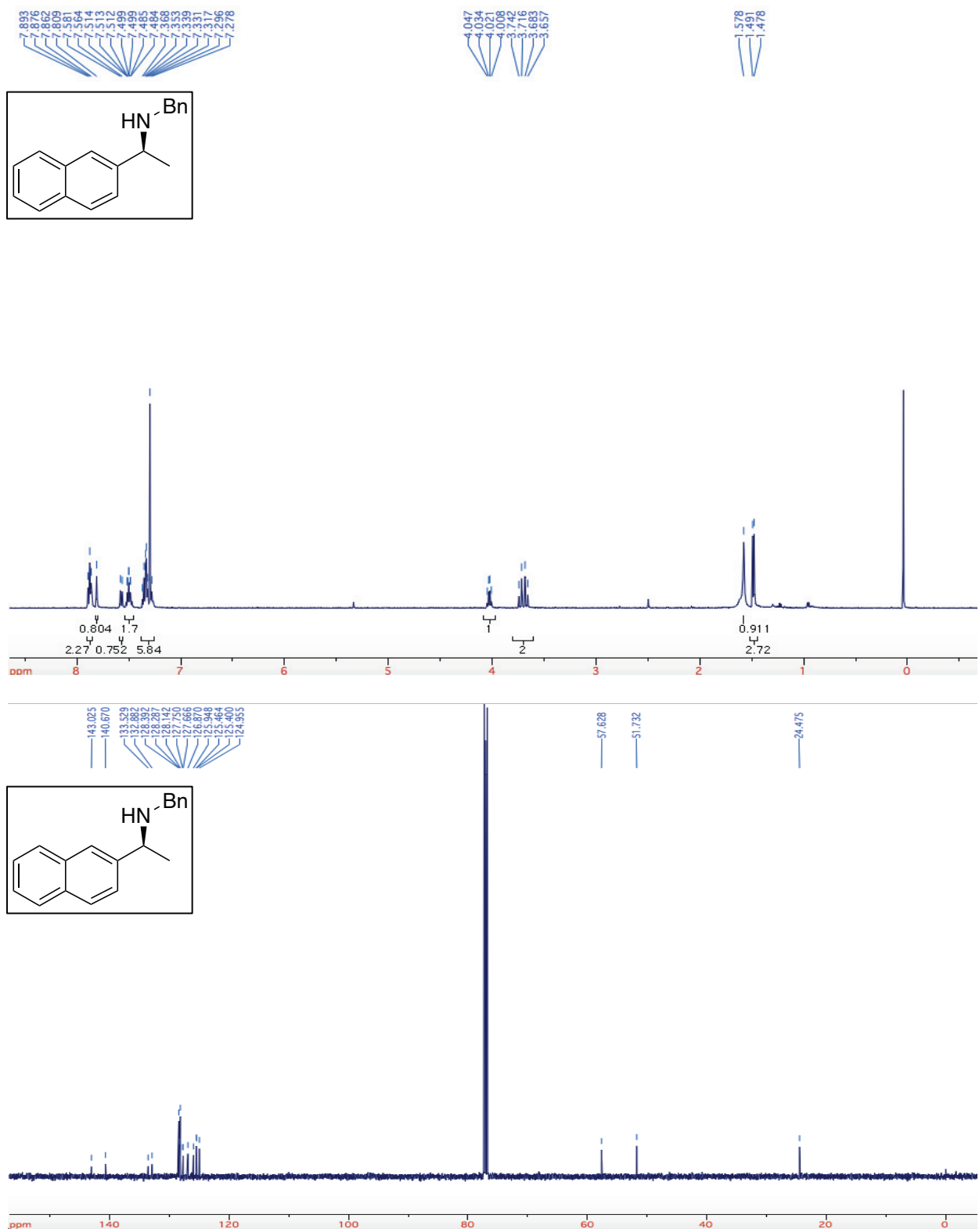
(*S*)-*N*-Benzyl-*N'*(*tert*-butyloxycarbonyl)-1-(2-napthyl)ethylamine (3.52):
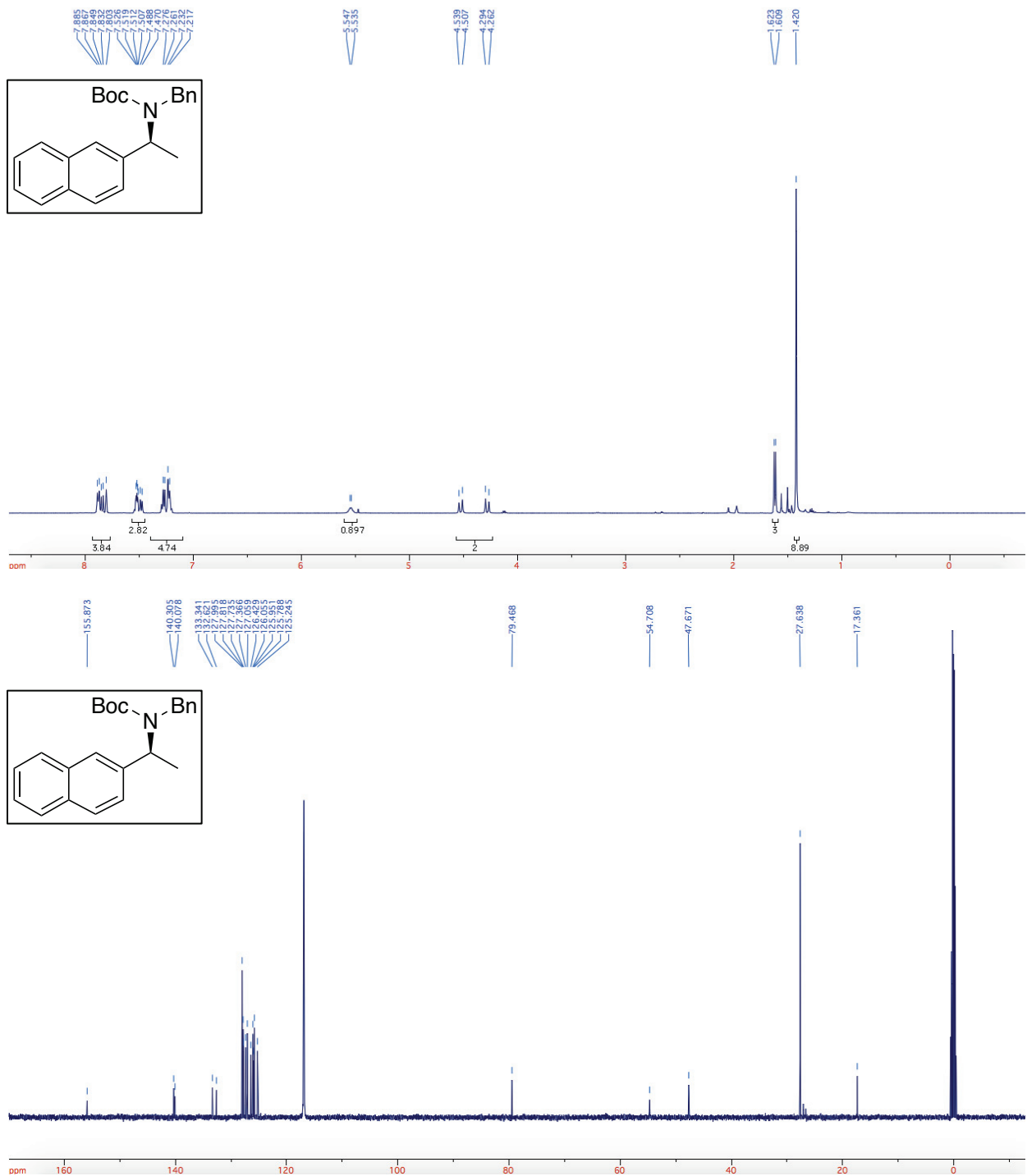
(*S*)-*N*-Benzyl-1-(1-napthyl)ethylamine (3.53):

(*S*)-*N*-(4-Methoxybenxyl)-1-(2'-chlorophenyl)ethylamine (3.54):

290
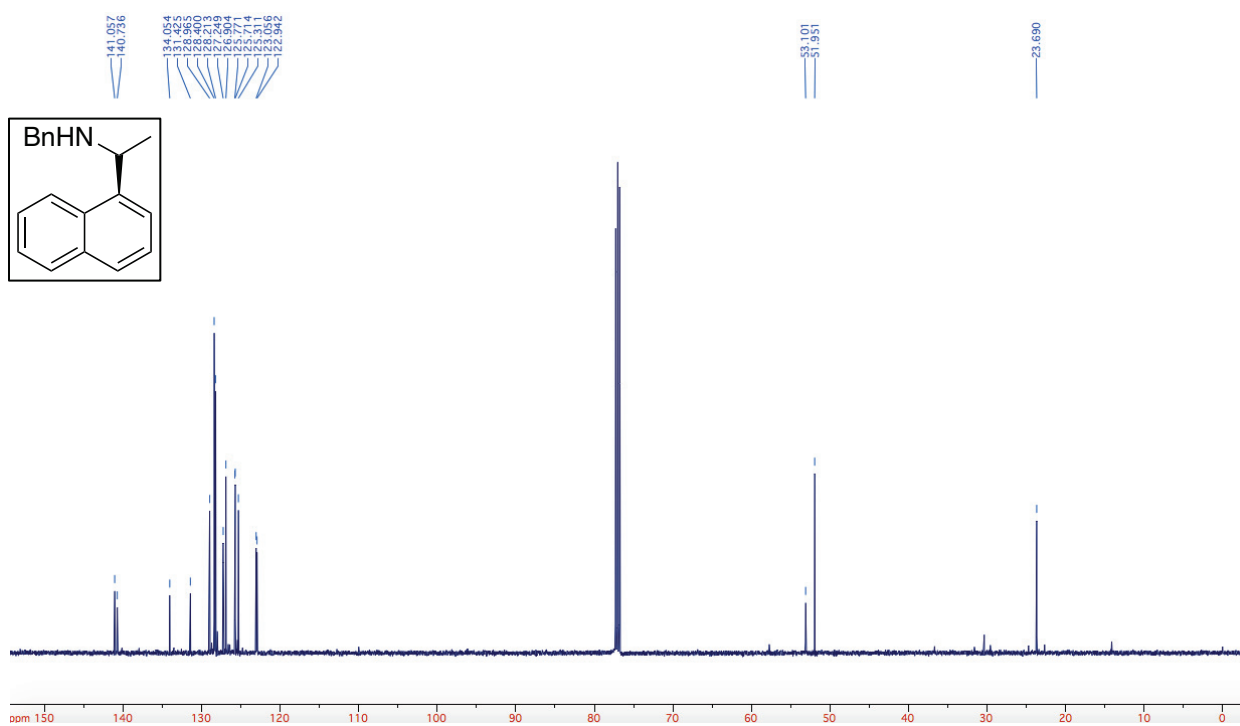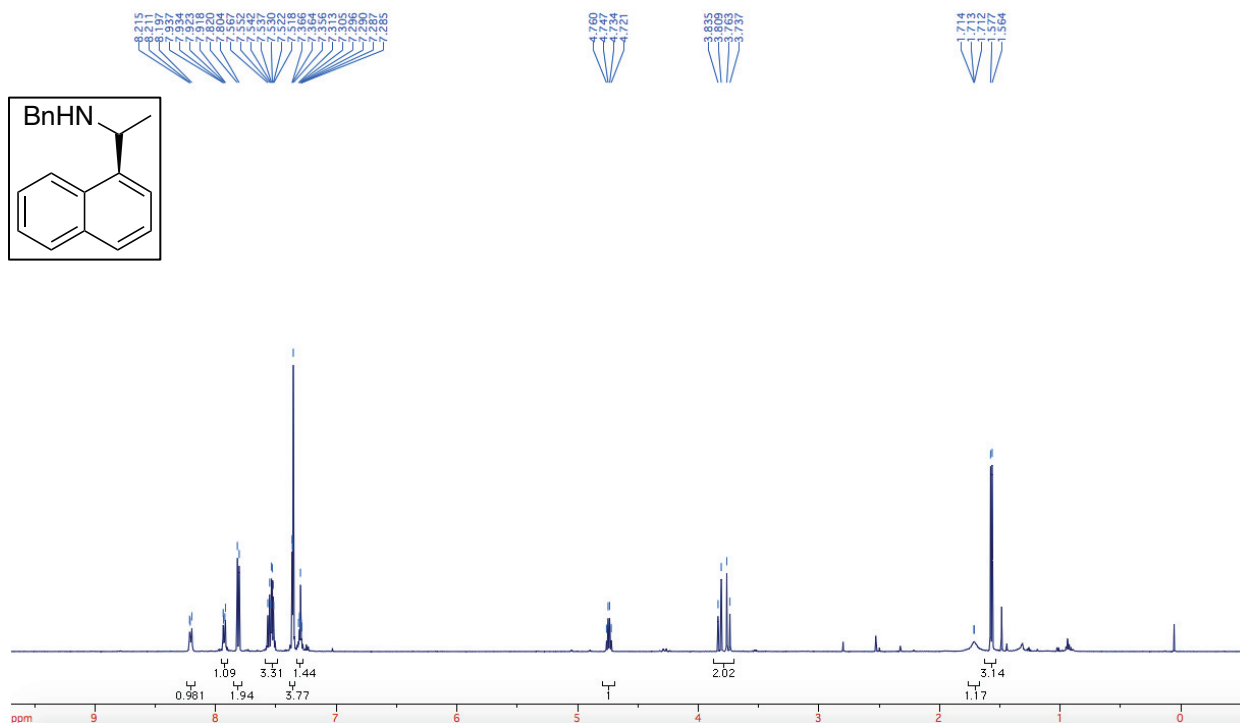
(*S*)-*N*-(4-Methoxybenxyl)-*N*'(*tert*-butyloxycarbonyl) -1-(2'-chlorophenyl)ethylamine (3.54):
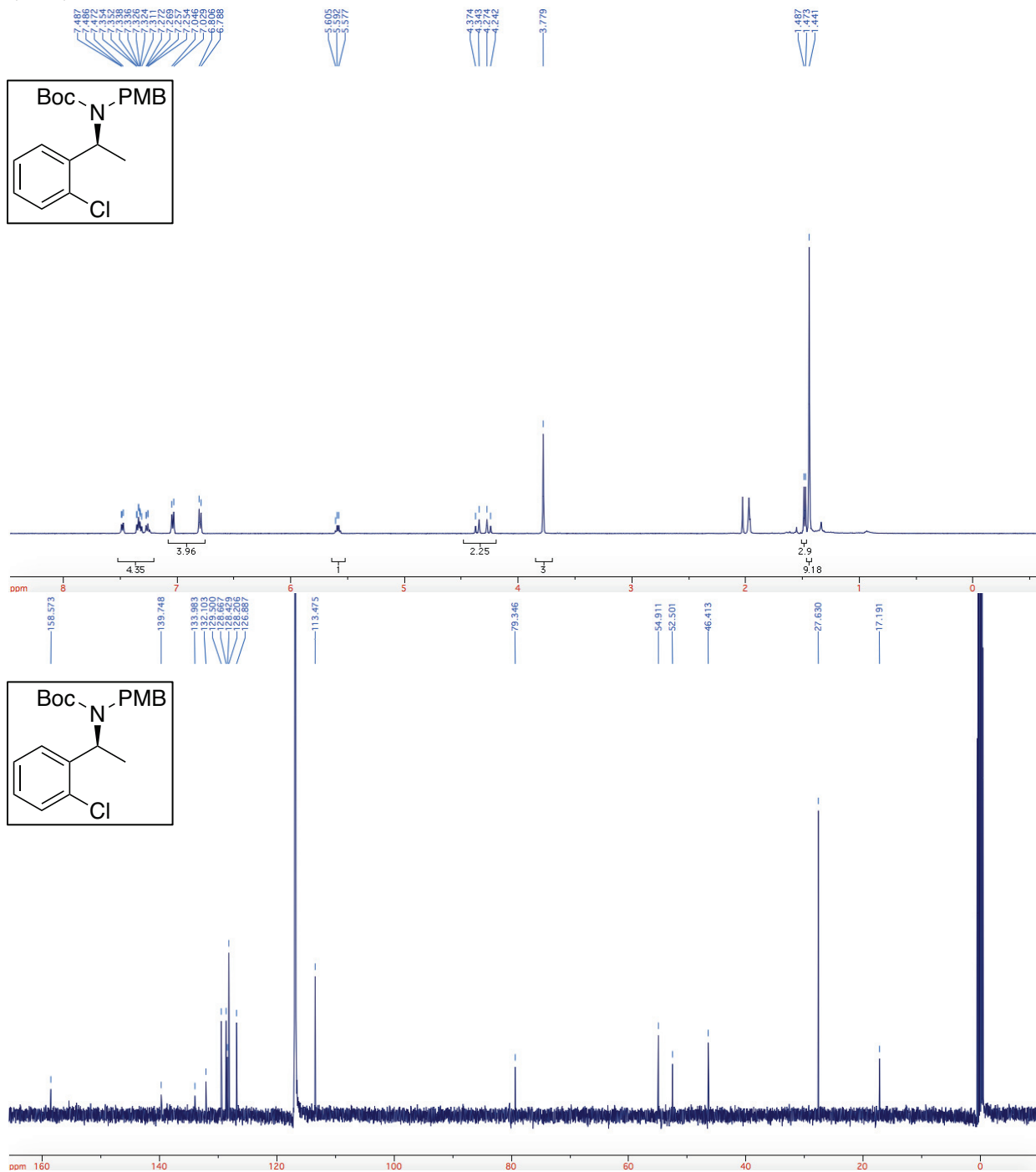
(*S*)-*N*-(4'-Methoxybenzyl)-1-propargylphenylethanamine (3.55):
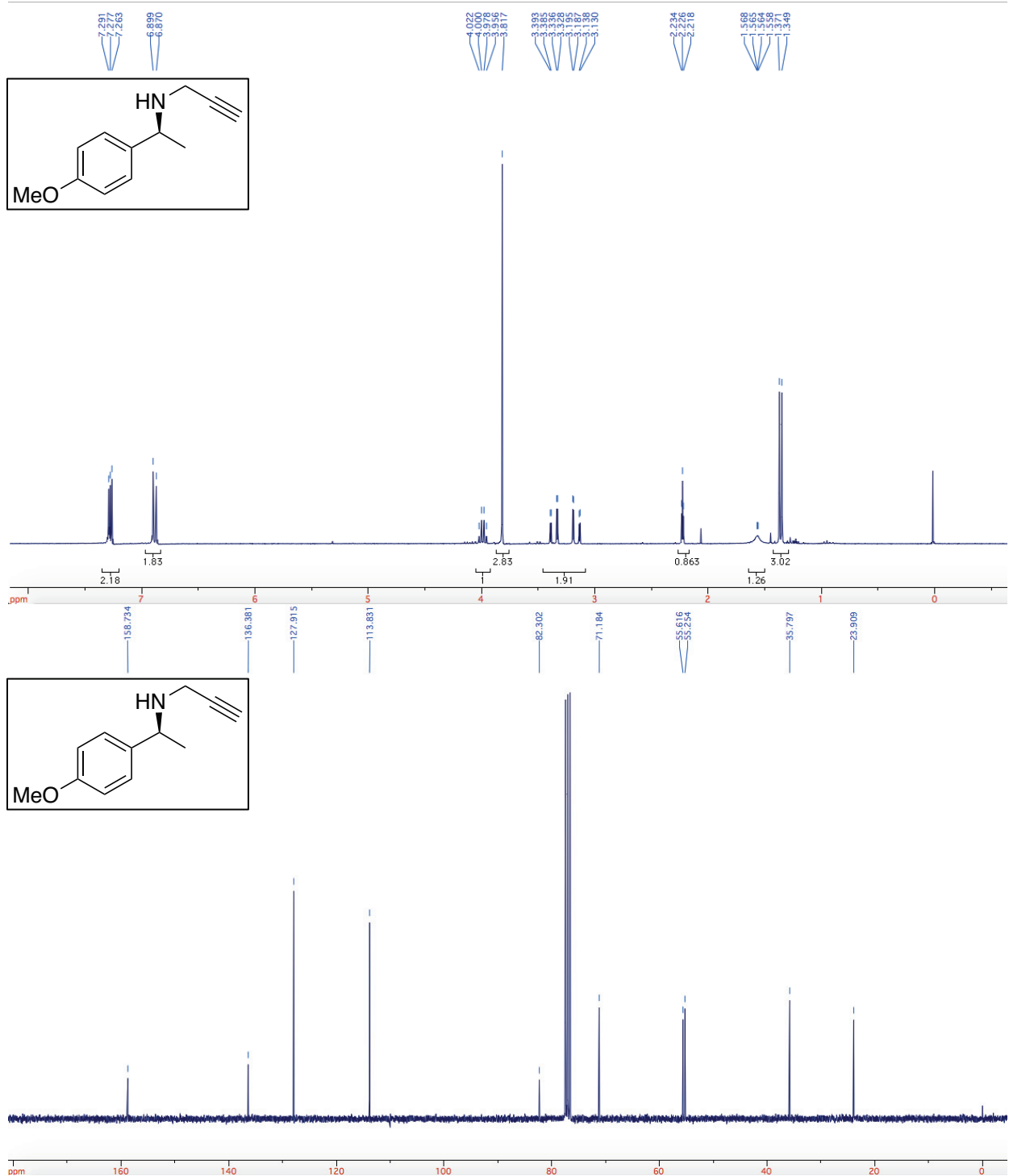
(*S*)-*N*-Propargyl-1-(4'-cyanophenyl)ethylamine (3.56):
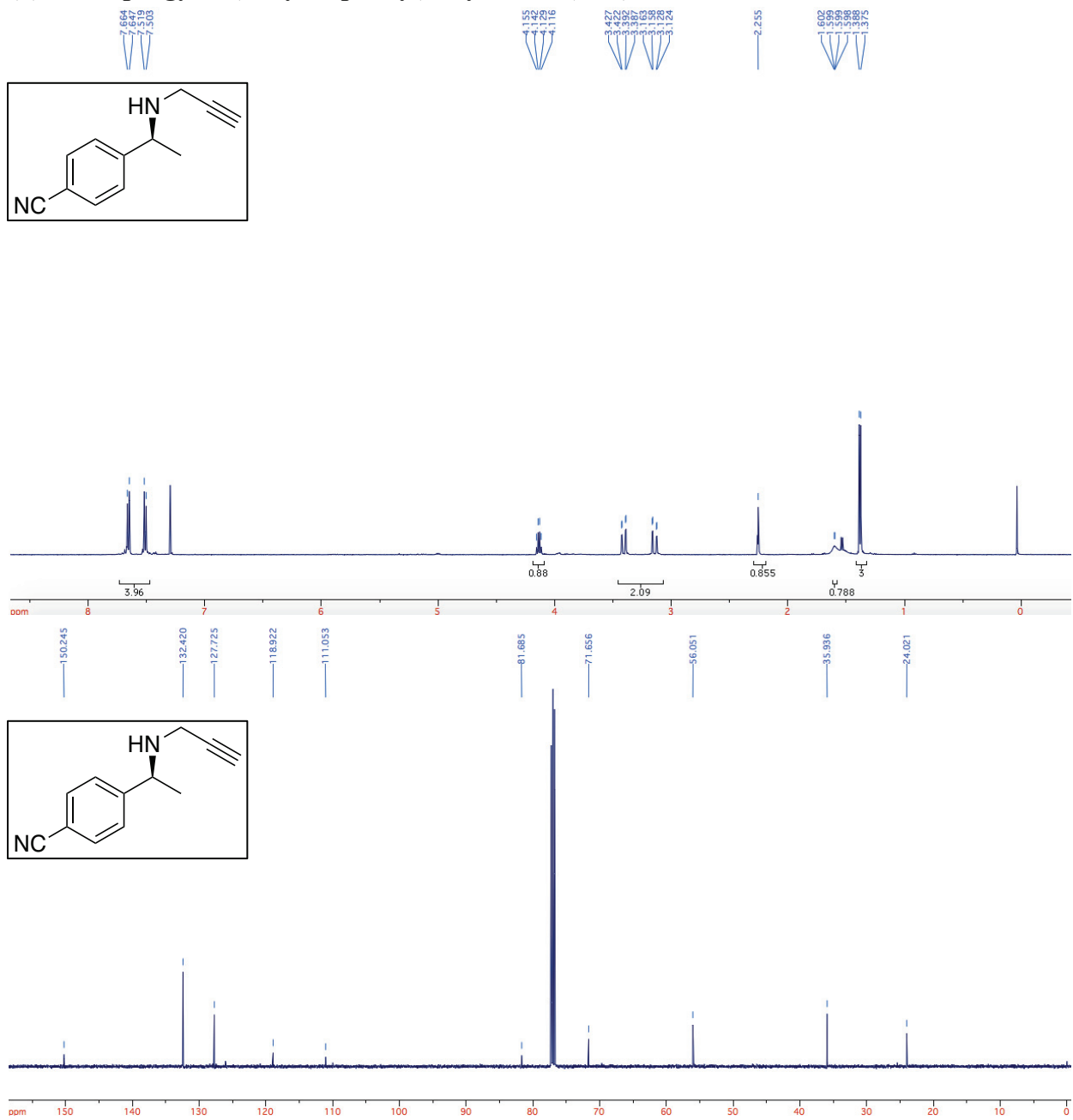
(*S*)-*N*-Benzyl-2-methyl-1-phenylpropylamine (3.57):
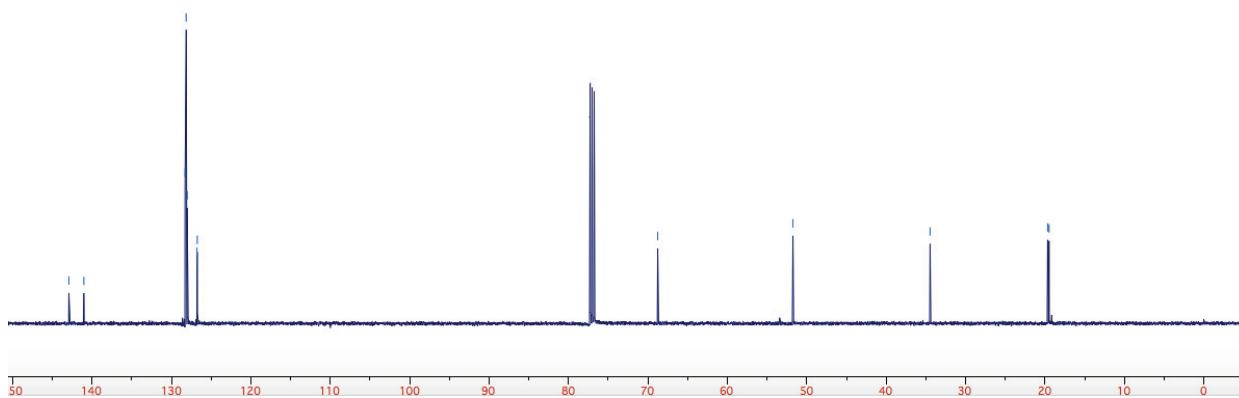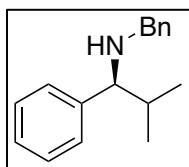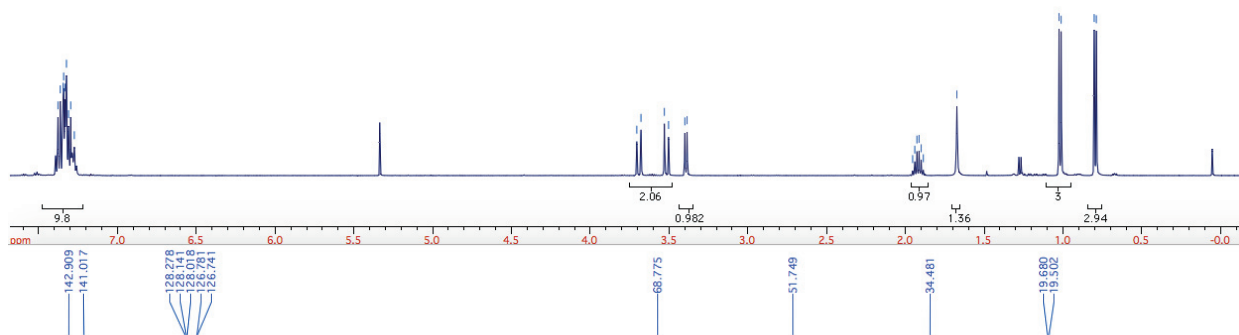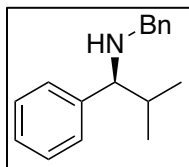
(*S*)-*N*-Benzyl-*N'*-(*tert*-butyloxycarbonyl)-2-methyl-1-phenylpropylamine (3.57):
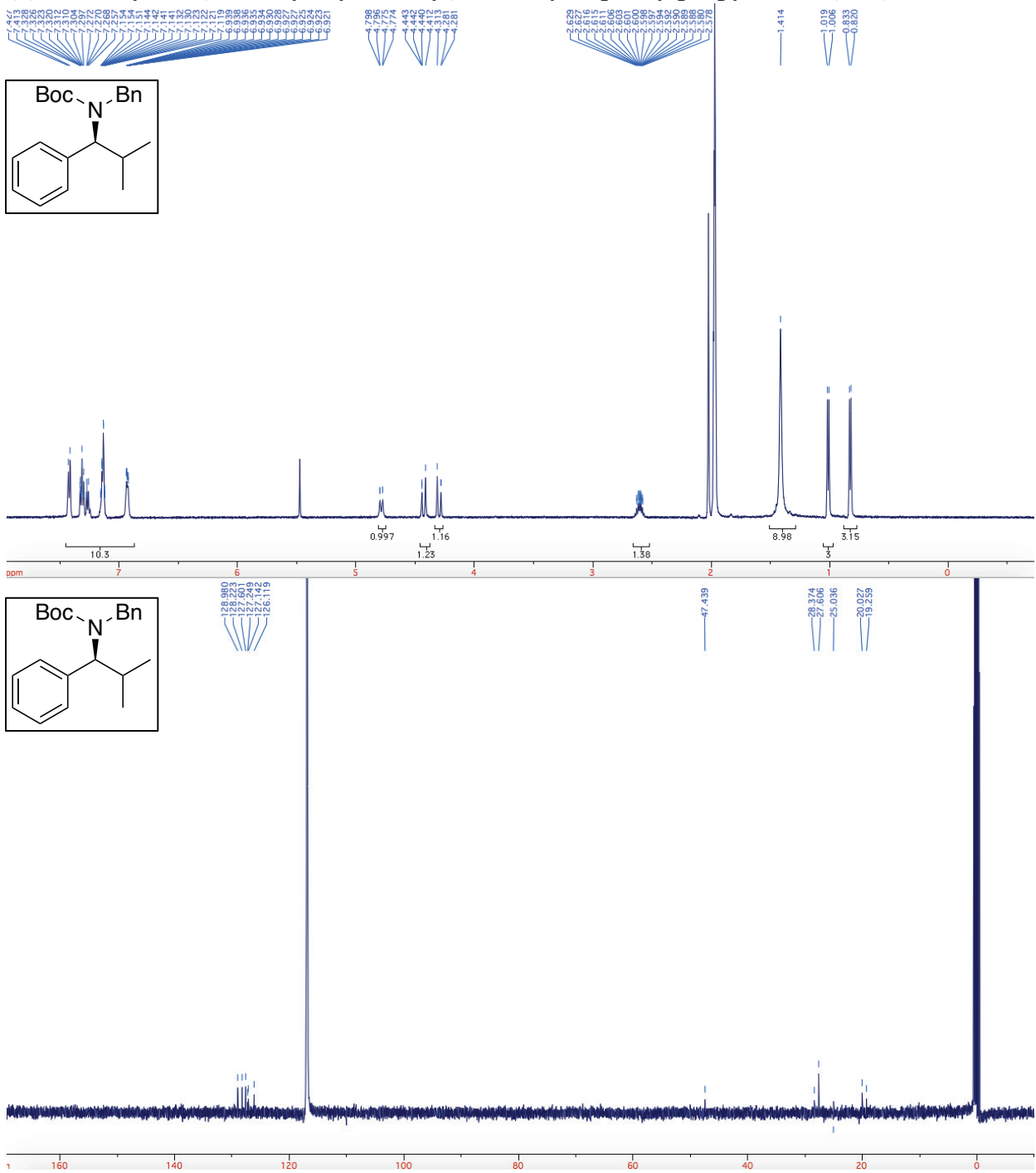
**(*S*)-*N*-Cyclohexyl-1-(4'-methoxyphenyl)ethylamine (3.58):**
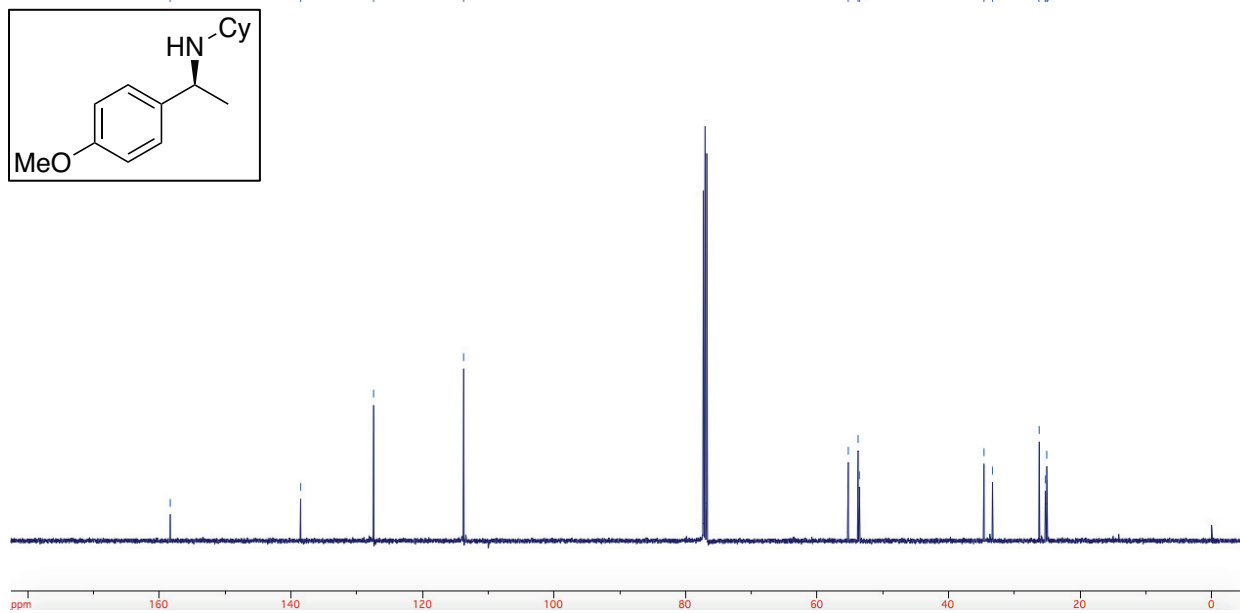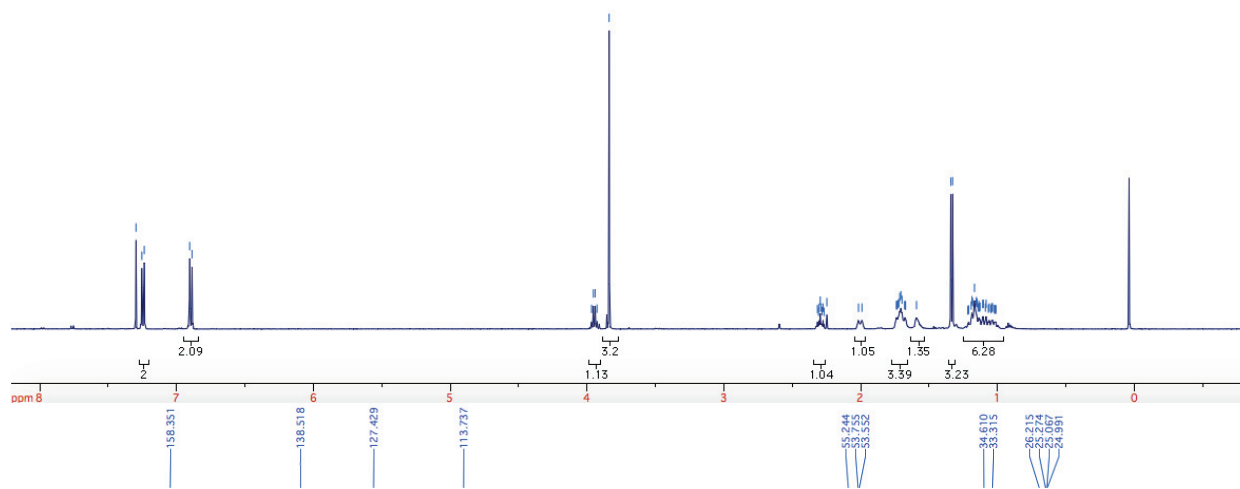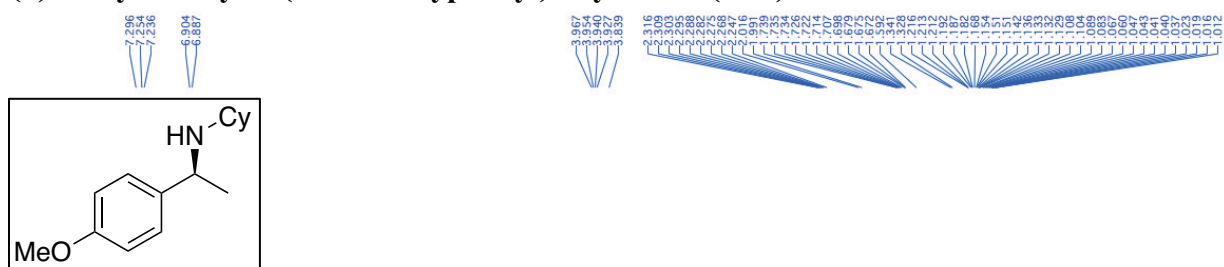
**(*S*)-*N*-Cyclohexyl-*N'*(*tert*-butyloxycarbonyl)-1-(4'-methoxyphenyl)ethylamine (3.58):**

(*S*)-*N*-Cyclopropyl-1-(4-methoxyphenyl)ethylamine (3.59):

(*S*)-*N*-Benzyl-1-(pyridin-2-yl)ethanamine (3.60):
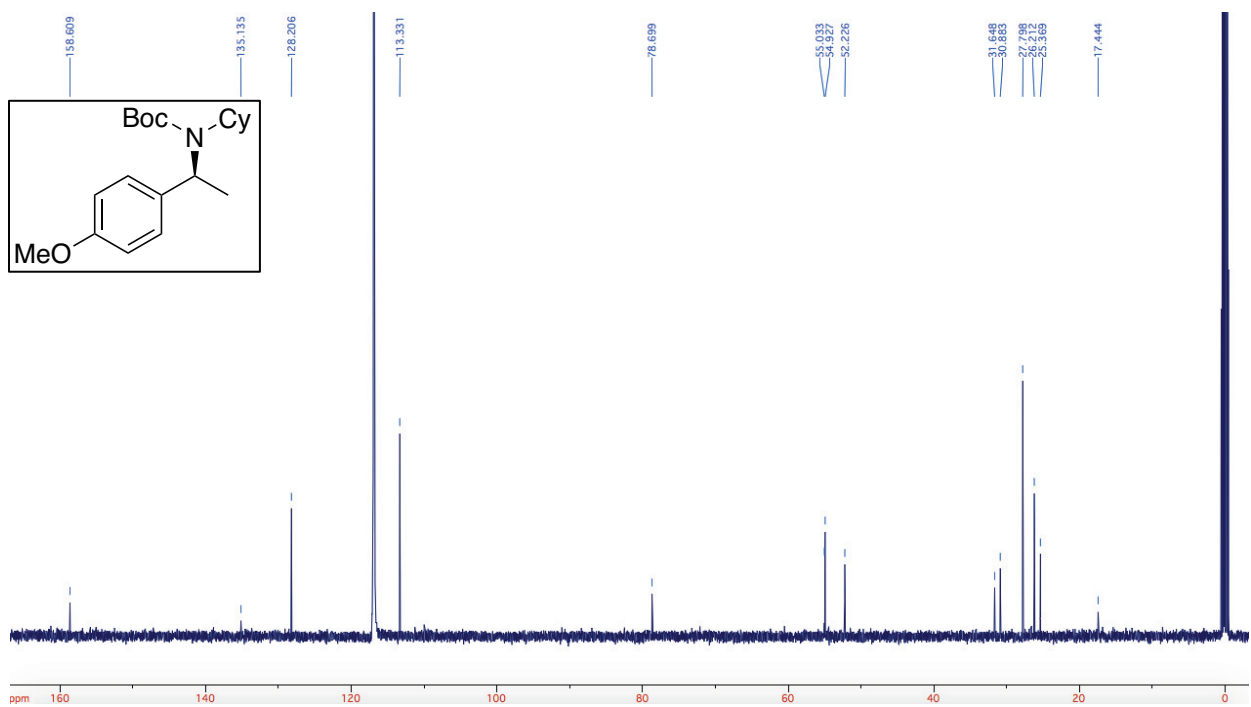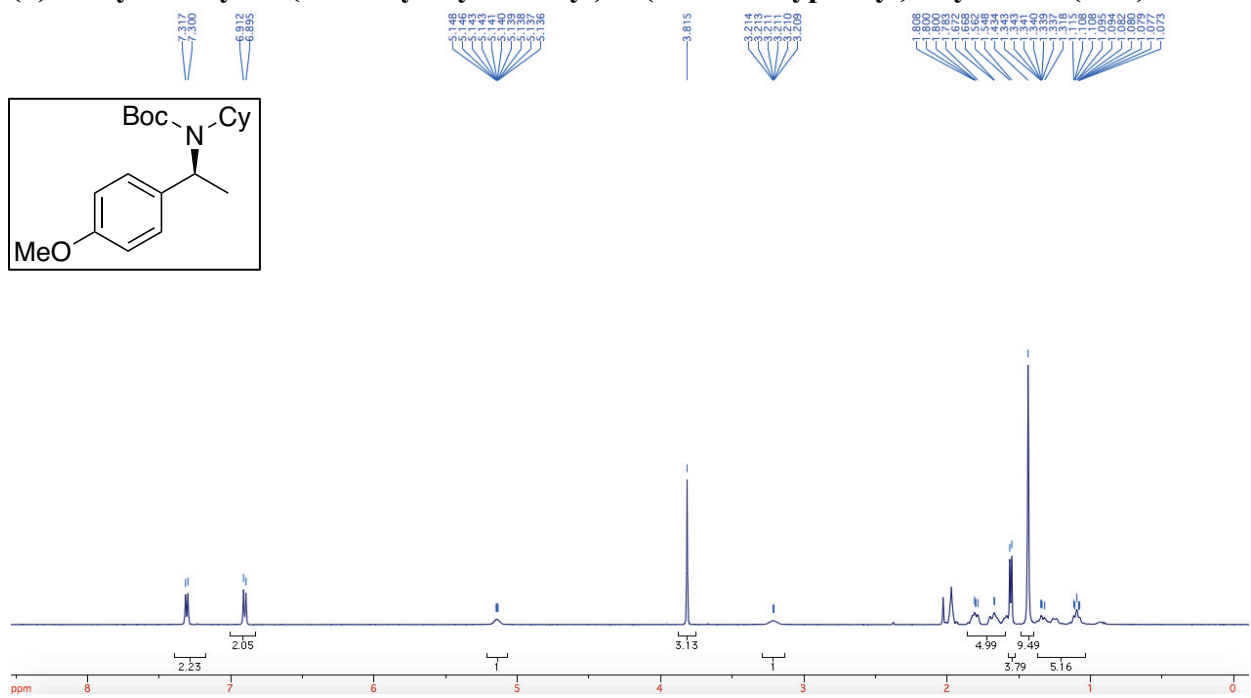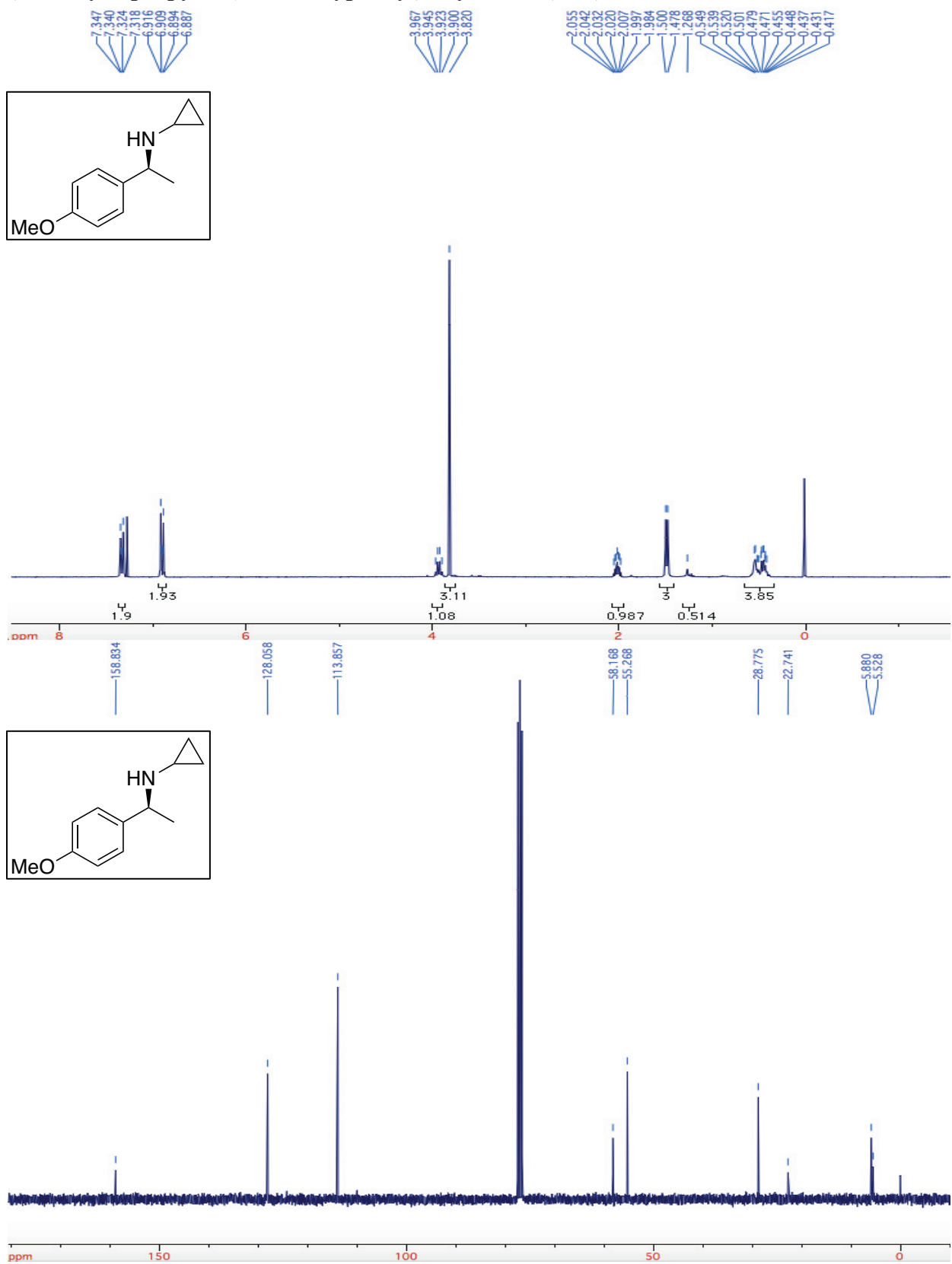
(*S*)-*N*-Furfuryl-1-(phenyl)ethylamine (3.61):
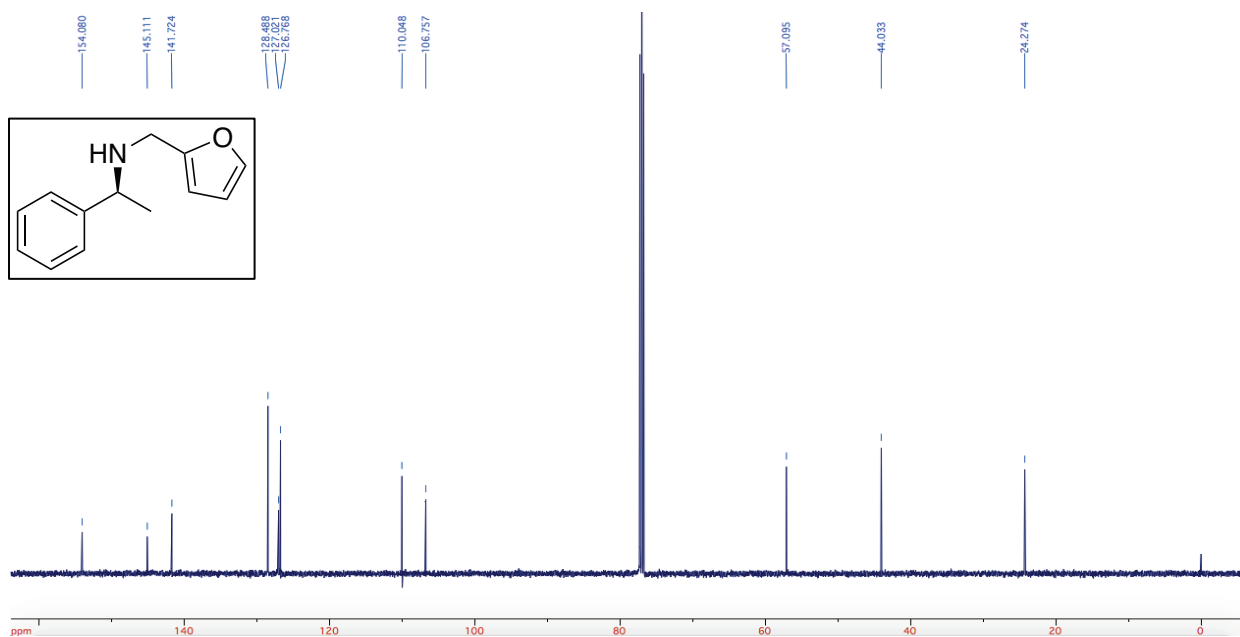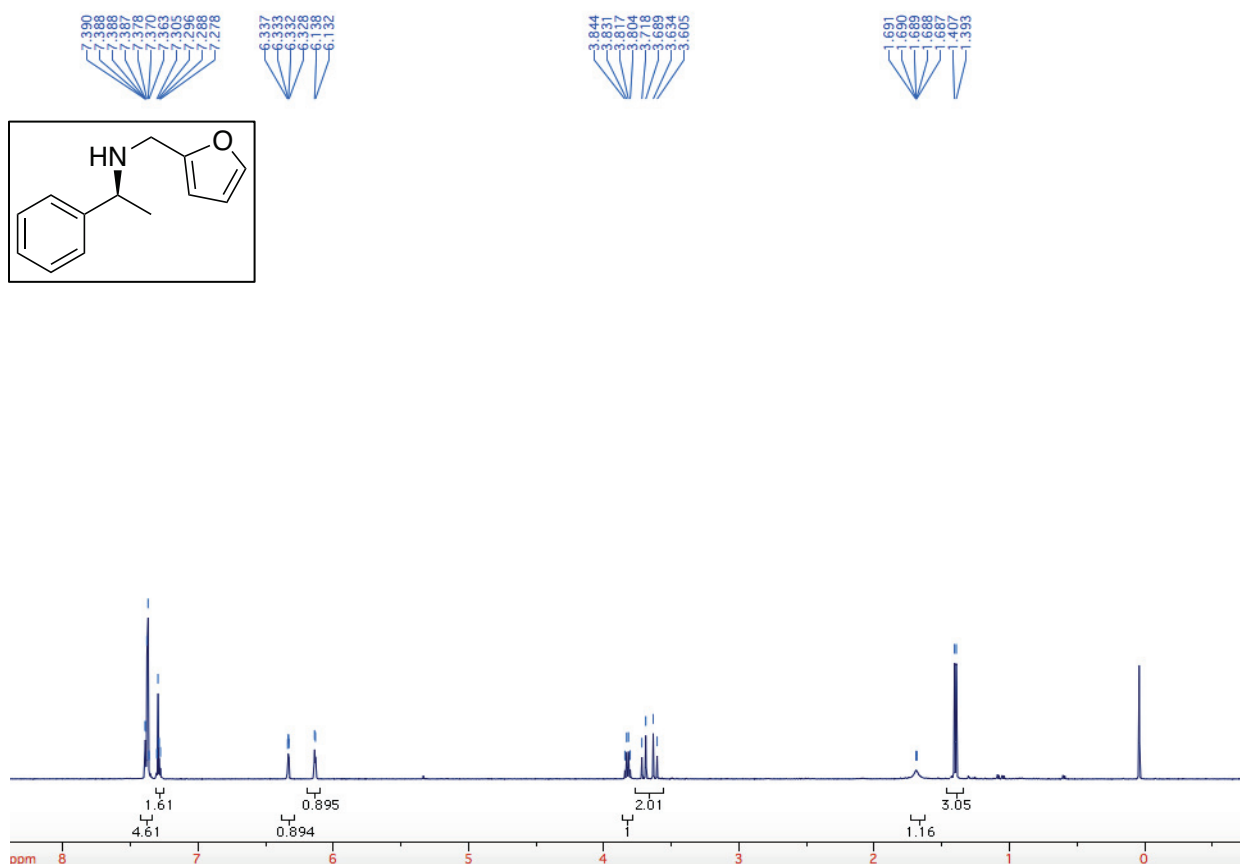
(*S*)-*N*-Furfuryl-*N'*(*tert*-butyloxycarbonyl)-1-(phenyl)ethylamine (3.61):
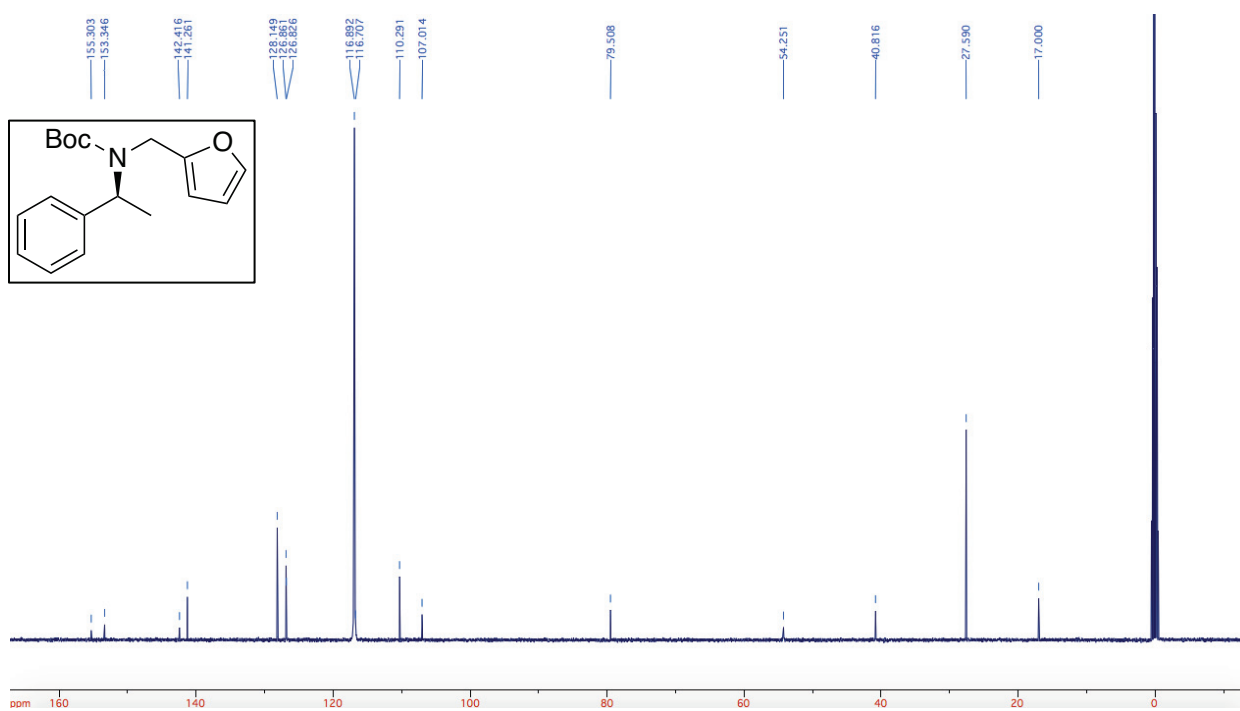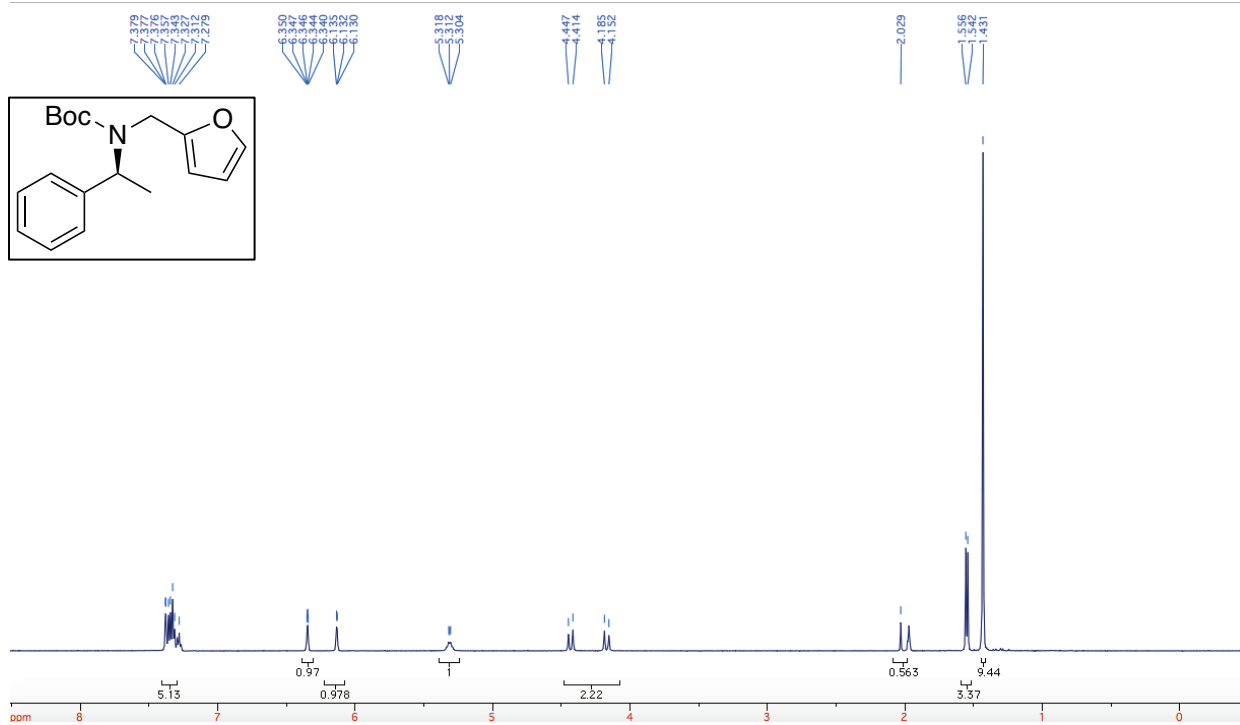
(*S*)-*N*-Benzyl-1-(ferrocene)ethylamine (3.62):
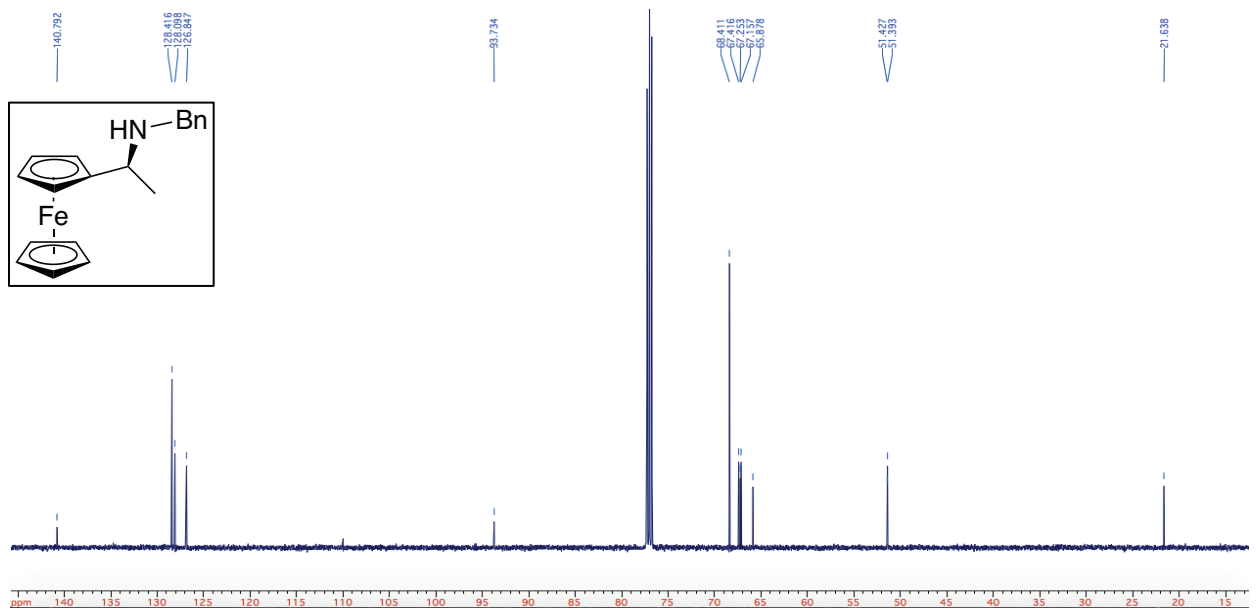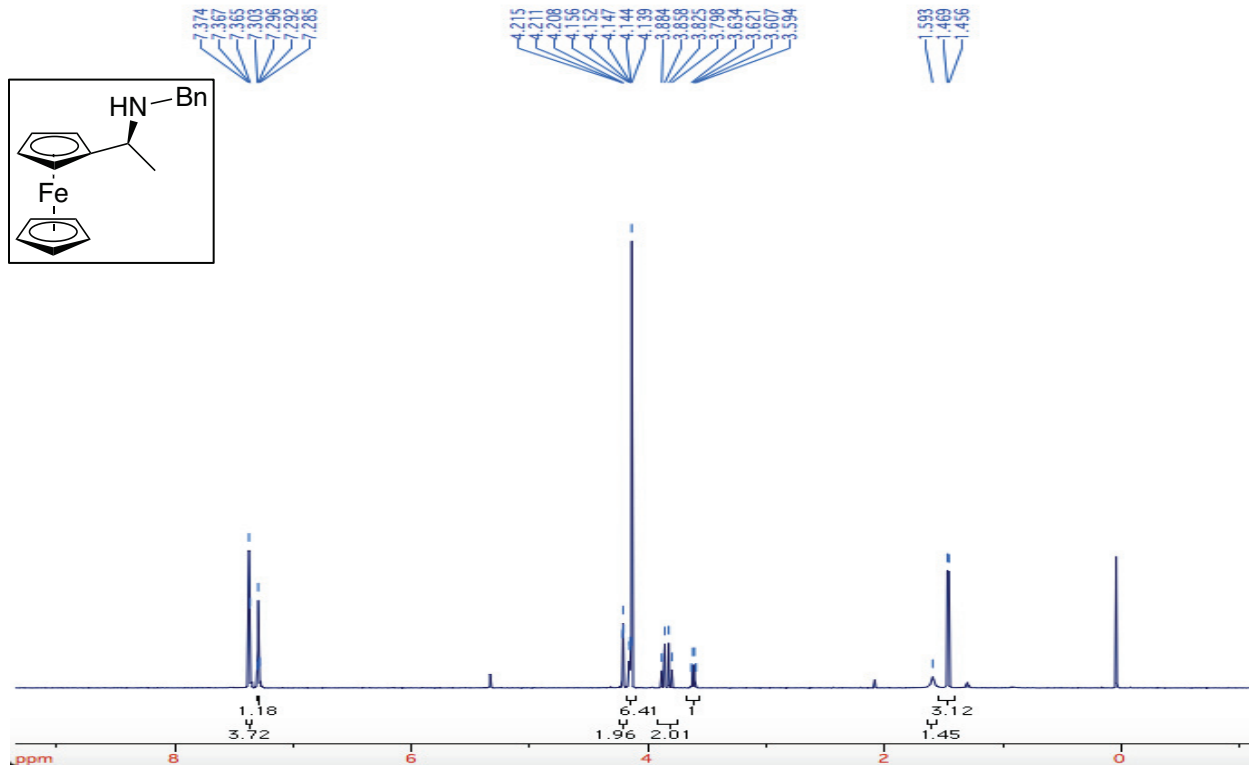
(*S*)-*N*-Benzyl-*N*'-(*tert*-butyloxycarbonyl)-1-(ferrocene)ethylamine (3.62):
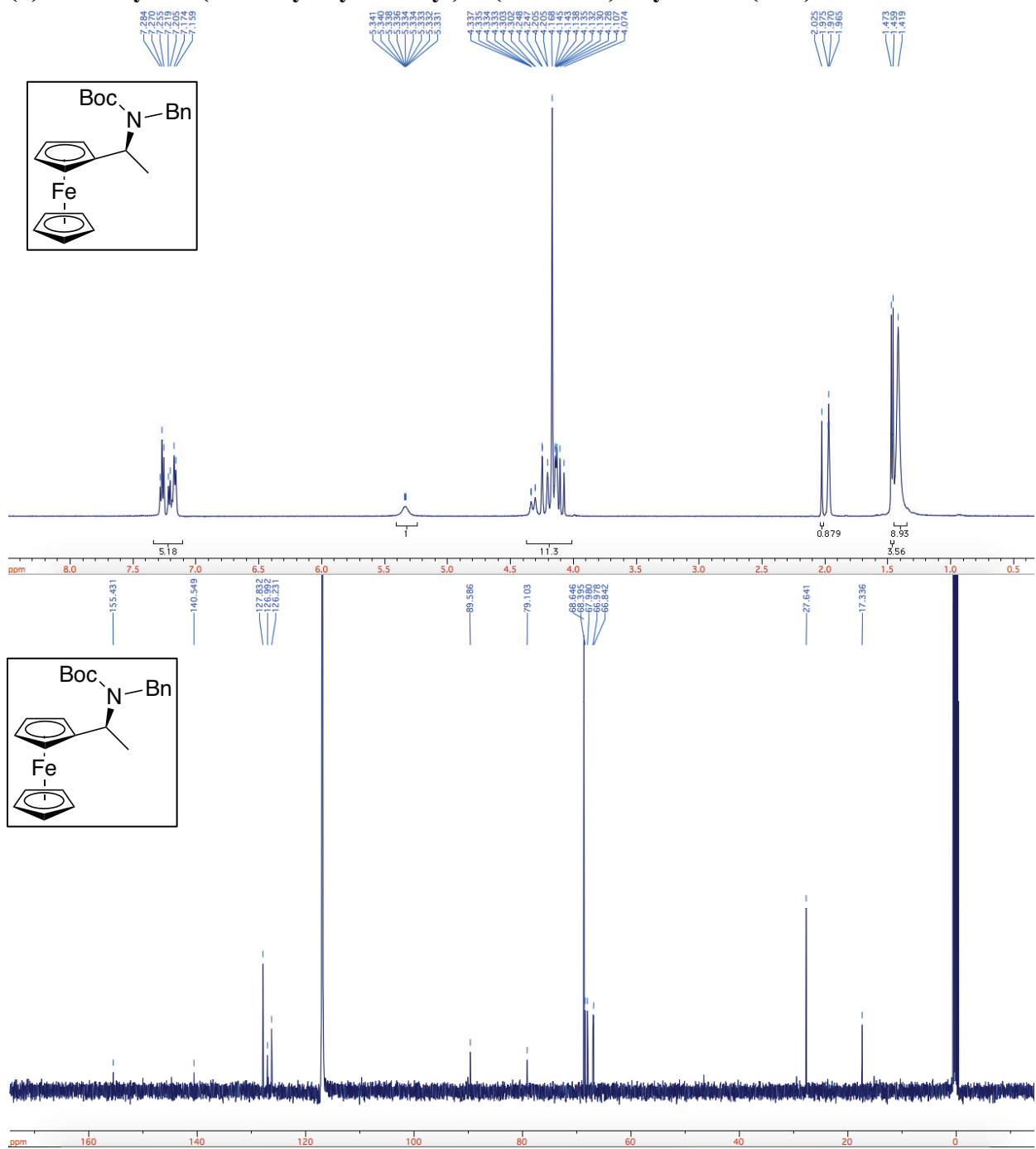
(*S*)-*N*-Benzyl-1-(3,4,5-trimethoxyphenyl)ethylamine (3.63):
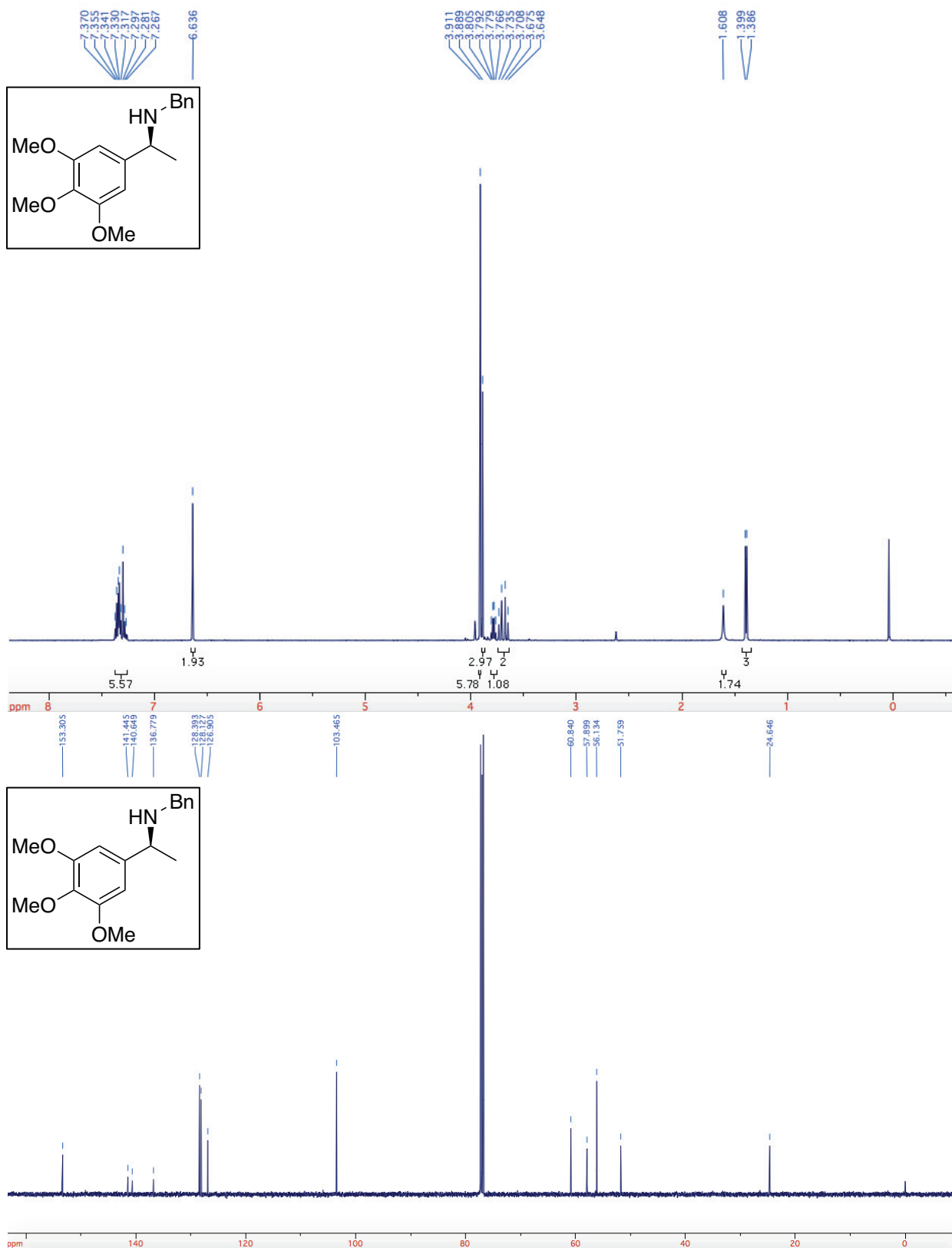
(*S*)-*N*-Benzyl-*N'*(*tert*-butyloxycarbonyl)-1-(3,4,5-trimethoxyphenyl)ethylamine
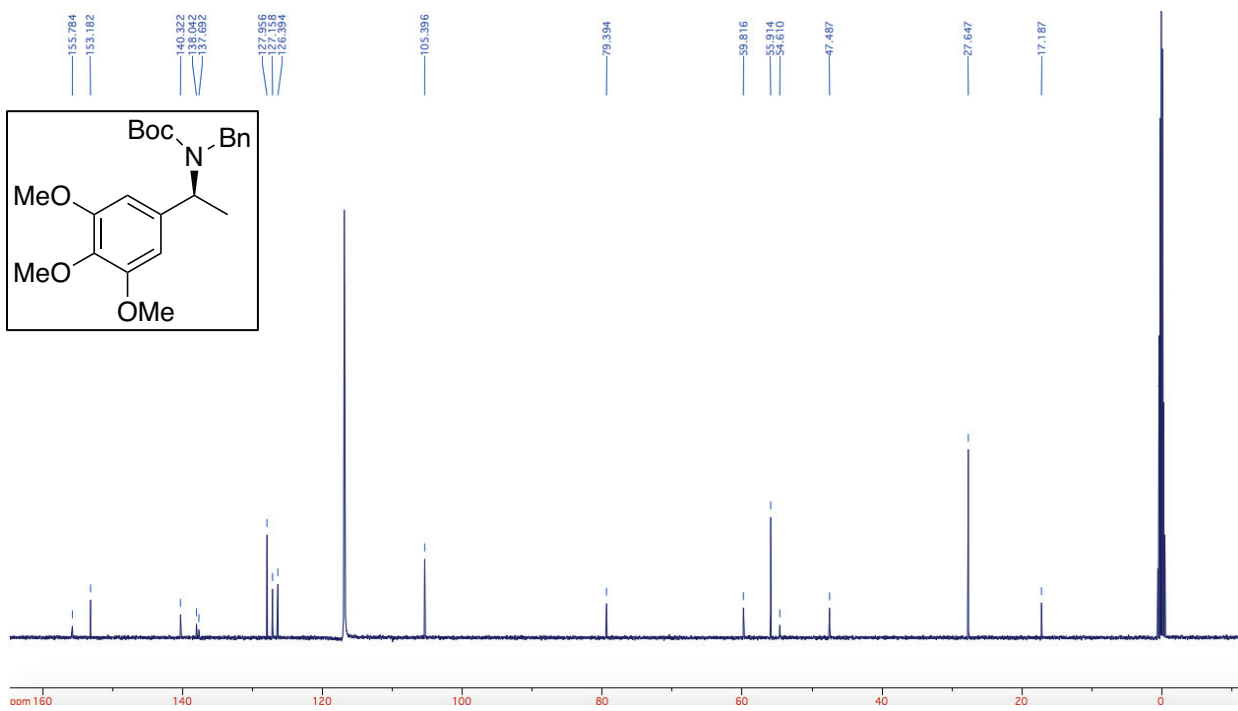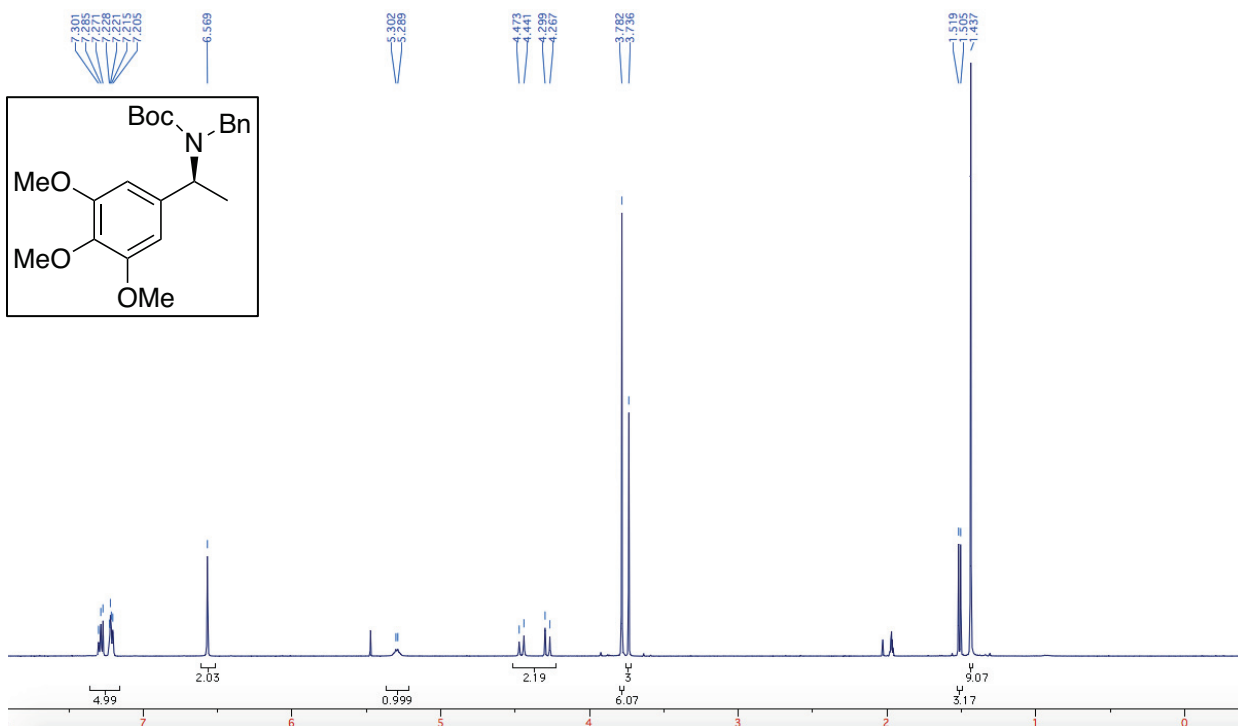
(3.63):

(*S*)-*N*-Paramethoxybenzyl-*N'*(*tert*-butyloxycarbonyl)-1-(3,4,5-trimethoxyphenyl)ethylamine (3.64):
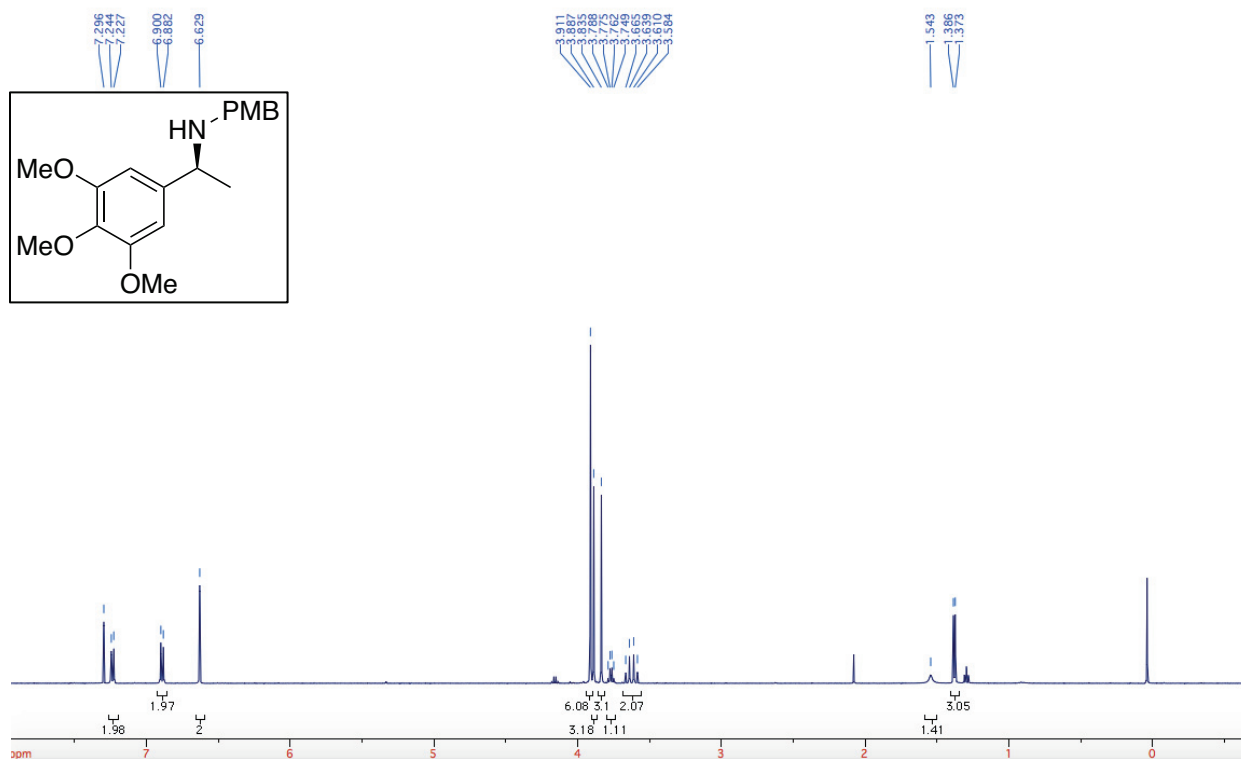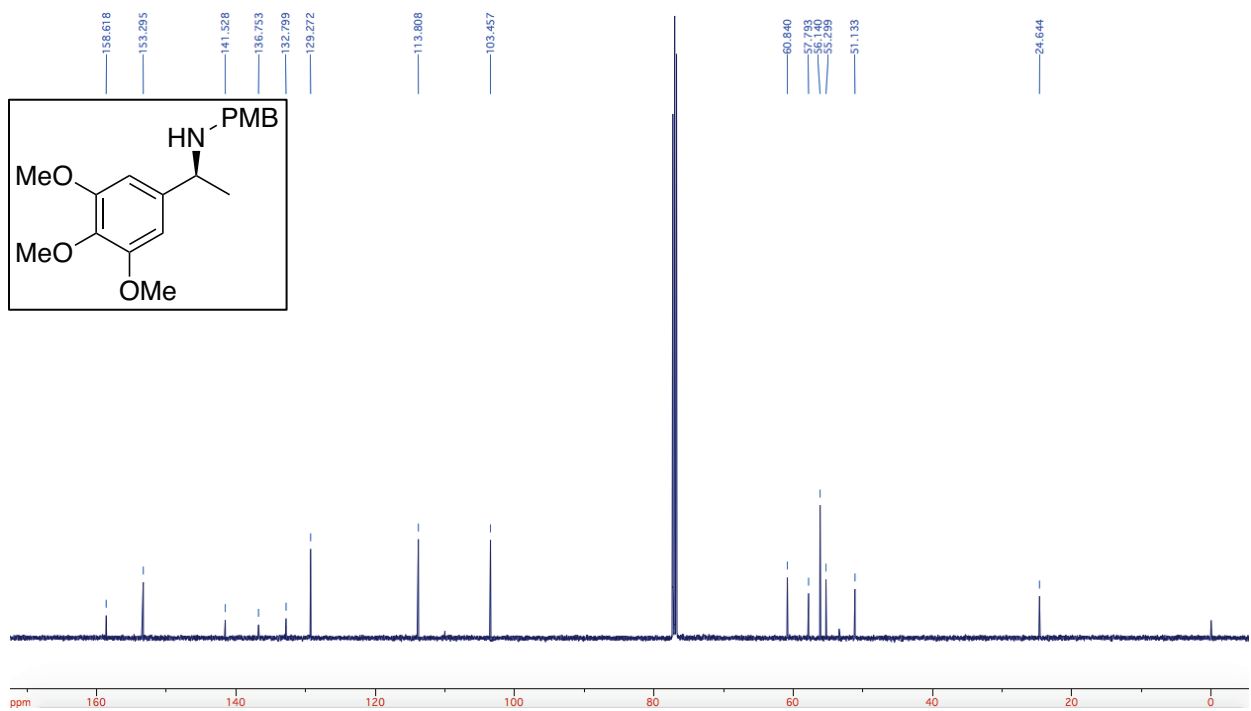
(*S*)-*N*-Paramethoxybenzyl-*N'*(*tert*-butyloxycarbonyl)-1-(3,4,5-

trimethoxyphenyl)ethylamine (3.64):

307

(S)-N-2,2-Diphenylpropyl-1-(phenyl)ethylamine (3.65):

308
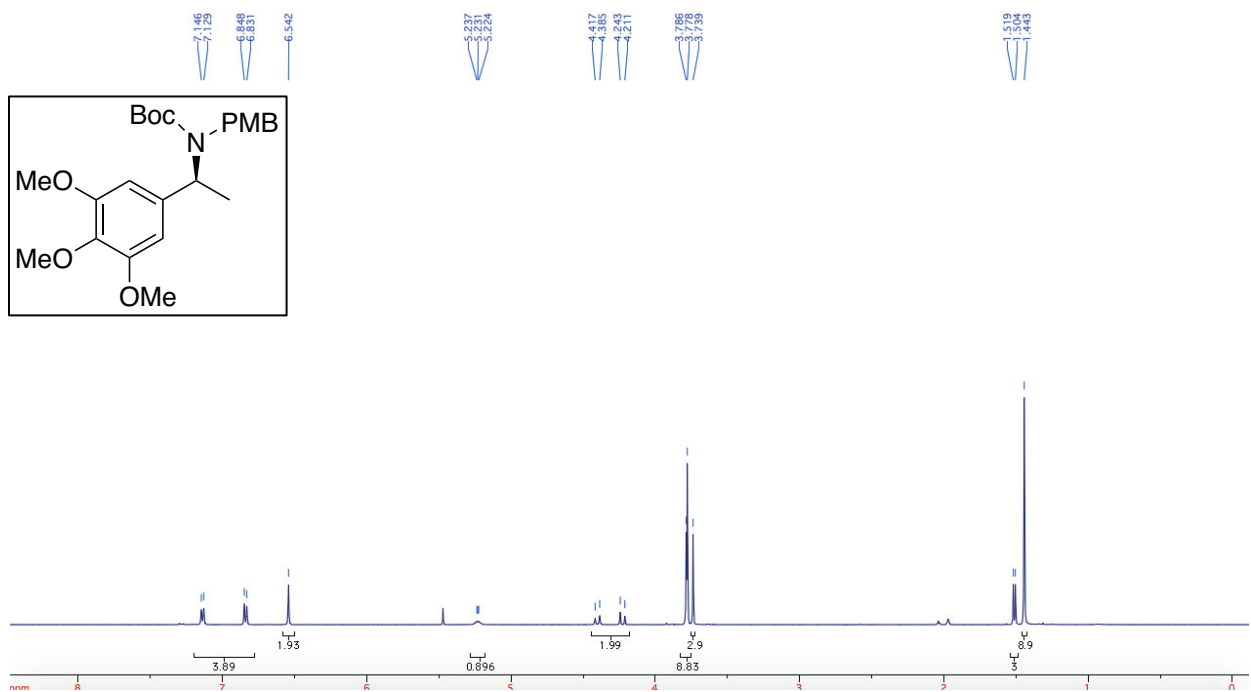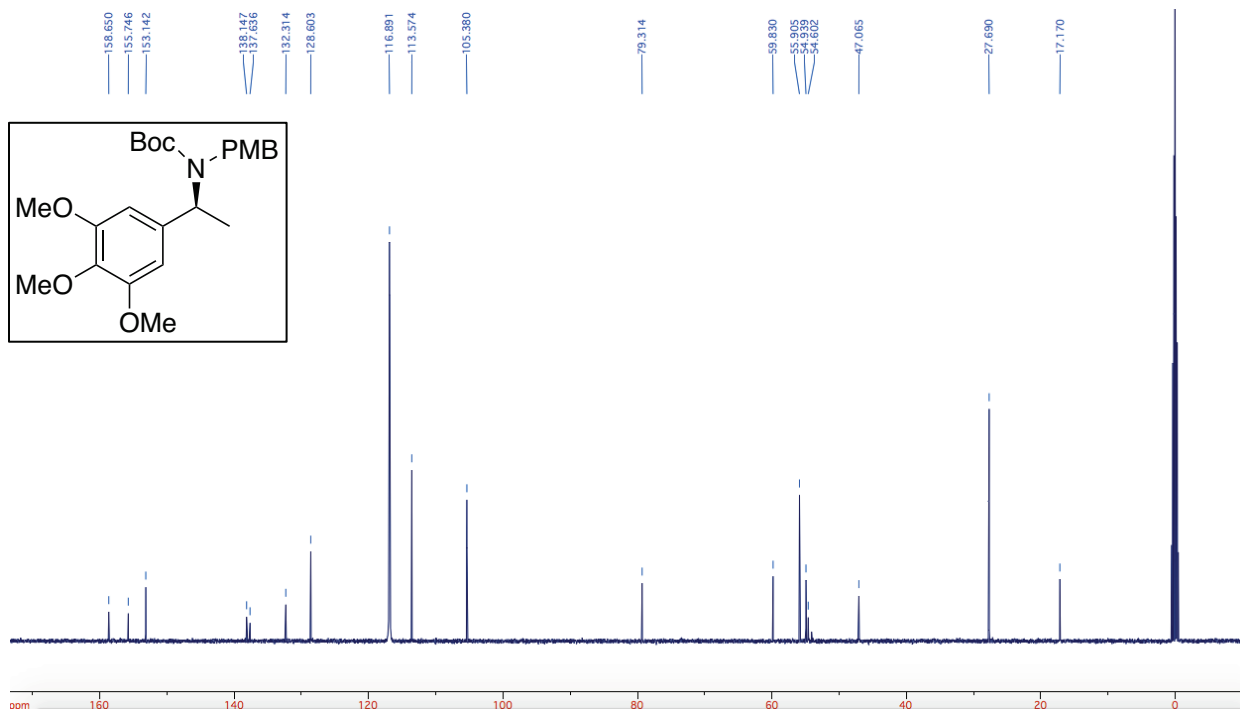
(*S*)-*N*-Phenyl-1-(phenyl)ethylamine (3.66):
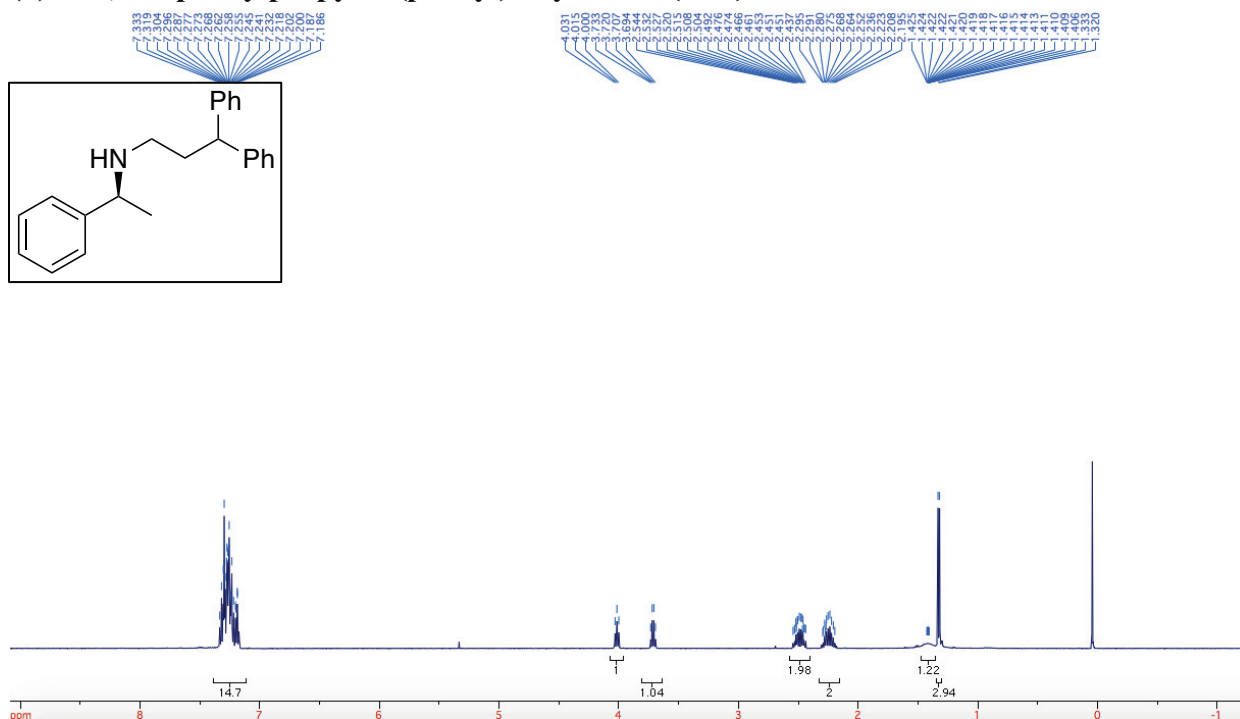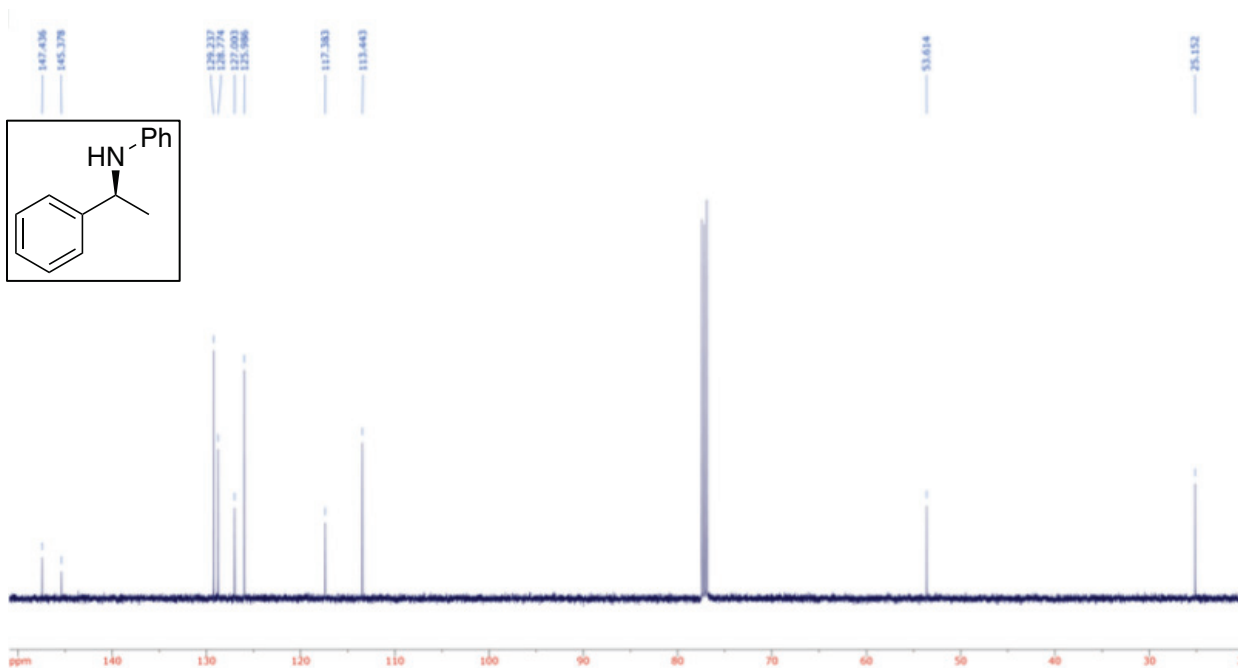
(*S*)-*N*-Phenyl-1-(4-methoxyphenyl)ethylamine (3.67):
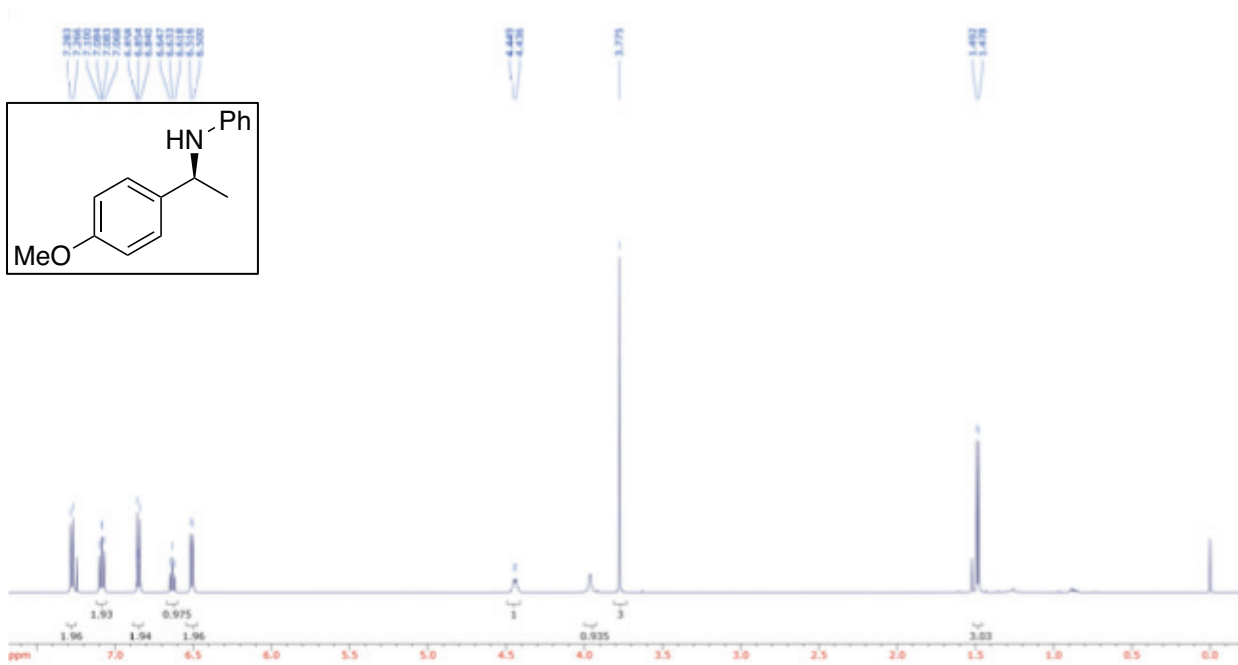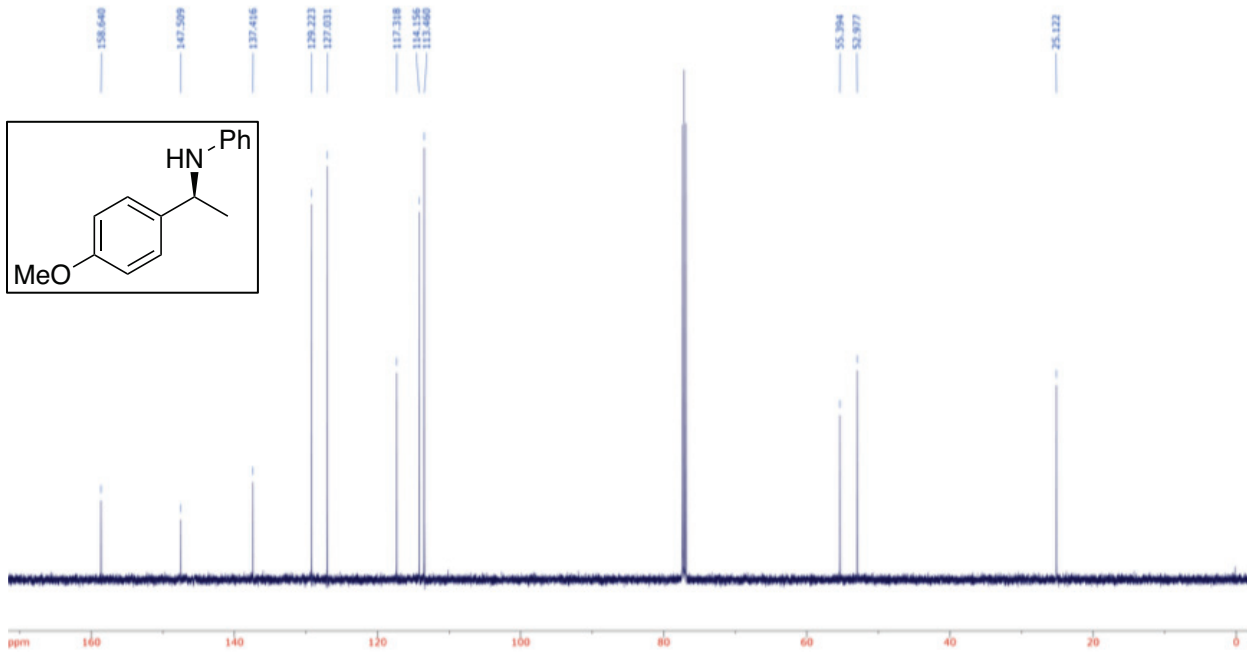
(S)-N-Benzyl-1-(furfuryl)ethylamine (3.68):
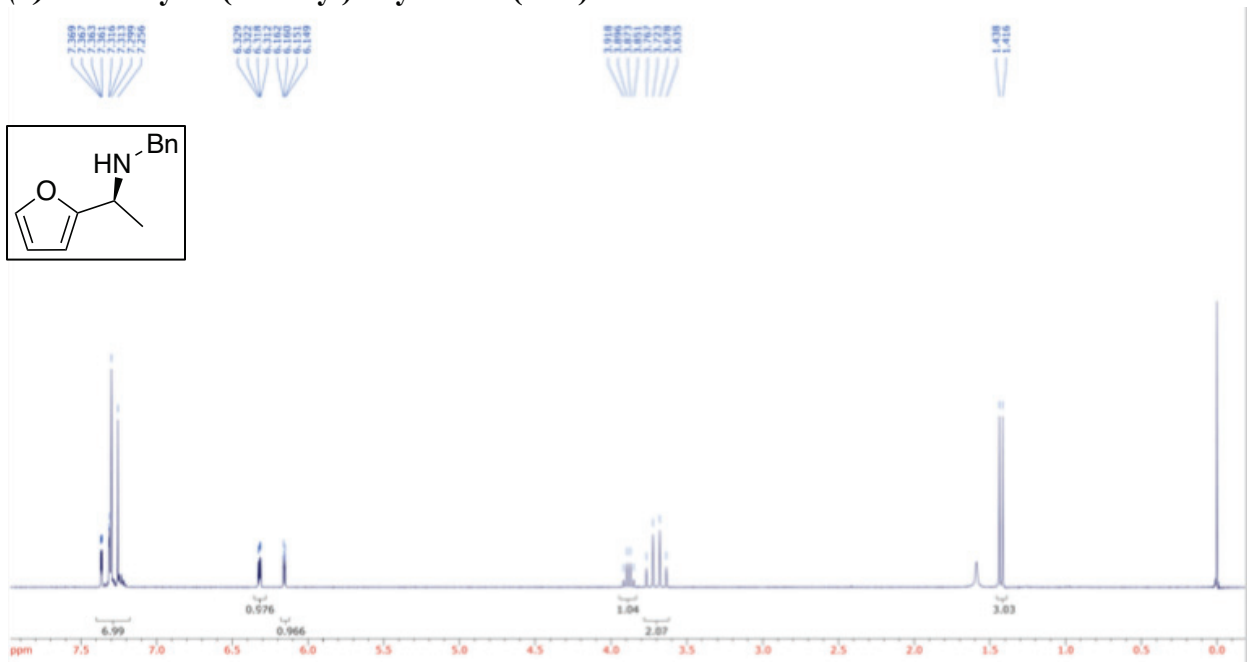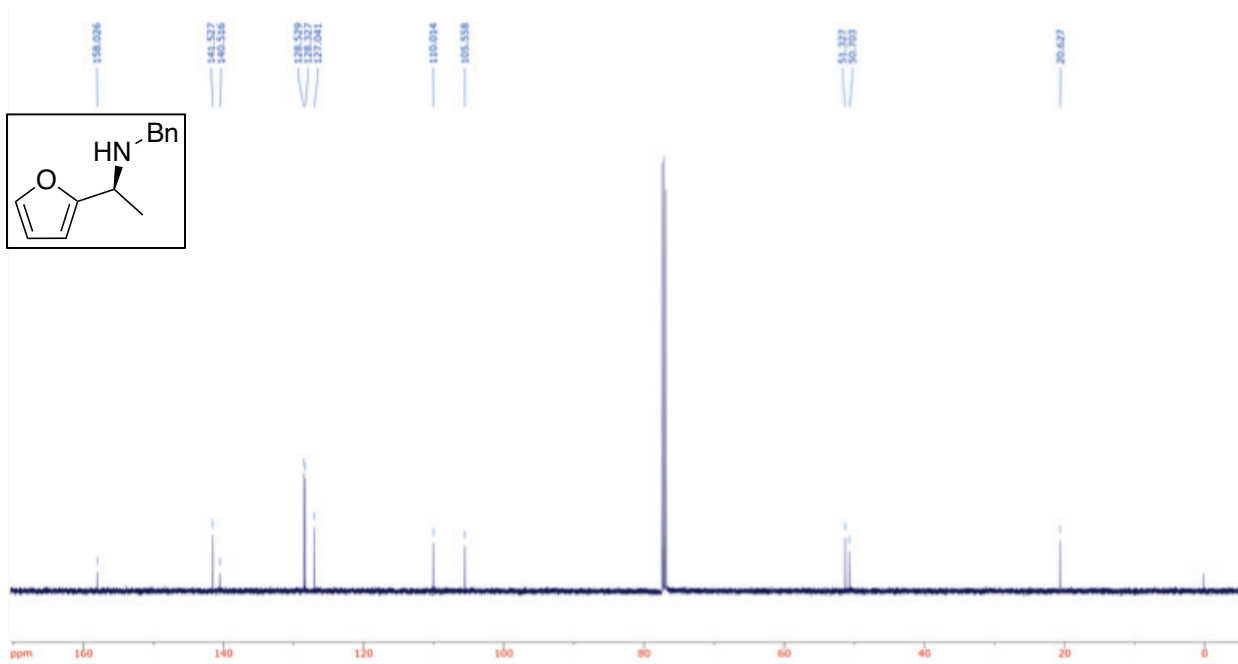
_(S)-N_-Benzyl-1-(2'-chlorophenyl)ethylamine (3.69):
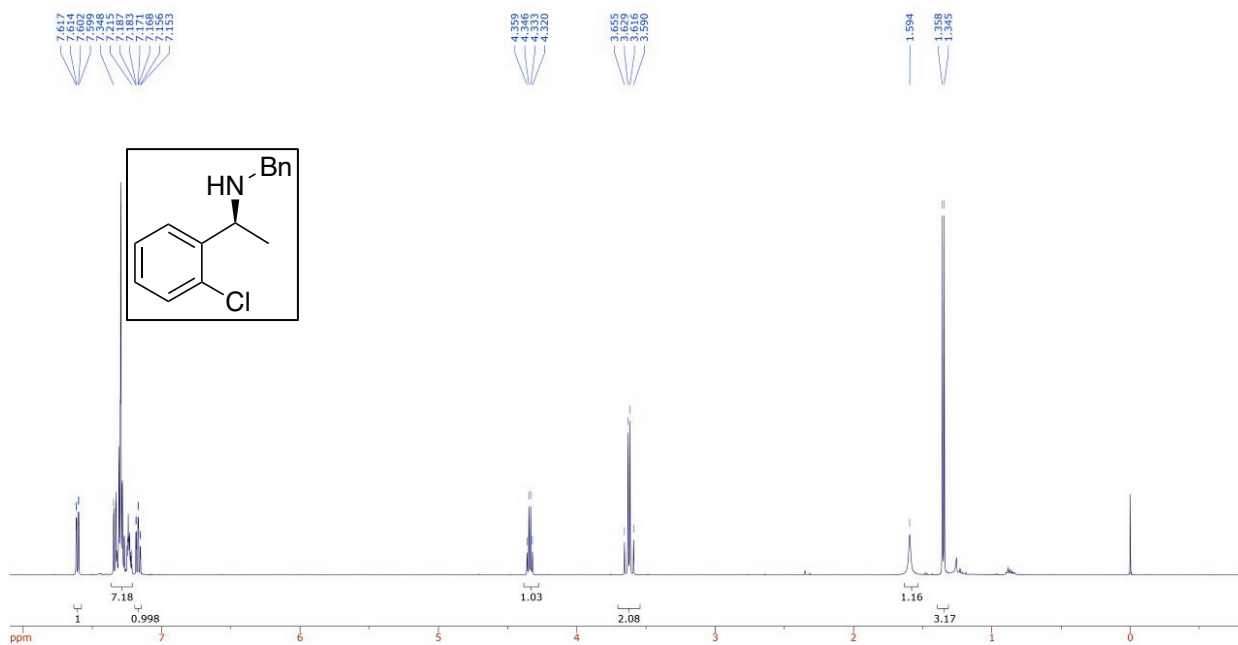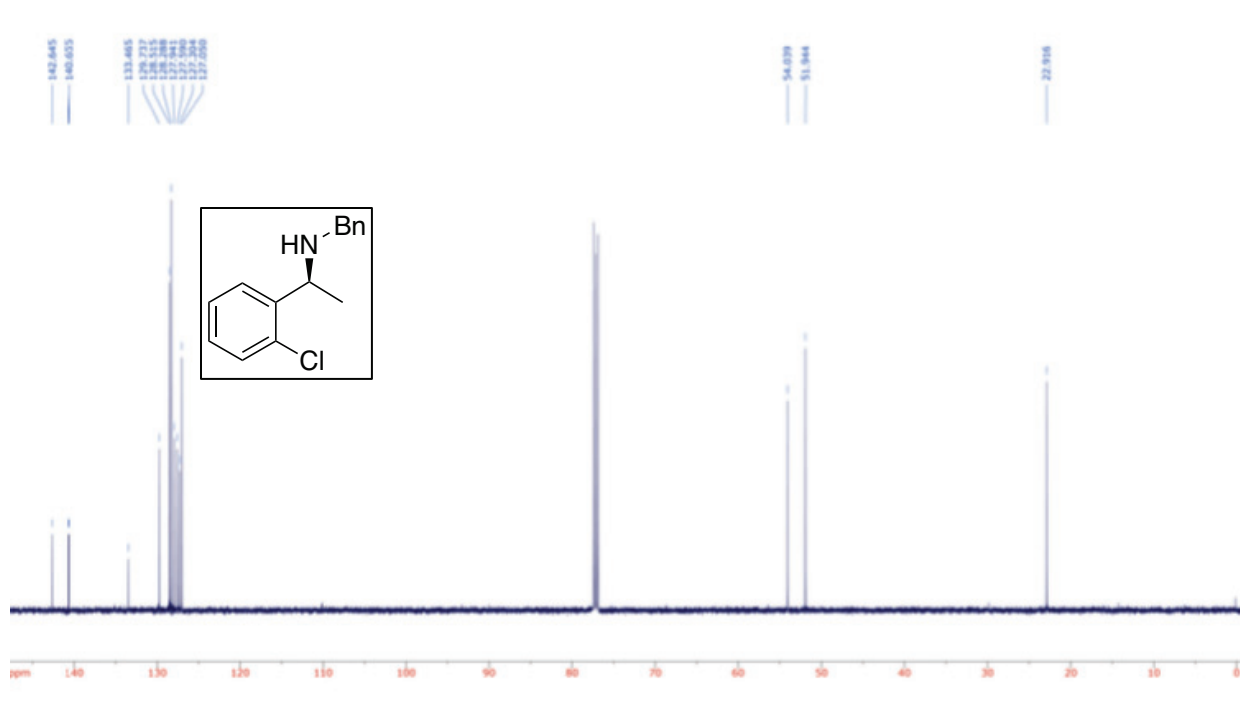
(S)-N-Methyl-1-(4-methoxyphenyl)ethylamine (3.70):
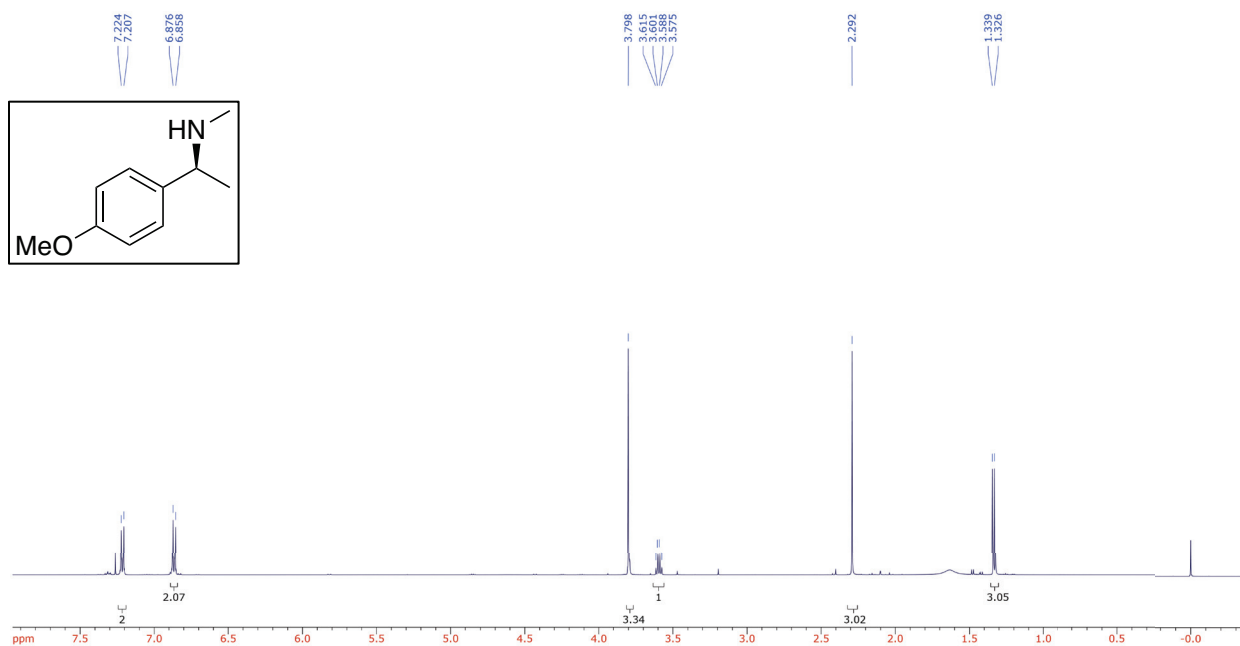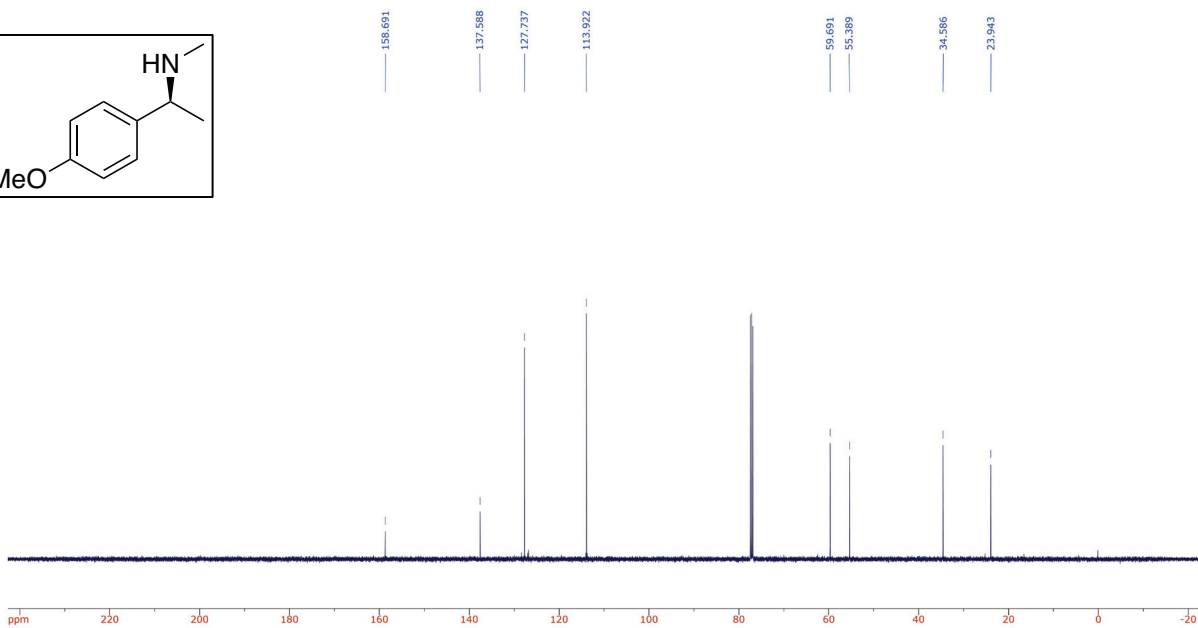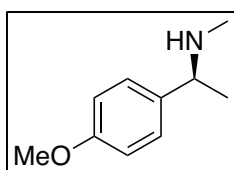
(*S*)-*N*-Methyl-*N'*-(*tert*-butyloxycarbonyl)-1-(4-methoxyphenyl)ethylamine (3.70):
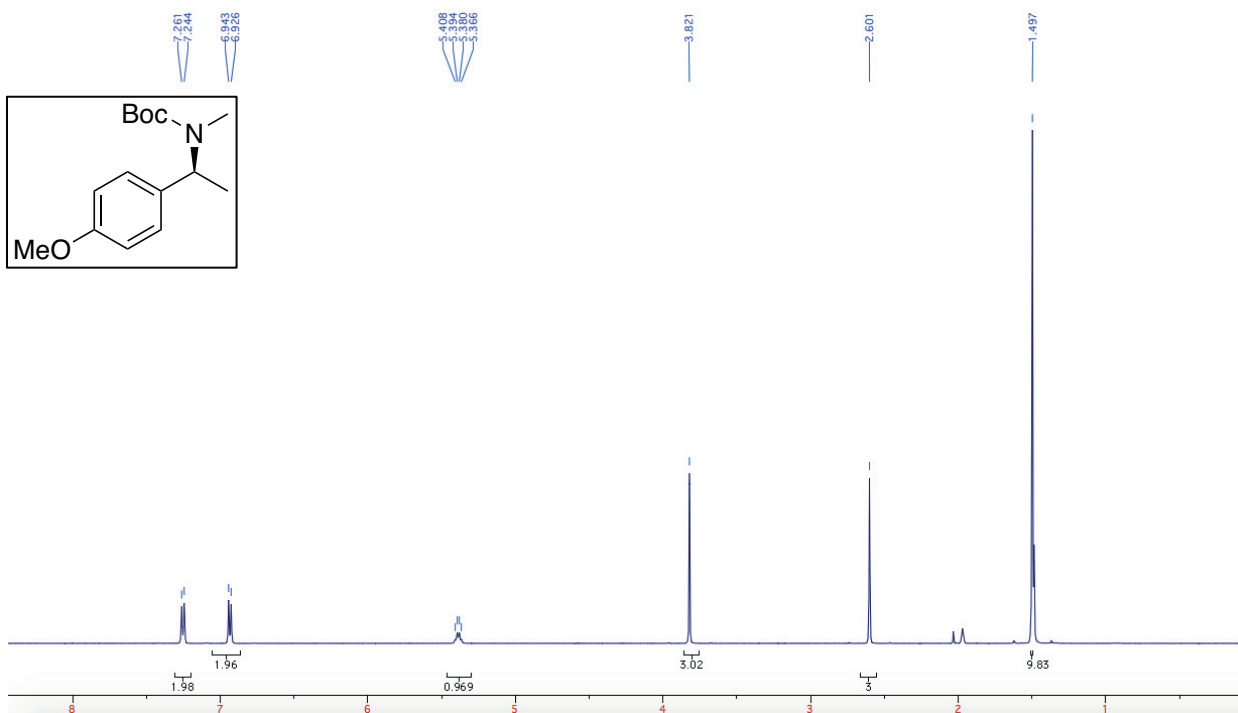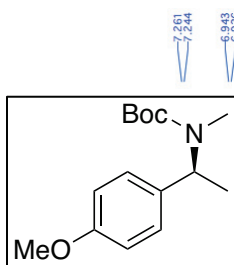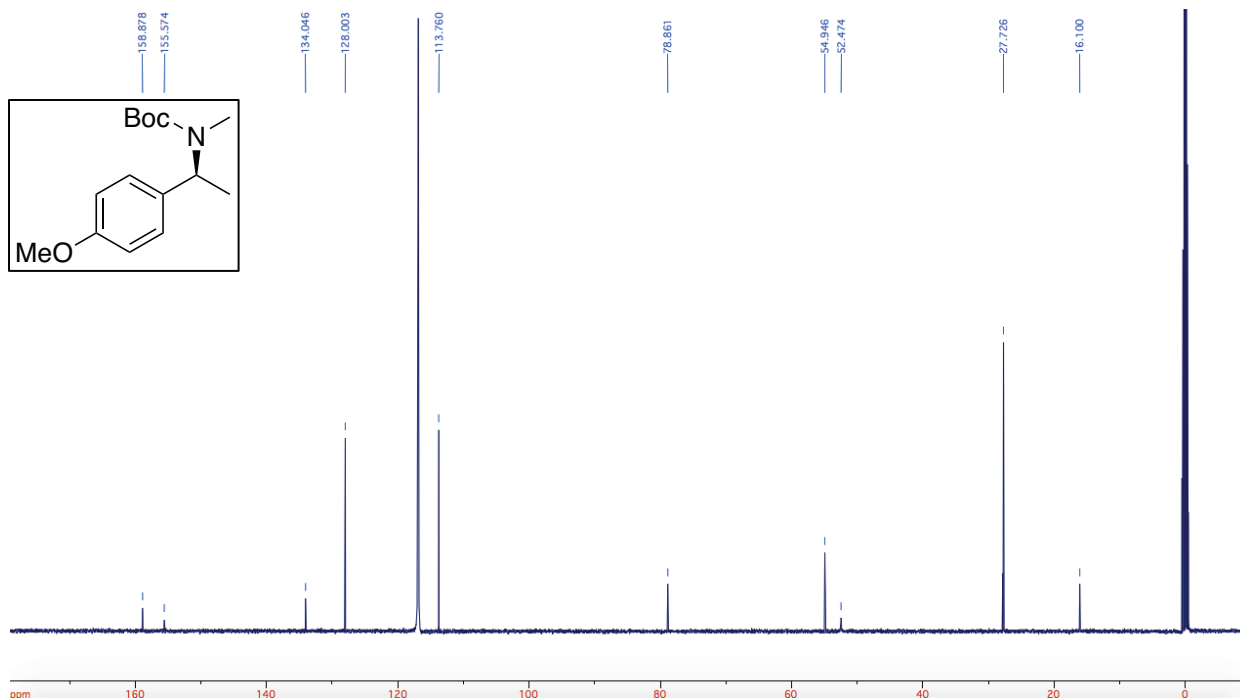
(*S*)-*N*-2-Phenylpropyl-1-(4-methoxyphenyl)ethylamine (3.71):
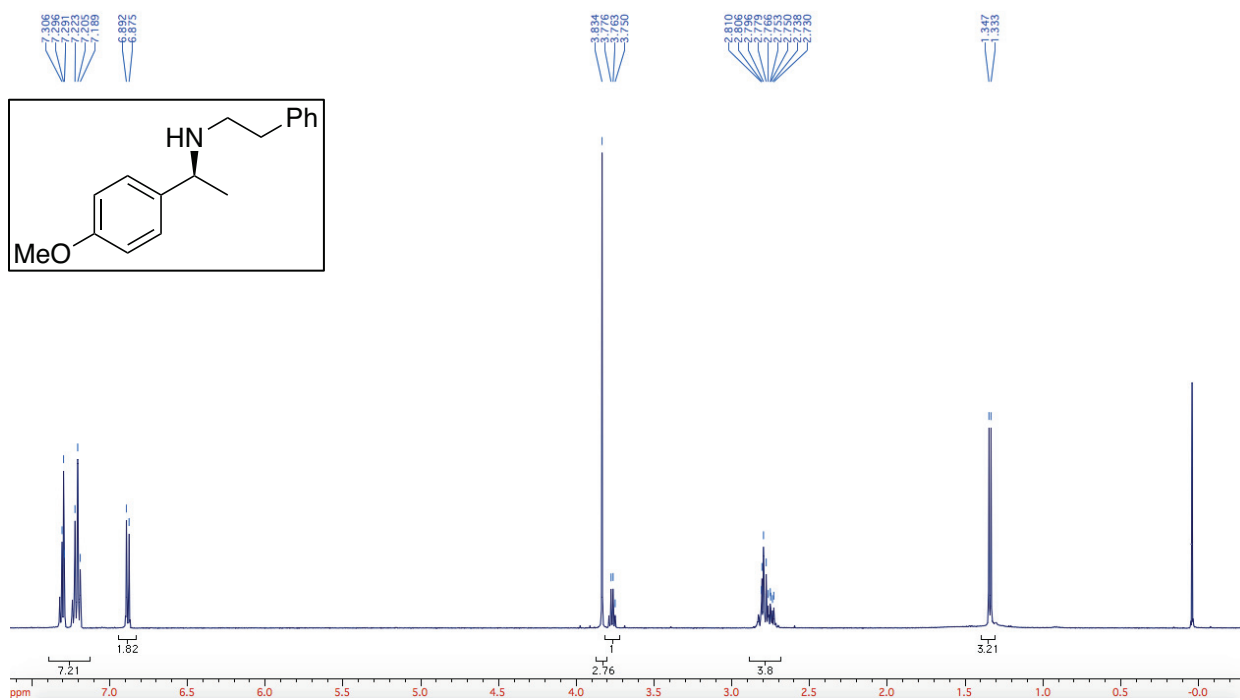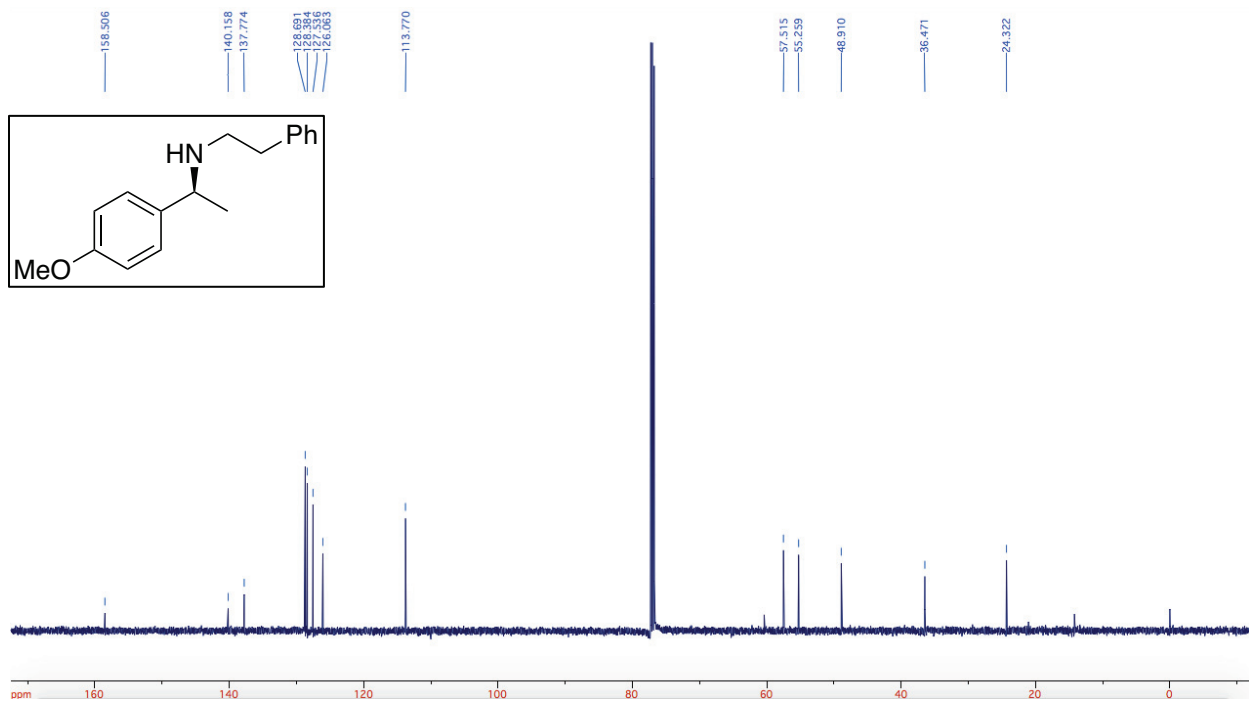
(*S*)-*N*-2,2-Diphenylpropyl-1-(4-methoxyphenyl)ethylamine (3.72):
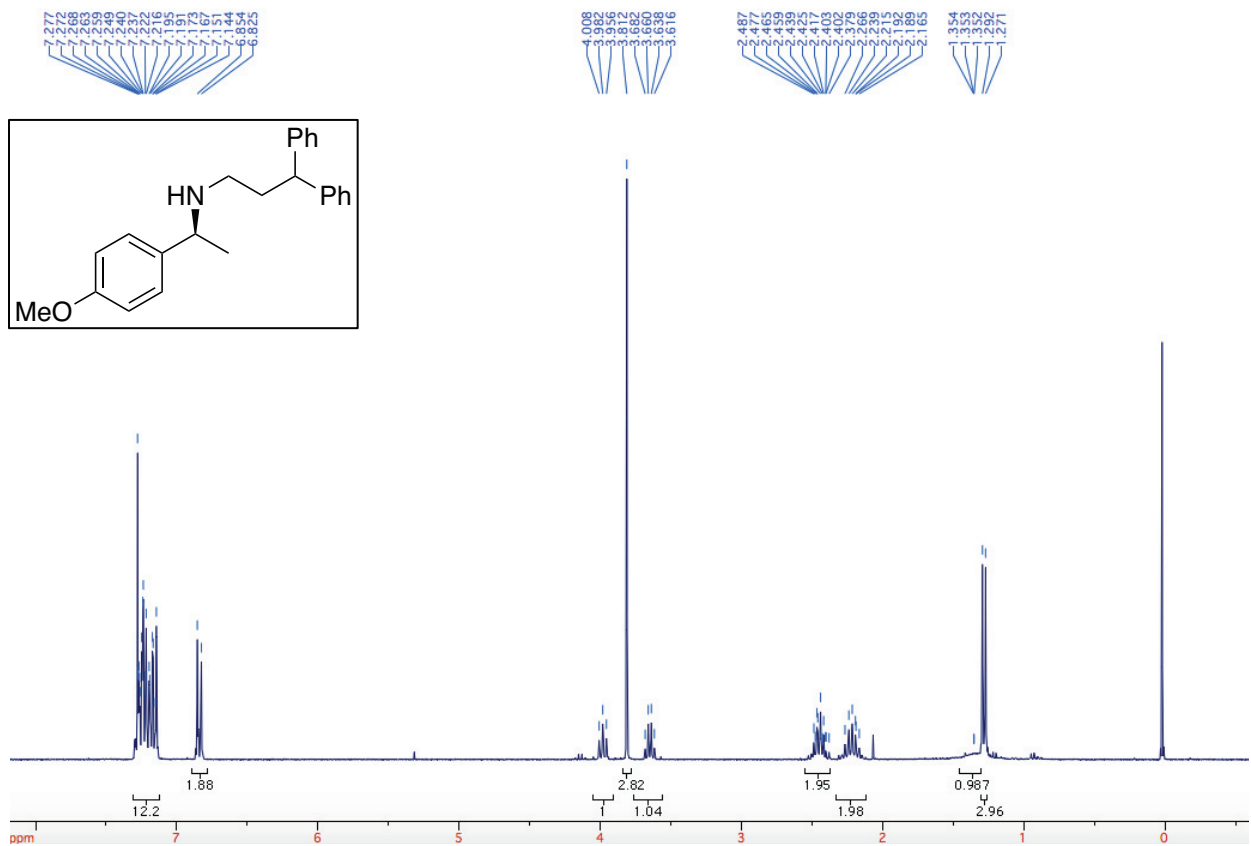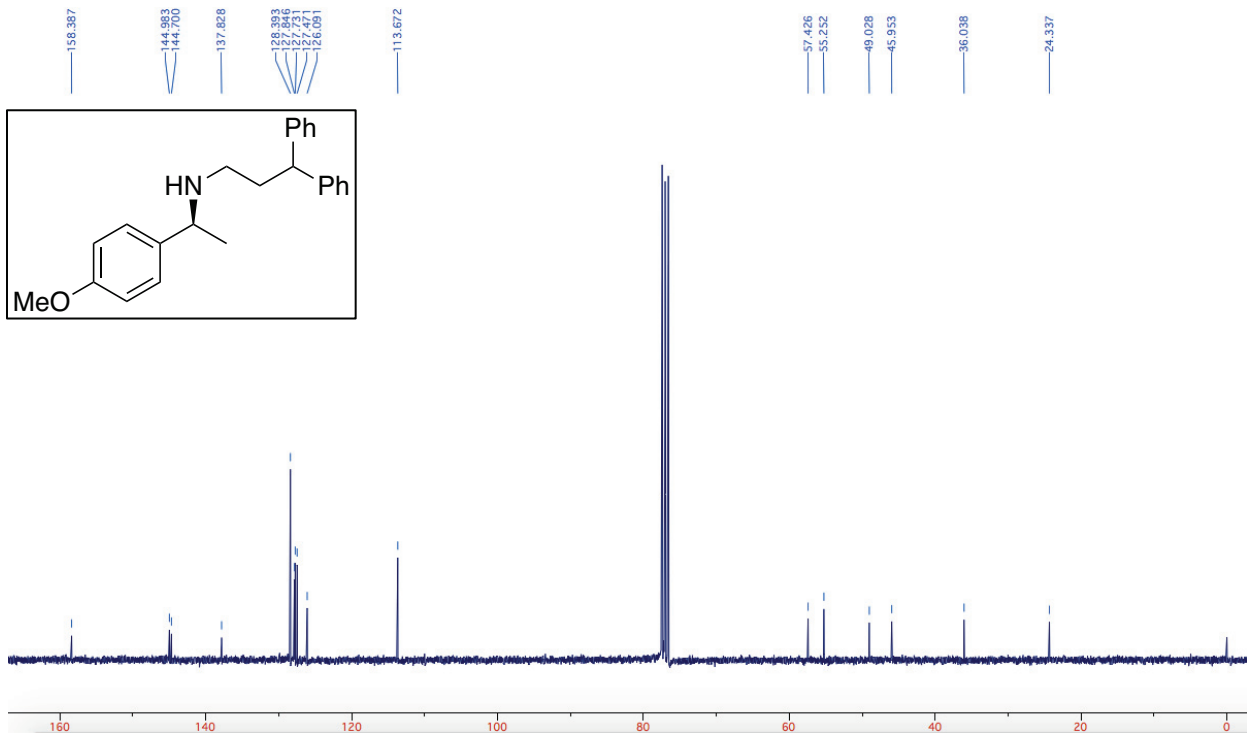
HPLC Data:

(*S*)-*N*-(Prop-2-ynyl)-2,3-dihydro-1*H*-inden-1-amine (3.46):
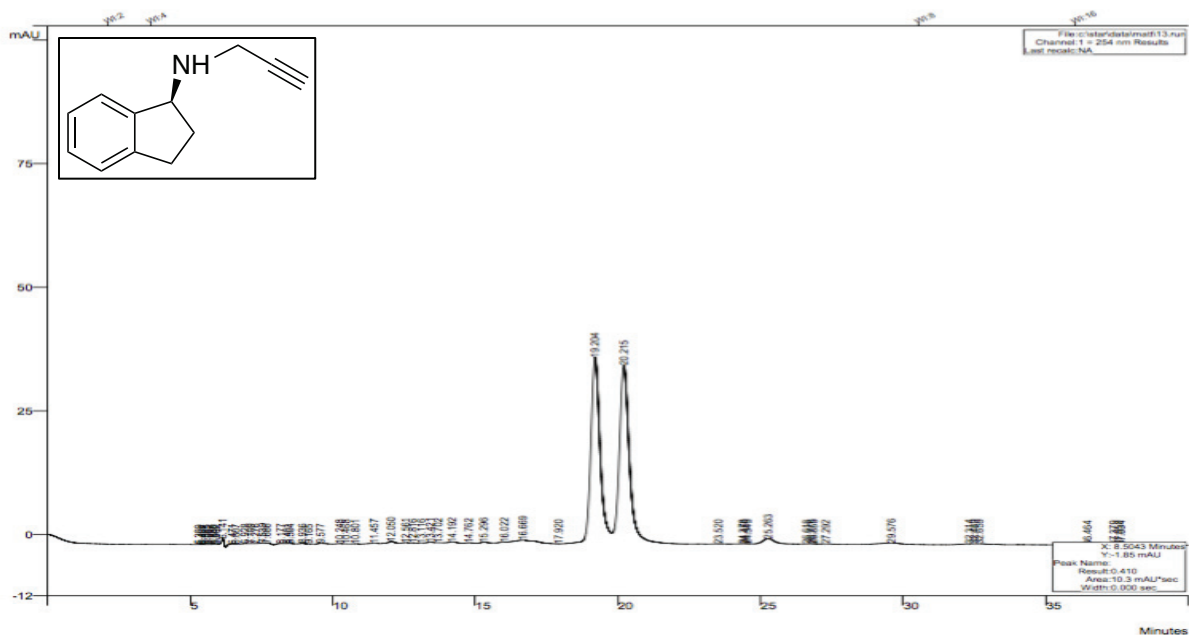
Peak Number	Retention Time	Area Number	Area Percent
1	19.204	9084260	47.1
2	20.215	10200370	52.9
Total			100
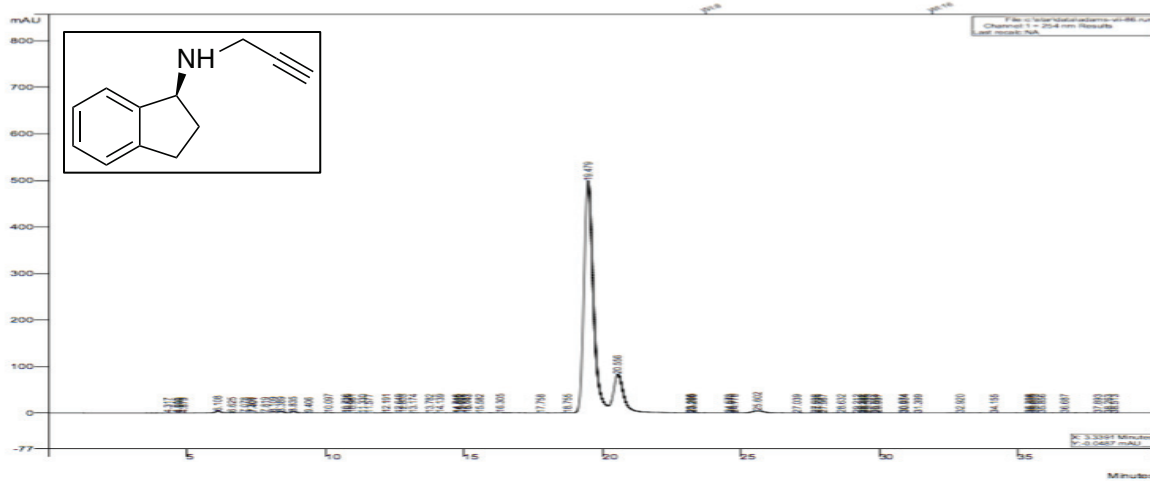
Peak Number	Retention Time	Area Number	Area Percent
1	19.479	117237760	84.0
2	20.556	22666524	16.0
Total			100

(*S*)-*N*-Benzyl-*N'*-(*tert*-butyloxycarbonyl)-2,3-dihydro-1*H*-inden-1-amine (3.47):
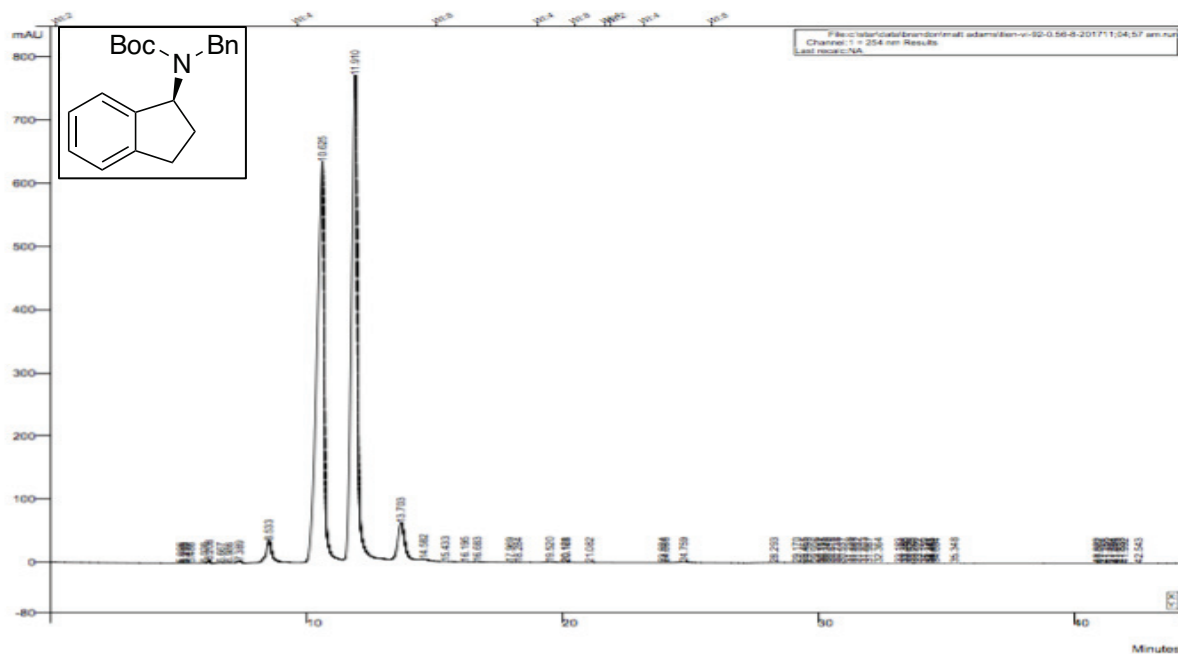
Peak Number	Retention Time	Area Number	Area Percent
1	10.273	31616758	49.5
2	11.989	32270902	50.5
Total			100
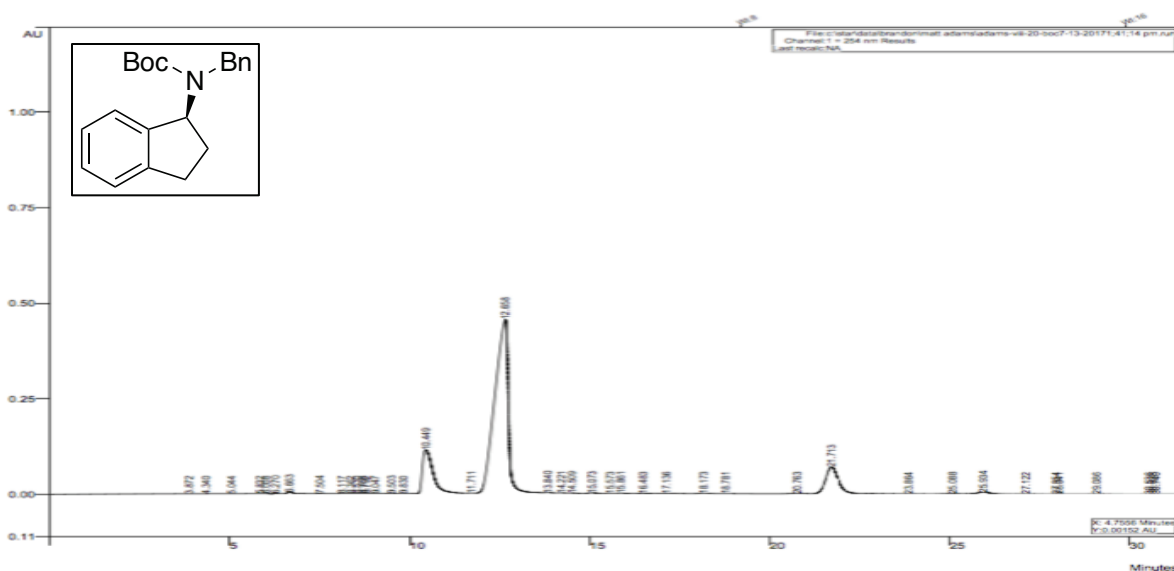
Peak Number	Retention Time	Area Number	Area Percent
1	10.449	24880406	16.7
2	12.658	123652936	83.3
Total			100

(*S*)-*N*-(4-Methoxybenzyl)-1-phenylethanamine (3.48):
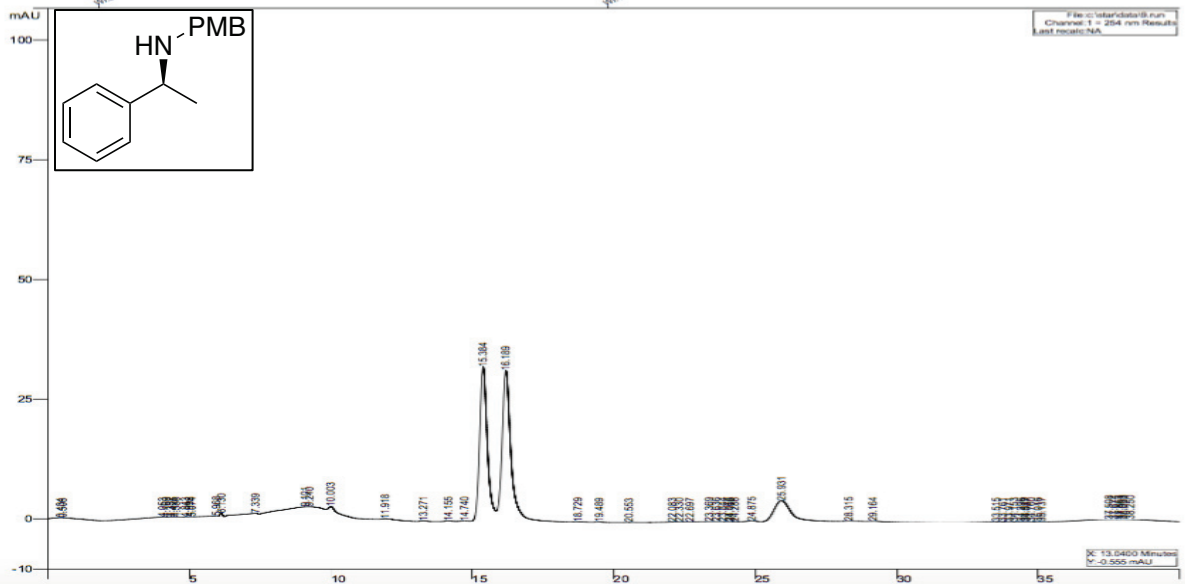
Peak Number	Retention Time	Area Number	Area Percent
1	15.385	6170014	46.4
2	16.189	7127264	53.6
Total			100
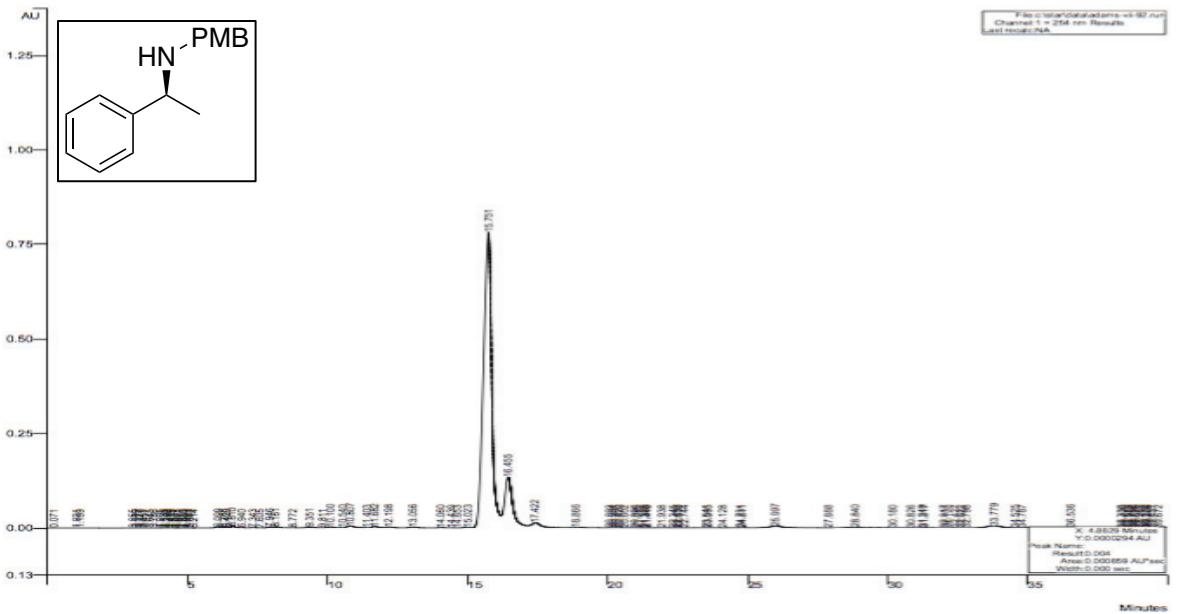
Peak Number	Retention Time	Area Number	Area Percent
1	15.751	159346912	85.2
2	16.455	27598154	14.8
Total			100

(*S*)-*N*-Benzyl-1-(4'-cyanophenyl)ethylamine (3.49):
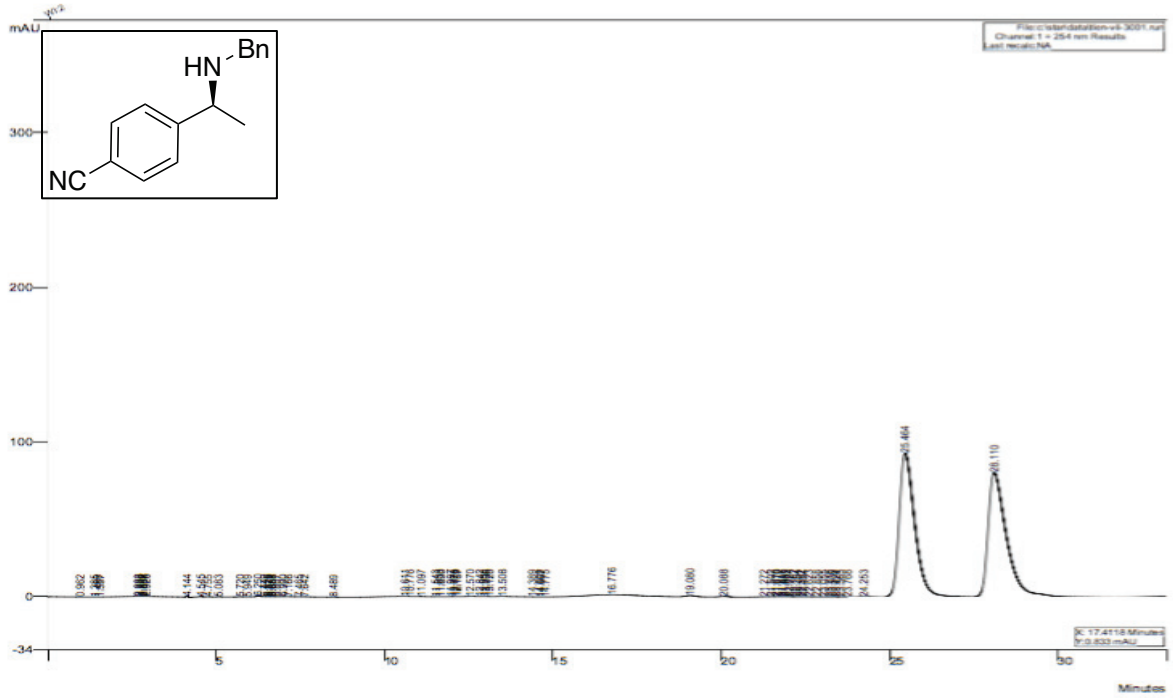
Peak Number	Retention Time	Area Number	Area Percent
1	25.464	30129798	49.5
2	28.110	30733636	50.5
Total			100
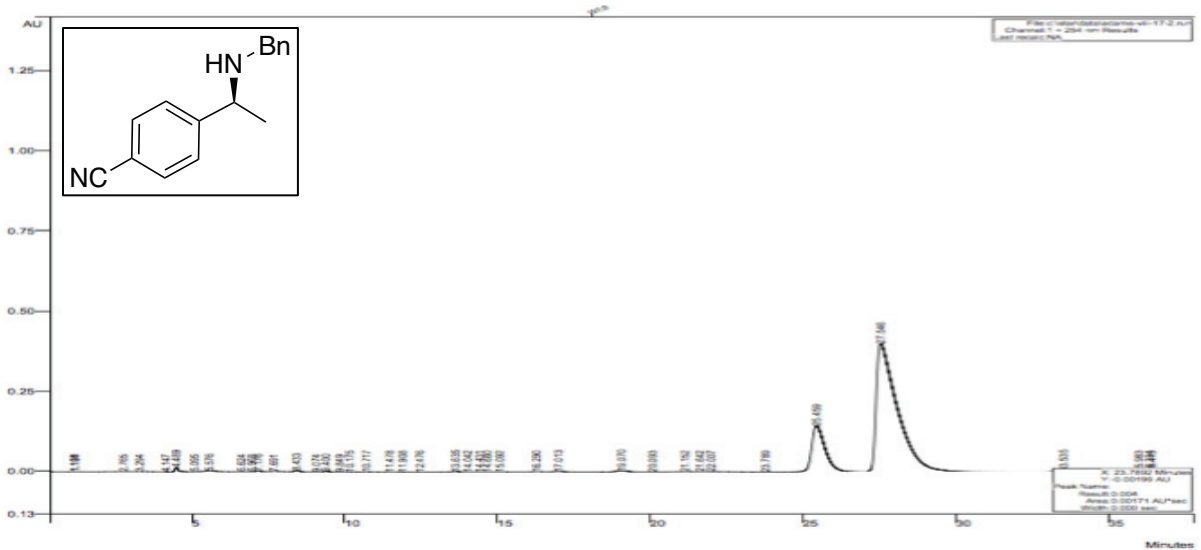
Peak Number	Retention Time	Area Number	Area Percent
1	25.459	44209412	18.6
2	27.546	193222704	81.4
Total			100

(*S*)- *N*-Benzyl-1-(4'-methoxy)phenylethylamine (3.50):
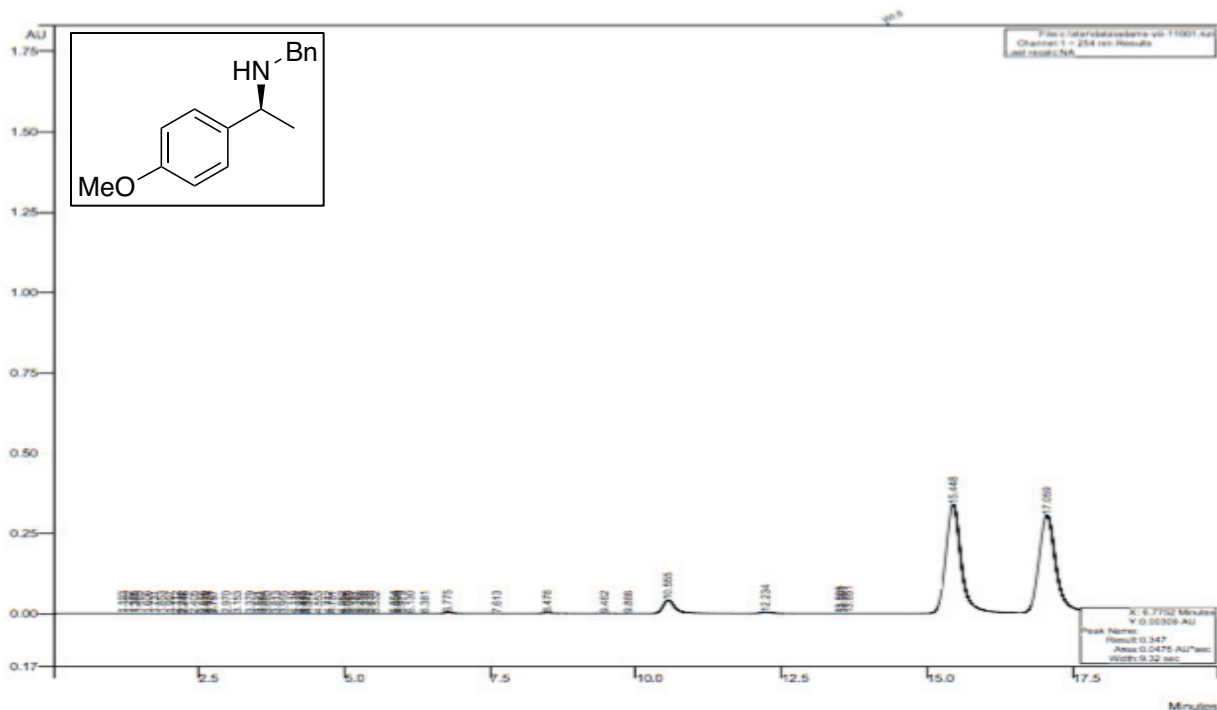
Peak Number	Retention Time	Area Number	Area Percent
1	15.448	63563876	49.4
2	17.059	65099068	50.6
Total			100
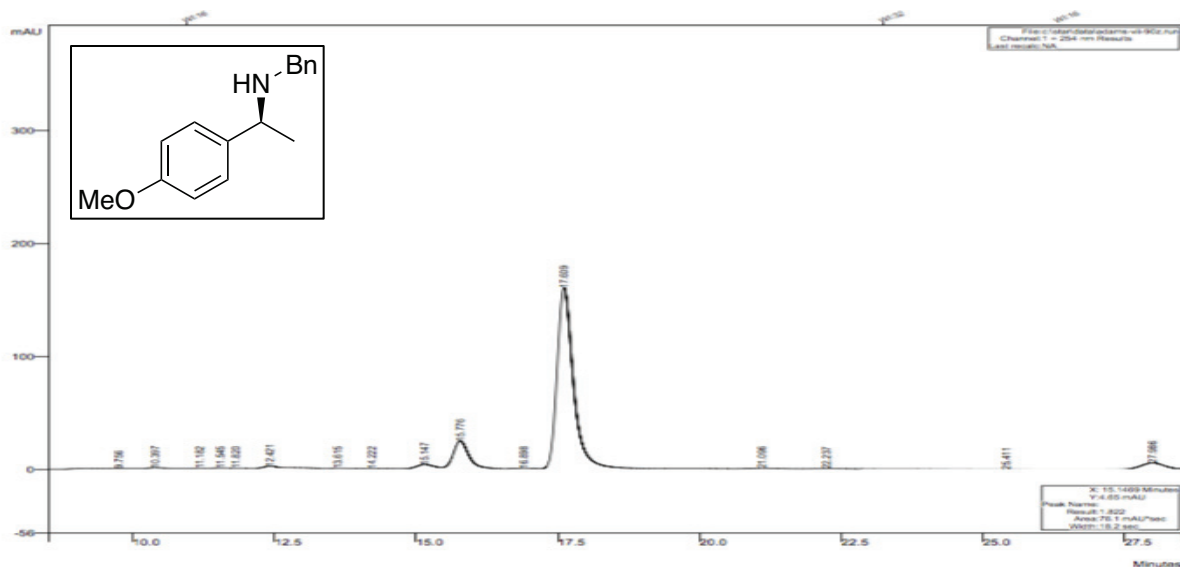
Peak Number	Retention Time	Area Number	Area Percent
1	15.776	4657942	12.7
2	17.609	32082836	87.3
Total			100

(*S*)-*N*-(4-Methoxybenzyl)-1-4-methoxyphenylethanamine (3.51):
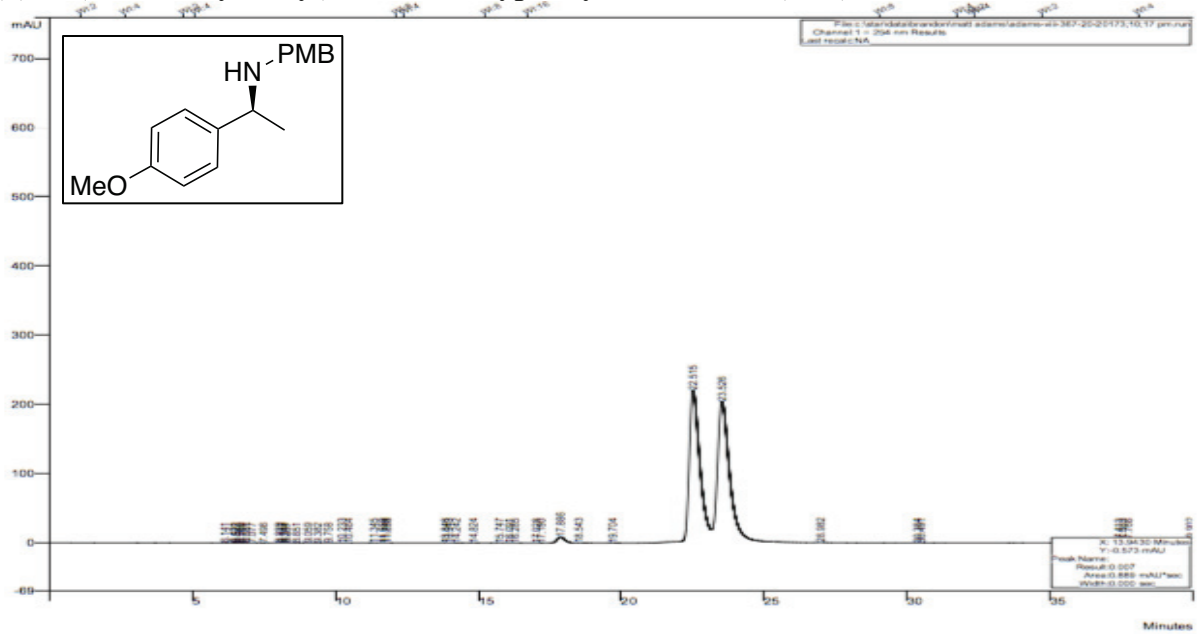
Peak Number	Retention Time	Area Number	Area Percent
1	22.515	57959160	48.1
2	23.526	62616672	51.9
Total			100
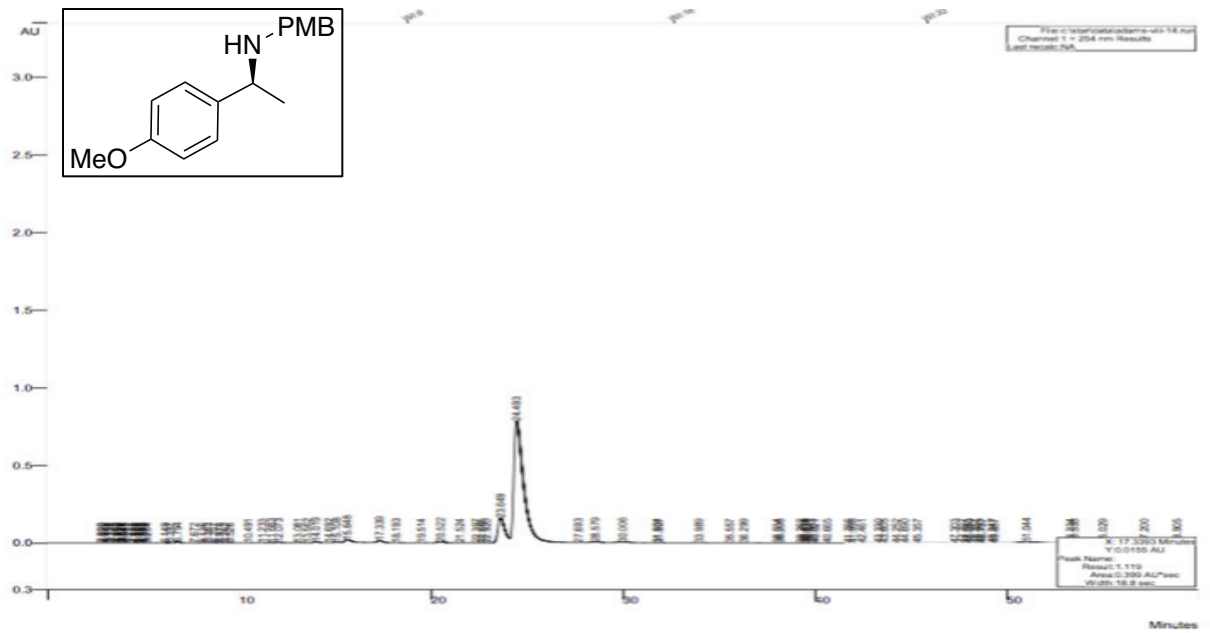
Peak Number	Retention Time	Area Number	Area Percent
1	23.649	40245664	12.4
2	24.493	283656256	87.6
Total			100

(*S*)-*N*-Benzyl-*N*'(*tert*-butyloxycarbonyl)-1-(2-napthyl)ethylamine (3.52):
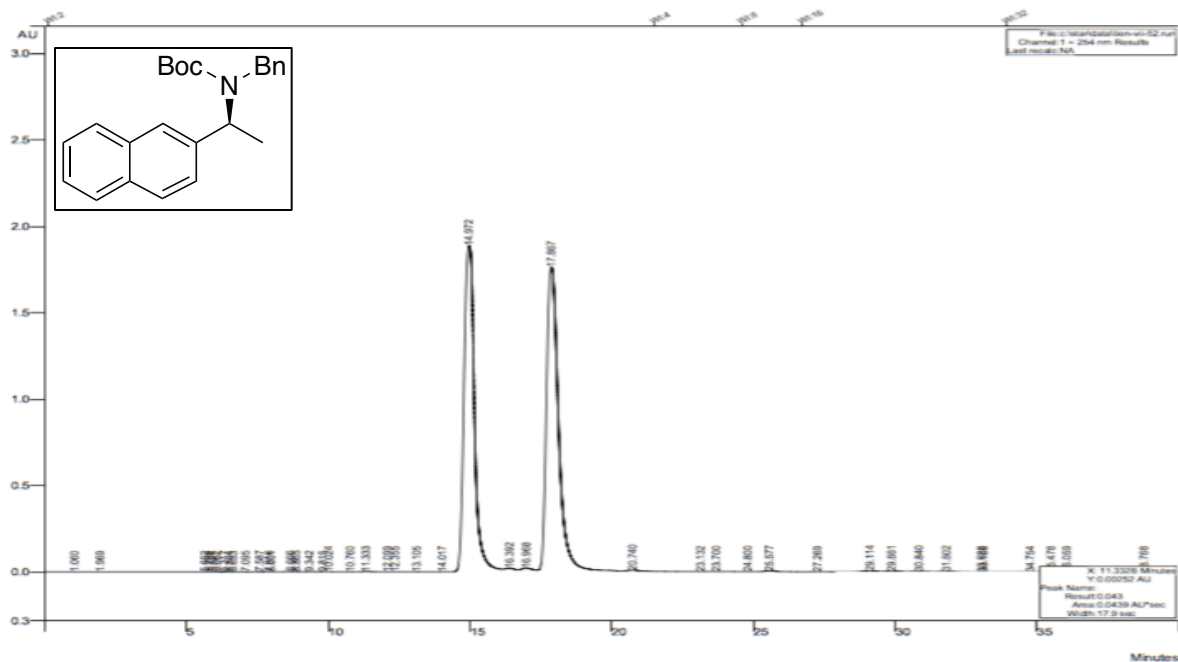
Peak Number	Retention Time	Area Number	Area Percent
1	14.972	487970880	48.3
2	17.867	521642656	51.7
Total			100
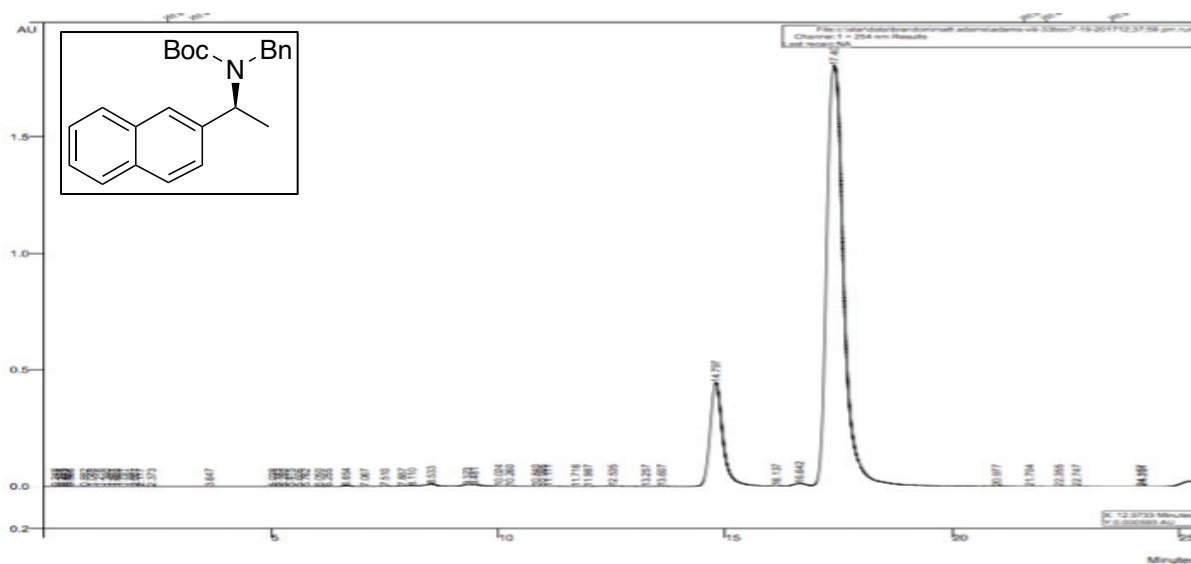
Peak Number	Retention Time	Area Number	Area Percent
1	14.797	89348232	15.9
2	17.409	473328256	84.1
Total			100

(*S*)-*N*-Benzyl-1-(1-napthyl)ethylamine (3.53):
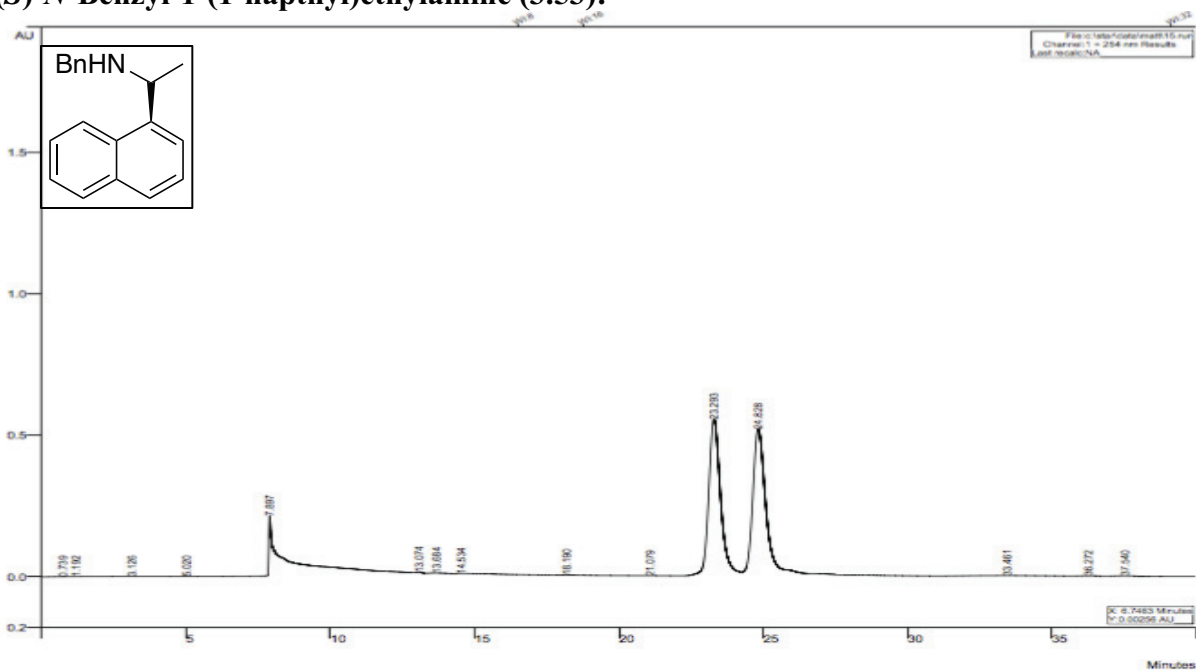
Peak Number	Retention Time	Area Number	Area Percent
1	23.293	159327408	46.7
2	24.828	182111408	53.3
Total			100
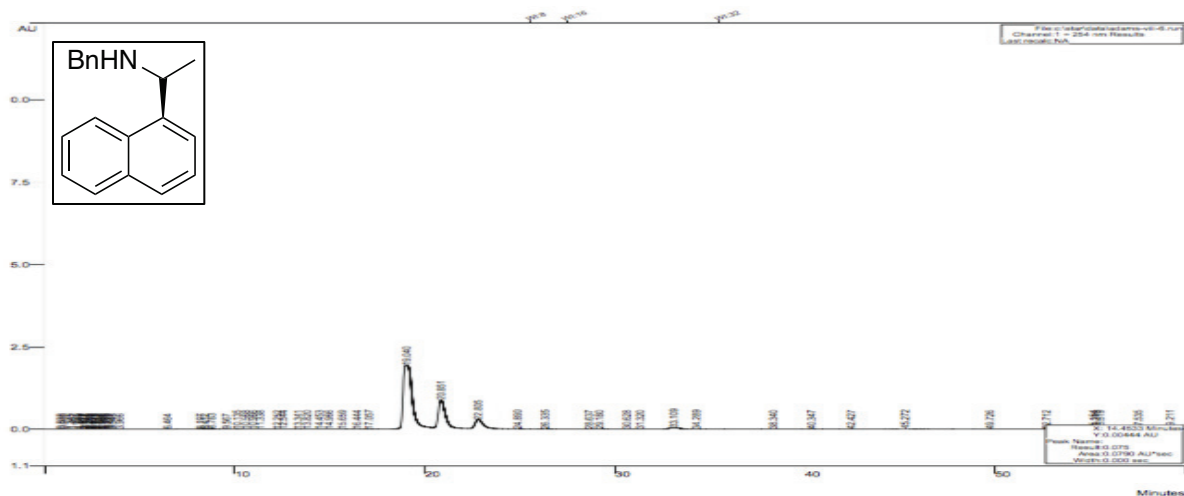
Peak Number	Retention Time	Area Number	Area Percent
1	19.040	650321792	73.0
2	20.851	240944624	27.0
Total			100

(*S*)-*N*-(4-Methoxybenxyl)-*N*'(*tert*-butyloxycarbonyl) -1-(2'-chlorophenyl)ethylamine

(3.54):
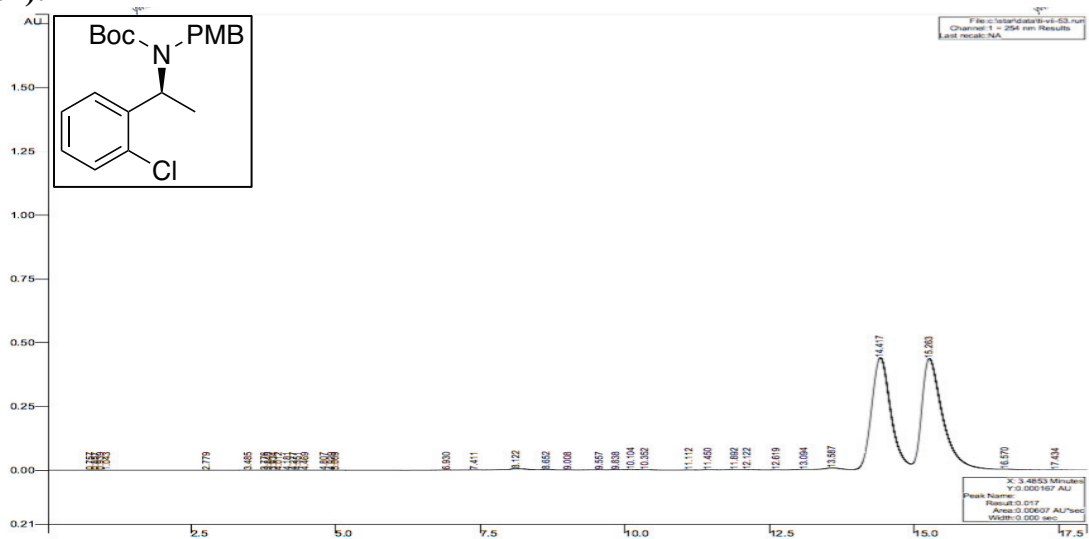
Peak Number	Retention Time	Area Number	Area Percent
1	14.417	101643136	48.0
2	15.263	110339000	52.0
Total			100
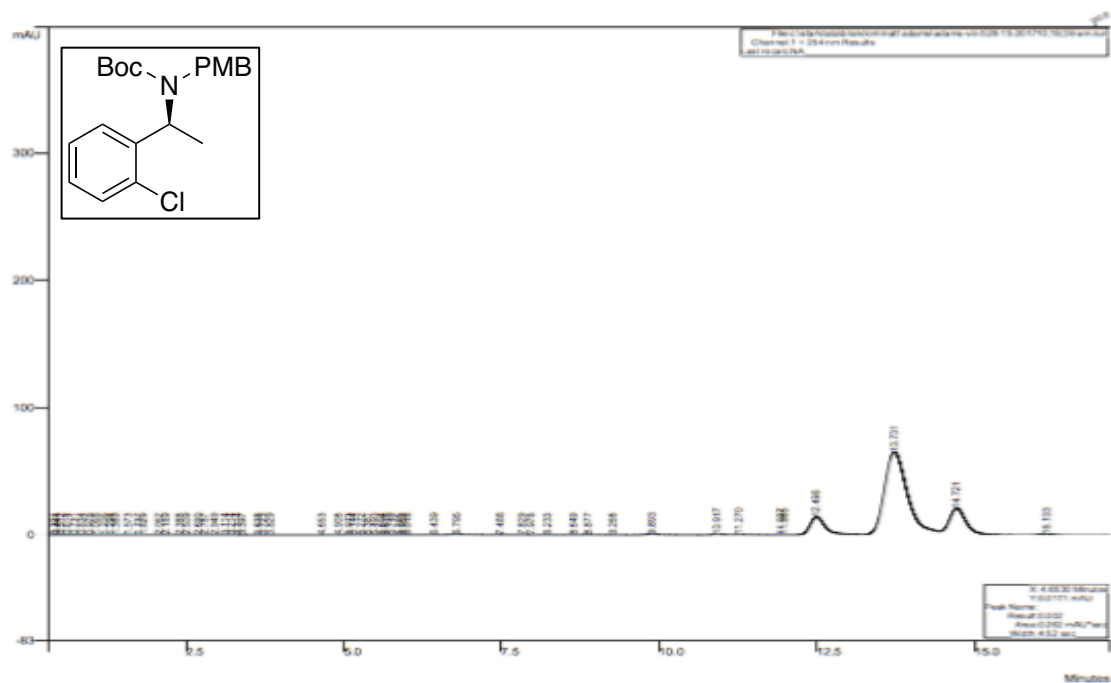
Peak Number	Retention Time	Area Number	Area Percent
1	13.731	16573251	80.2
2	14.721	4083228	19.8
Total			100

(*S*)-*N*-(4'-Methoxybenzyl)-1-propargylphenylethanamine (3.55):
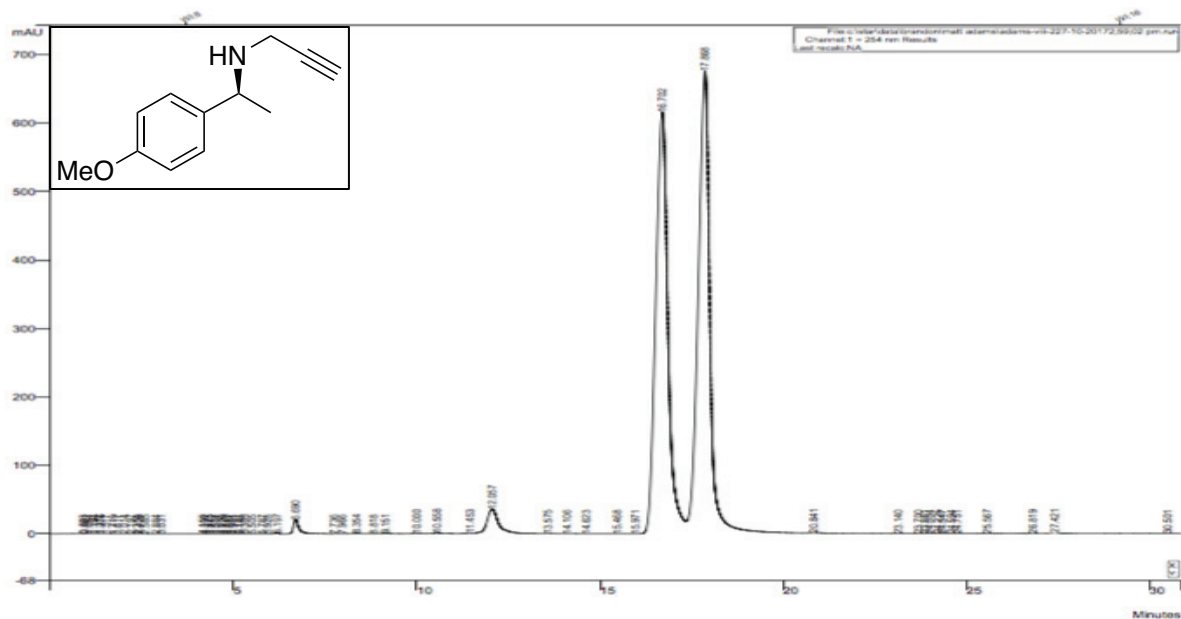
Peak Number	Retention Time	Area Number	Area Percent
1	16.702	142683344	48.7
2	17.868	150623104	51.4
Total			100
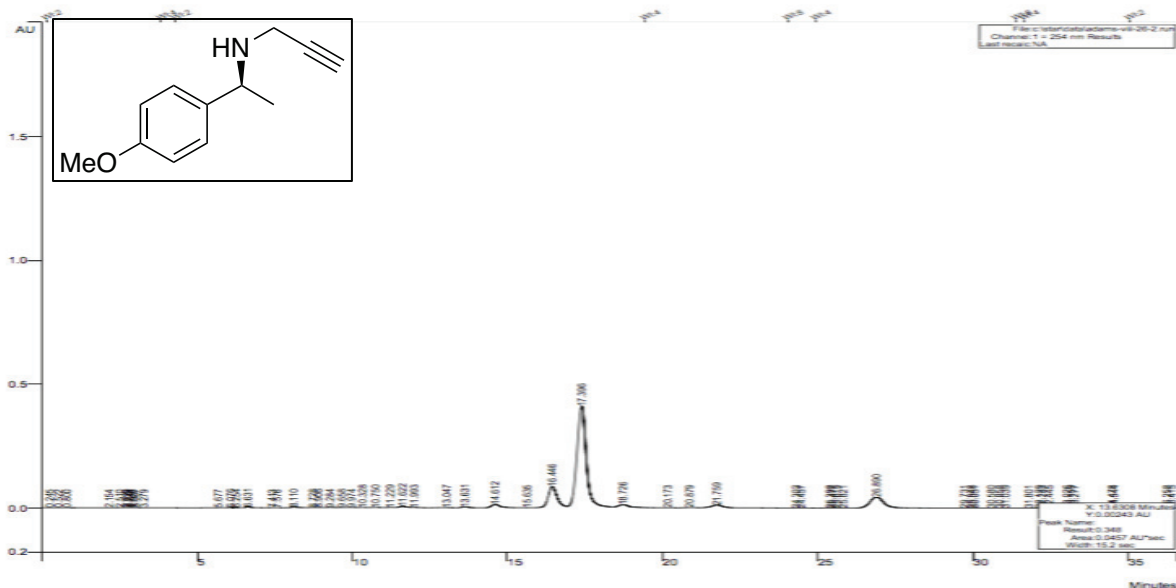
Peak Number	Retention Time	Area Number	Area Percent
1	16.446	17032282	16.3
2	17.396	87309864	83.7
Total			100

(S)-N-Propargyl-1-(4'-cyanophenyl)ethylamine (3.56):
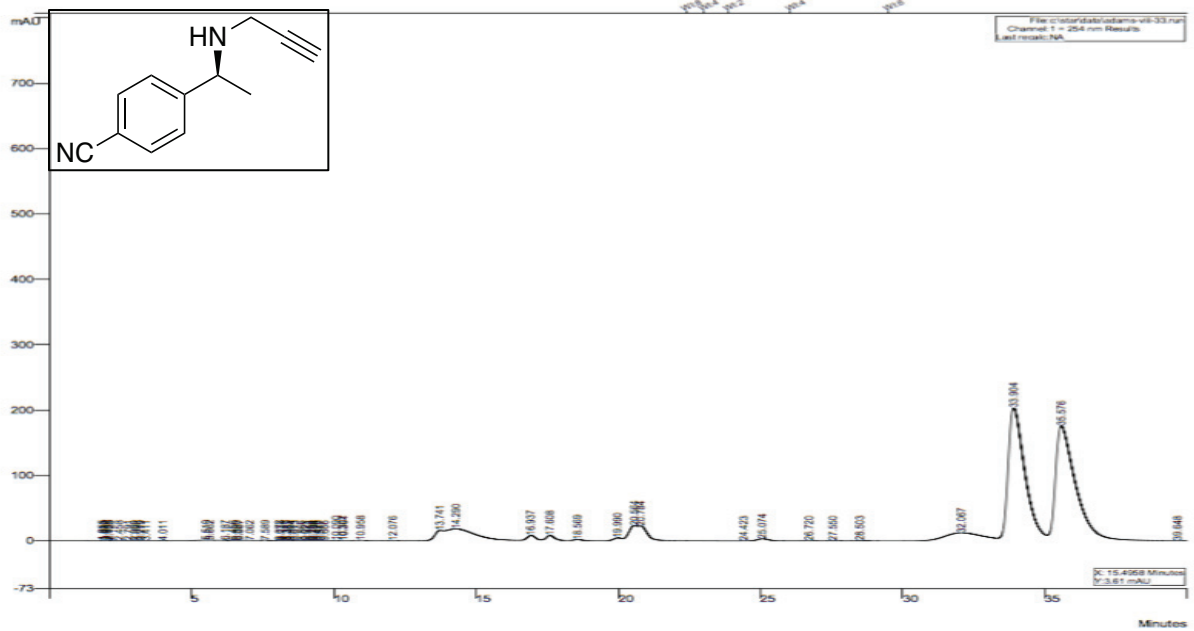
Peak Number	Retention Time	Area Number	Area Percent
1	33.904	83542896	49.0
2	35.576	86903032	51.0
Total			100
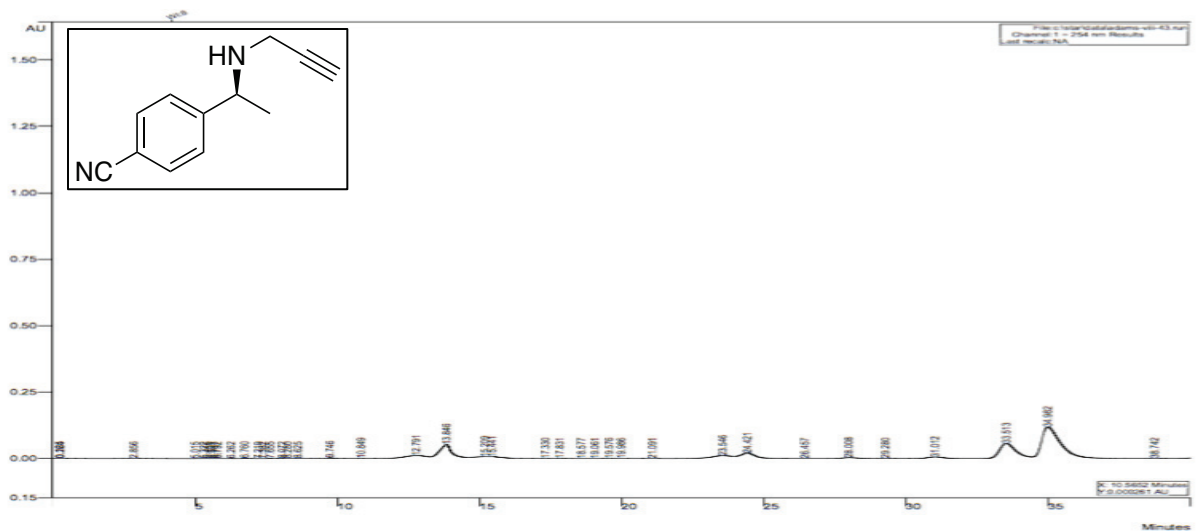
Peak Number	Retention Time	Area Number	Area Percent
1	33.513	22747478	29.3
2	34.982	54919888	70.7
Total			100

(*S*)-*N*-Benzyl-*N'*-(*tert*-butyloxycarbonyl)-2-methyl-1-phenylpropylamine (3.57):
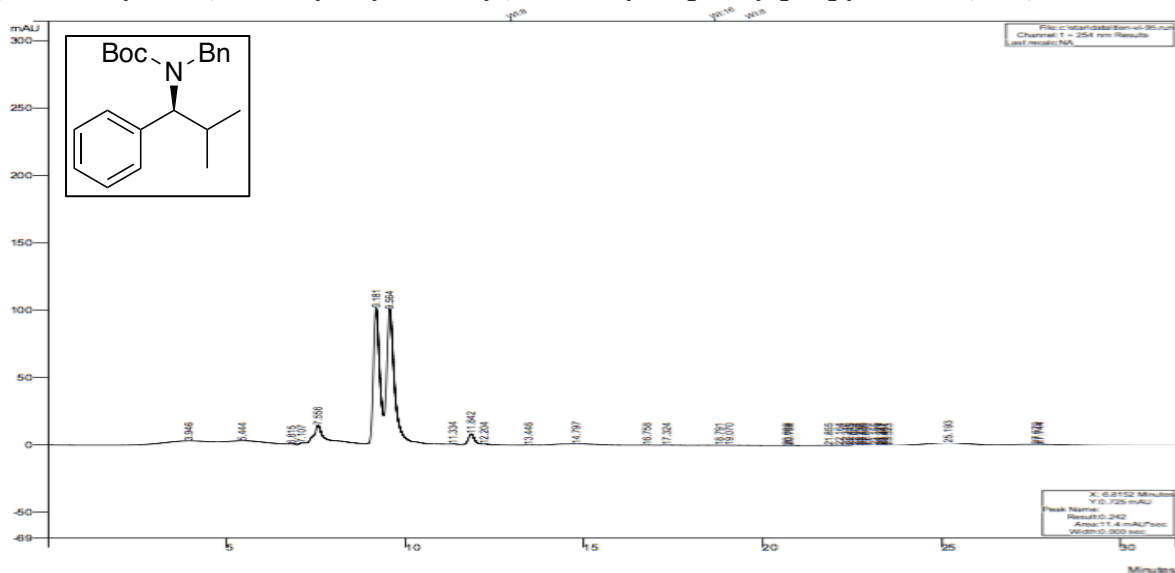
Peak Number	Retention Time	Area Number	Area Percent
1	9.181	12526939	43.1
2	9.564	16511595	56.9
Total			100
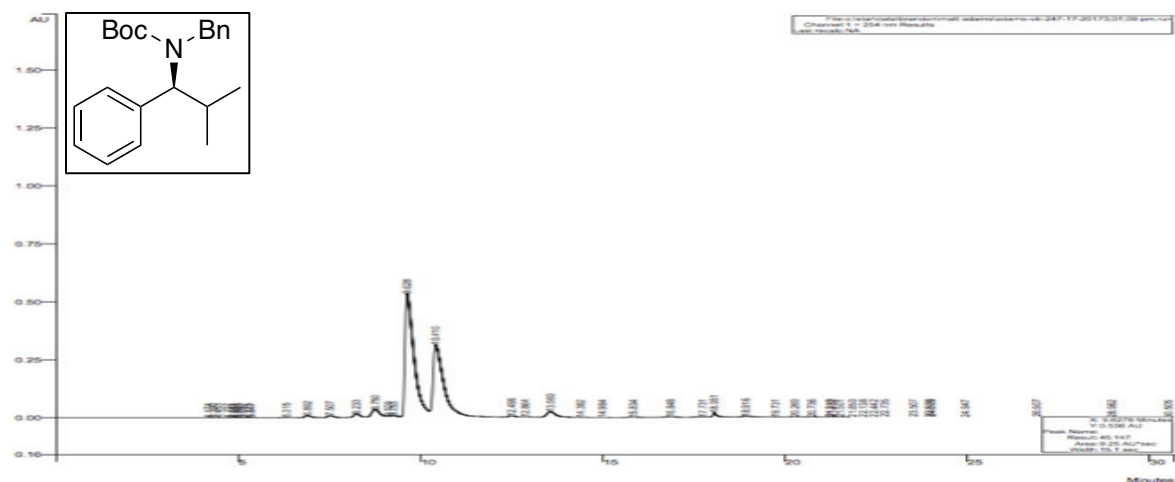
Peak Number	Retention Time	Area Number	Area Percent
1	9.628	92526752	55.0
2	10.410	75554792	45.0
Total			100

(*S*)-*N*-Cyclohexyl-*N*'(*tert*-butyloxycarbonyl)-1-(4'-methoxyphenyl)ethylamine (3.58):
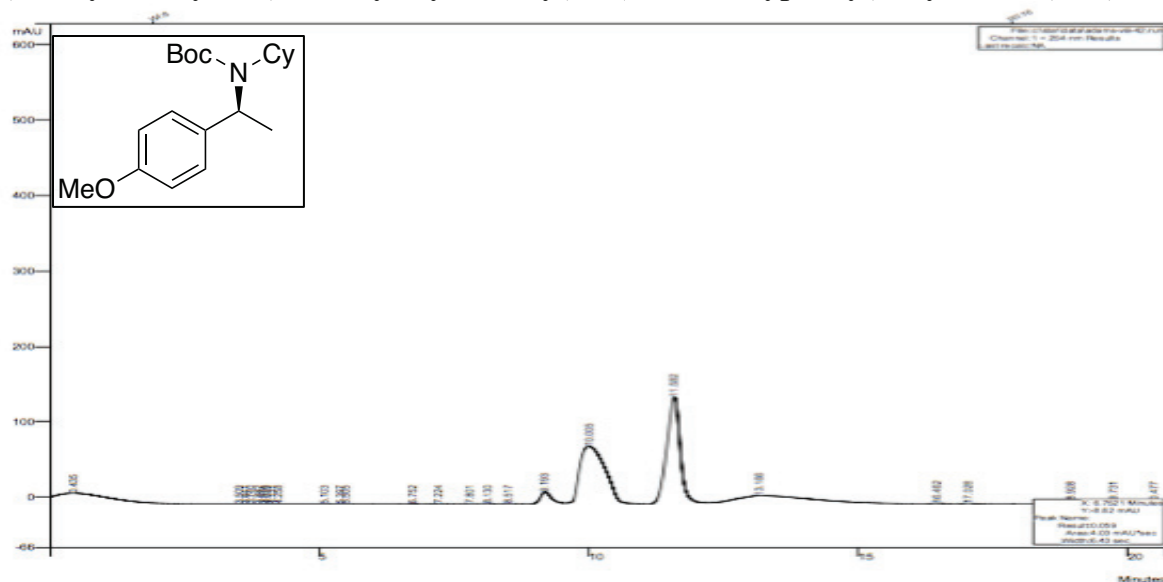
Peak Number	Retention Time	Area Number	Area Percent
1	10.005	24977048	48.1
2	11.582	26975324	51.9
Total			100
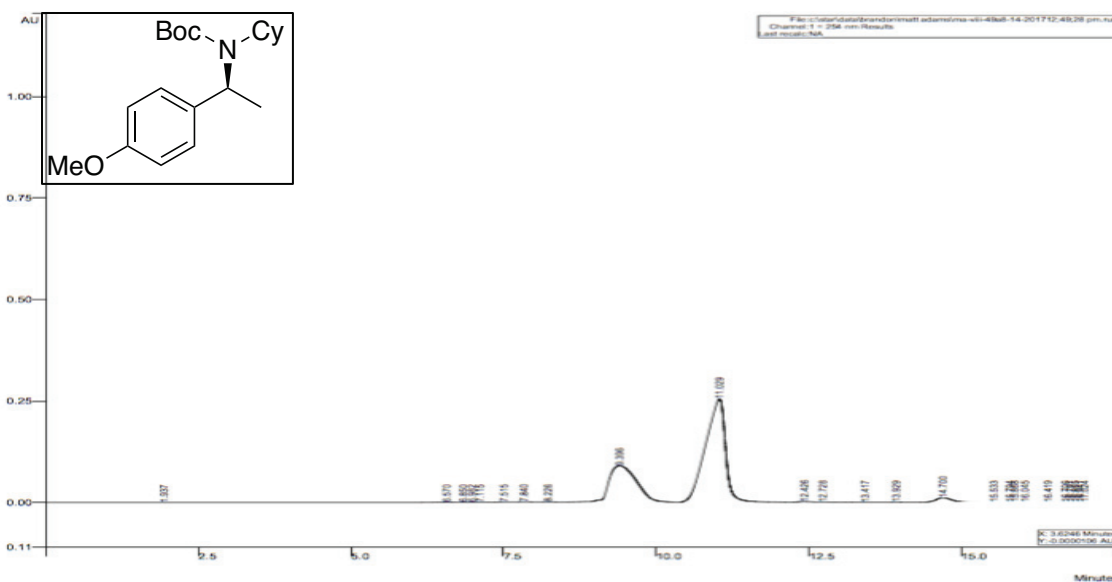
Peak Number	Retention Time	Area Number	Area Percent
1	9.396	28543750	32.8
2	11.029	58542280	67.2
Total			100

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(*S*)-*N*-Cyclopropyl-1-(4-methoxyphenyl)ethylamine (3.59):
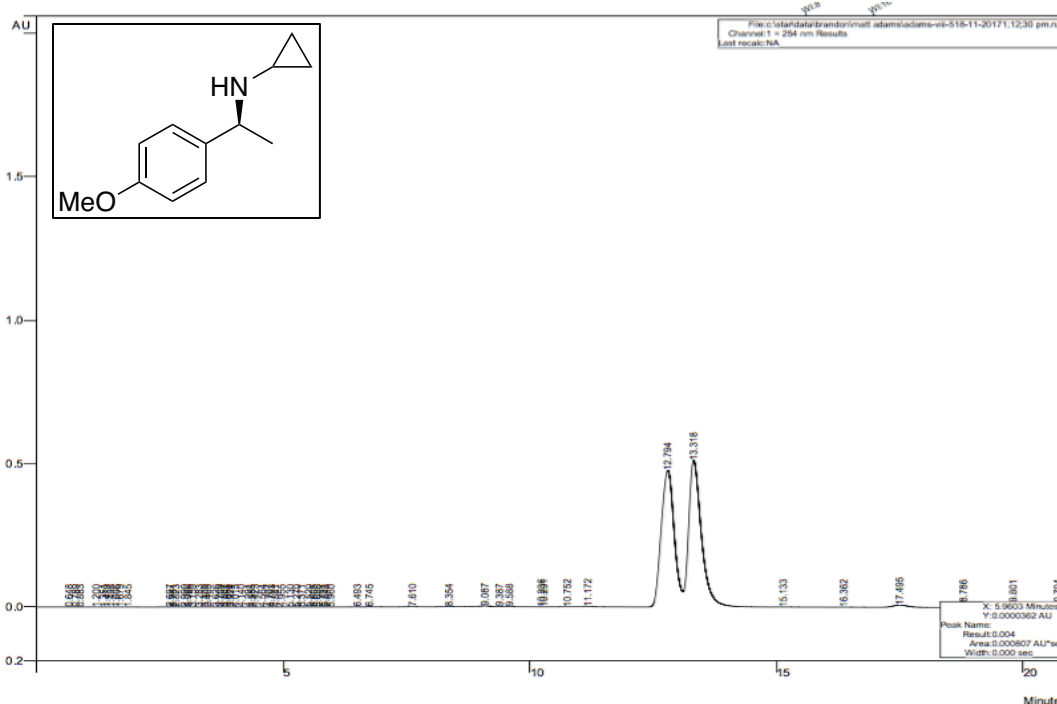
Peak Number	Retention Time	Area Number	Area Percent
1	12.794	86945880	48.4
2	13.318	92660976	51.6
Total			100
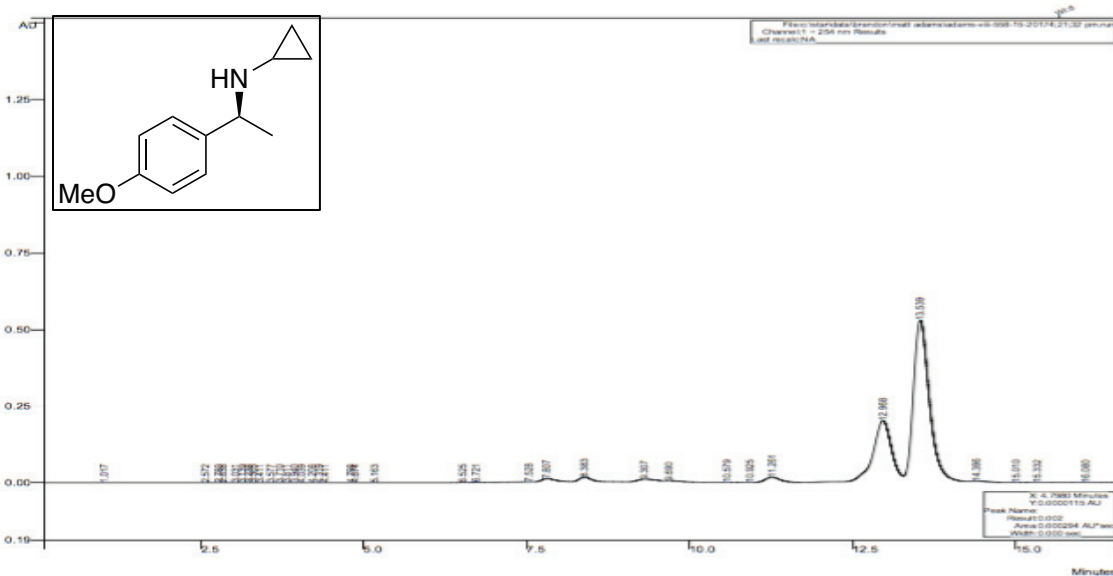
Peak Number	Retention Time	Area Number	Area Percent
1	12.968	41130564	31.0
2	13.539	91597512	69.0
Total			100

(*S*)-*N*-Benzyl-1-(pyridin-2-yl)ethanamine (3.60):
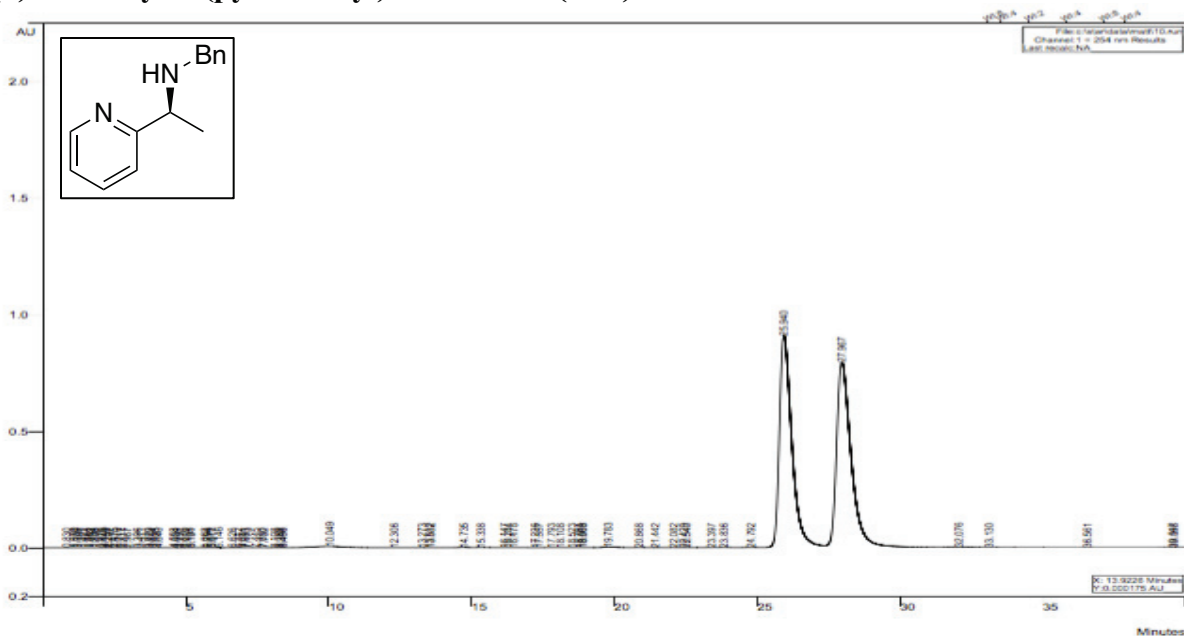
Peak Number	Retention Time	Area Number	Area Percent
1	25.940	274765728	49.3
2	27.967	282252512	50.7
Total			100
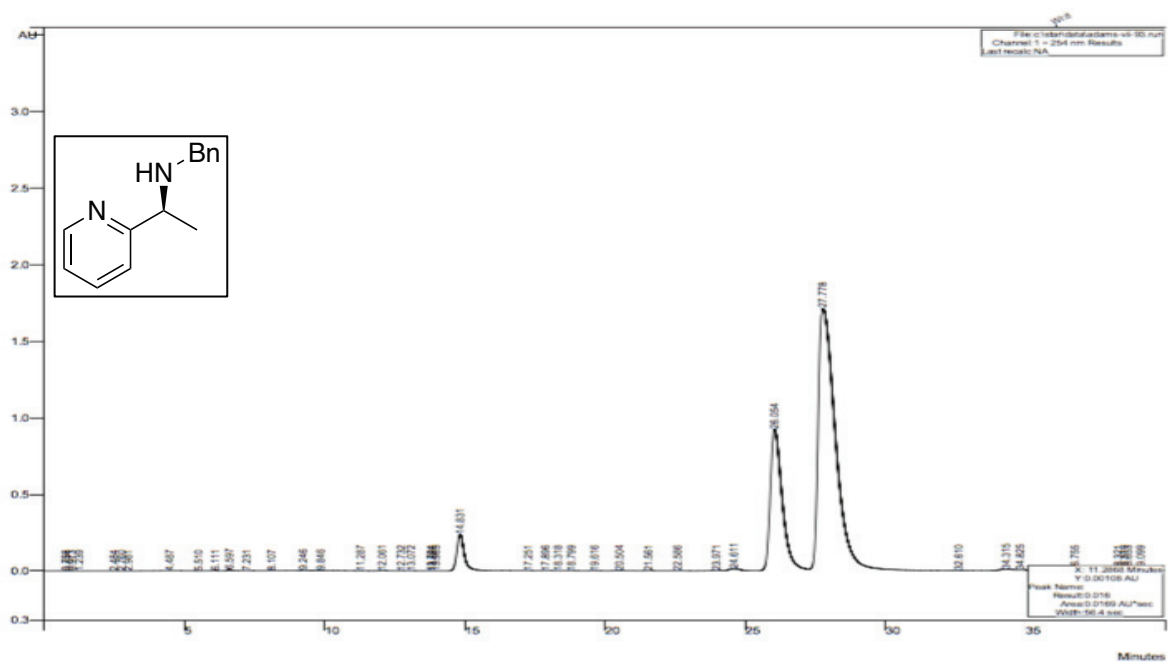
Peak Number	Retention Time	Area Number	Area Percent
1	26.054	274547328	27.1
2	27.778	737005440	72.9
Total			100

(*S*)-*N*-Furfuryl-*N*'(*tert*-butyloxycarbonyl)-1-(phenyl)ethylamine (3.61):
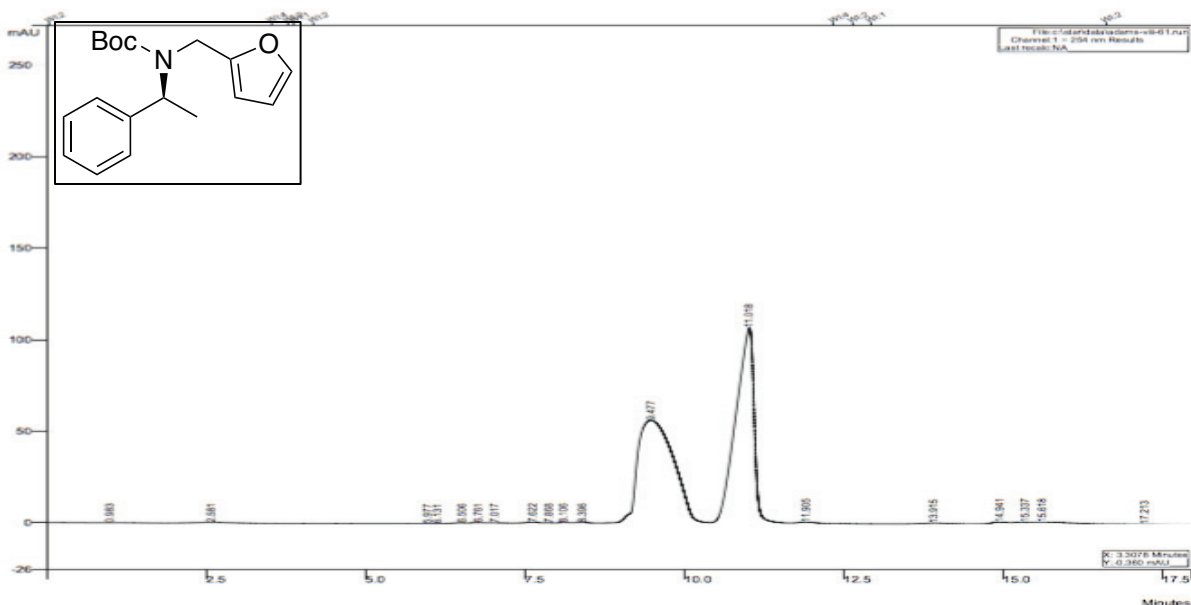
Peak Number	Retention Time	Area Number	Area Percent
1	9.477	22119146	50.9
2	11.018	21375070	49.1
Total			100
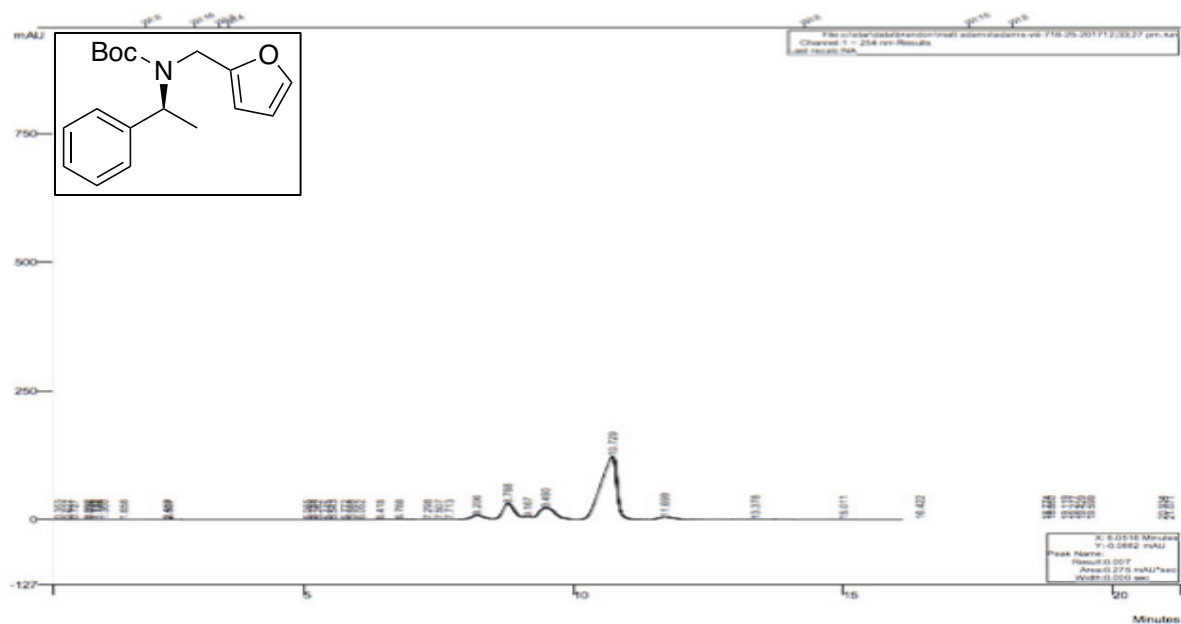
Peak Number	Retention Time	Area Number	Area Percent
1	9.490	4861976	16.1
2	10.729	25290782	83.9
Total			100

(*S*)-*N*-Benzyl-*N'*-(*tert*-butyloxycarbonyl)-1-(ferrocene)ethylamine (3.62):
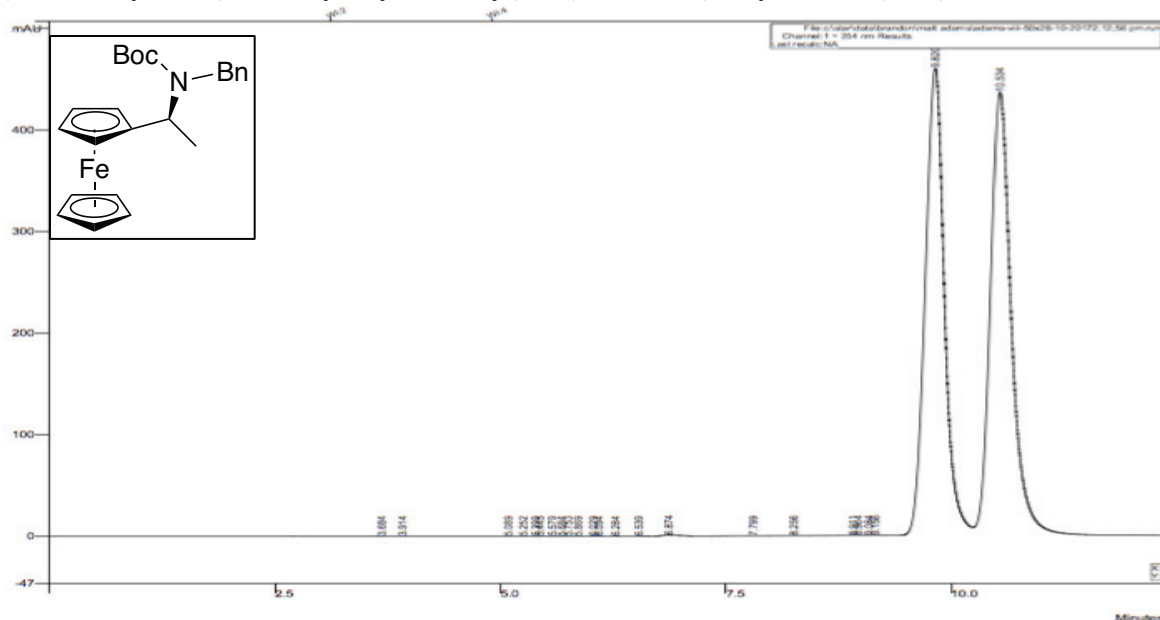
Peak Number	Retention Time	Area Number	Area Percent
1	9.820	67832912	49.4
2	10.534	69515256	50.6
Total			100
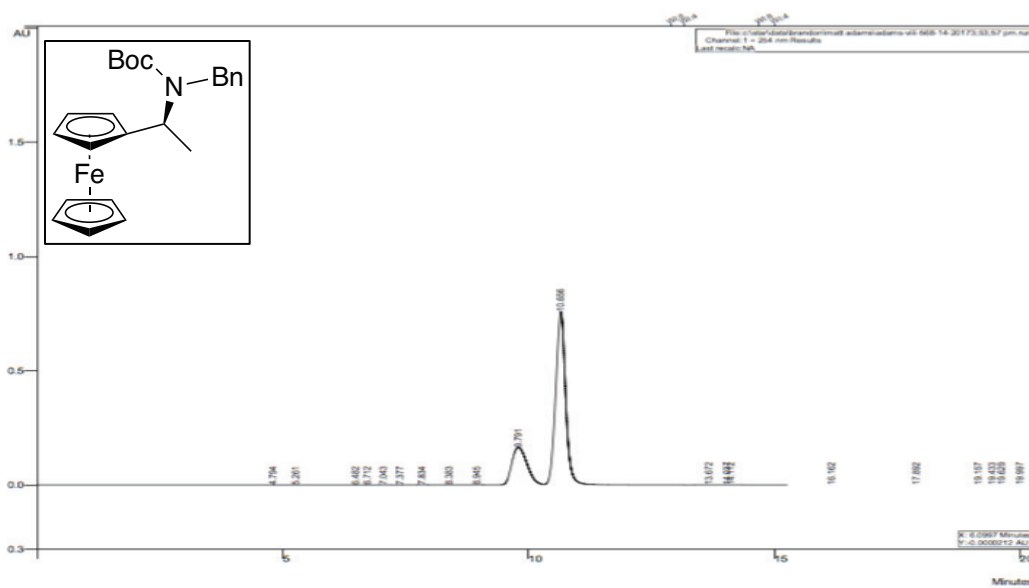
Peak Number	Retention Time	Area Number	Area Percent
1	9.791	35300960	24.8
2	10.656	106863392	75.2
Total			100

(S)-N-Benzyl-N'(tert-butyloxycarbonyl)-1-(3,4,5-trimethoxyphenyl)ethylamine

(3.63):
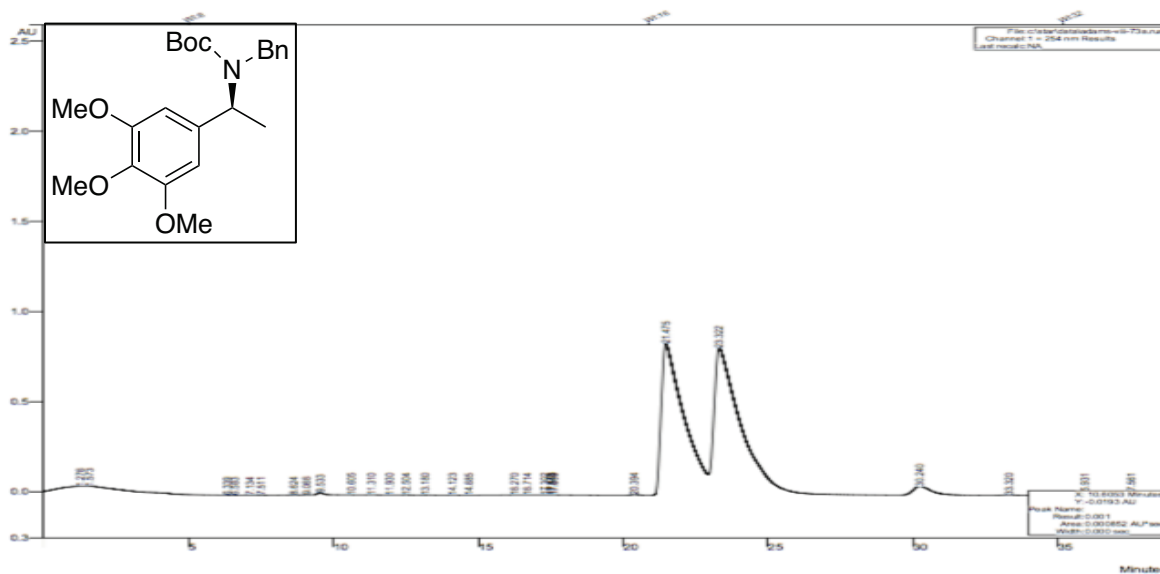
Peak Number	Retention Time	Area Number	Area Percent
1	21.475	457205024	46.0
2	23.322	535962944	54.0
Total			100
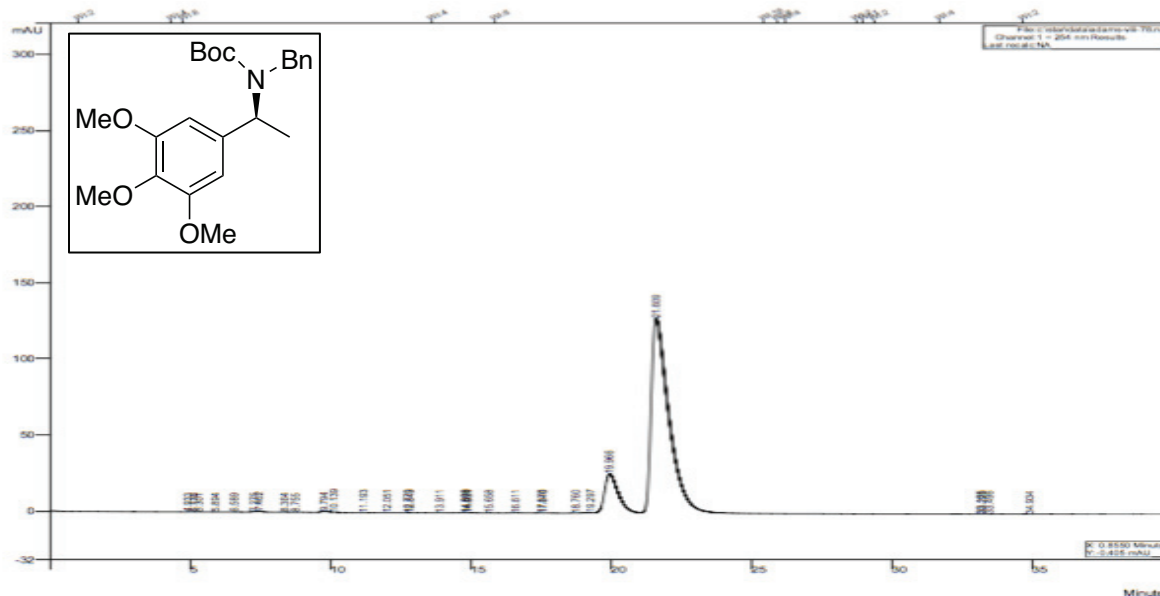
Peak Number	Retention Time	Area Number	Area Percent
1	19.966	8726246	13.4
2	21.609	56475168	86.6
Total			100

(*S*)-*N*-Paramethoxybenzyl-*N'*(*tert*-butyloxycarbonyl)-1-(3,4,5-

trimethoxyphenyl)ethylami-ne (3.64):
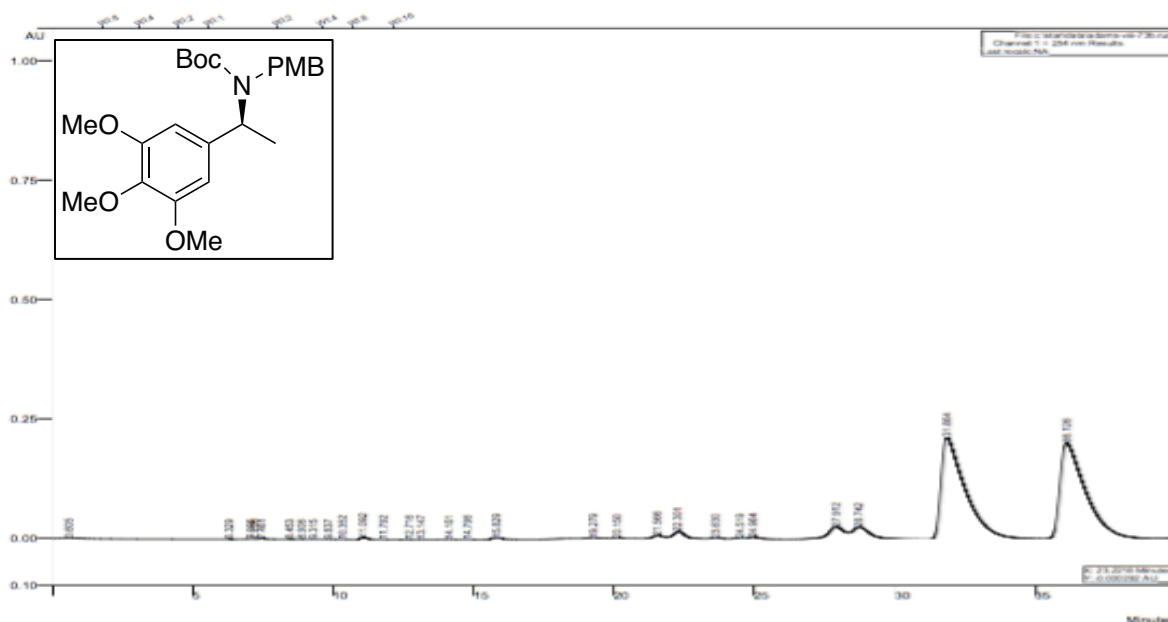
Peak Number	Retention Time	Area Number	Area Percent
1	31.864	126499648	50.1
2	36.126	125890680	49.9
Total			100
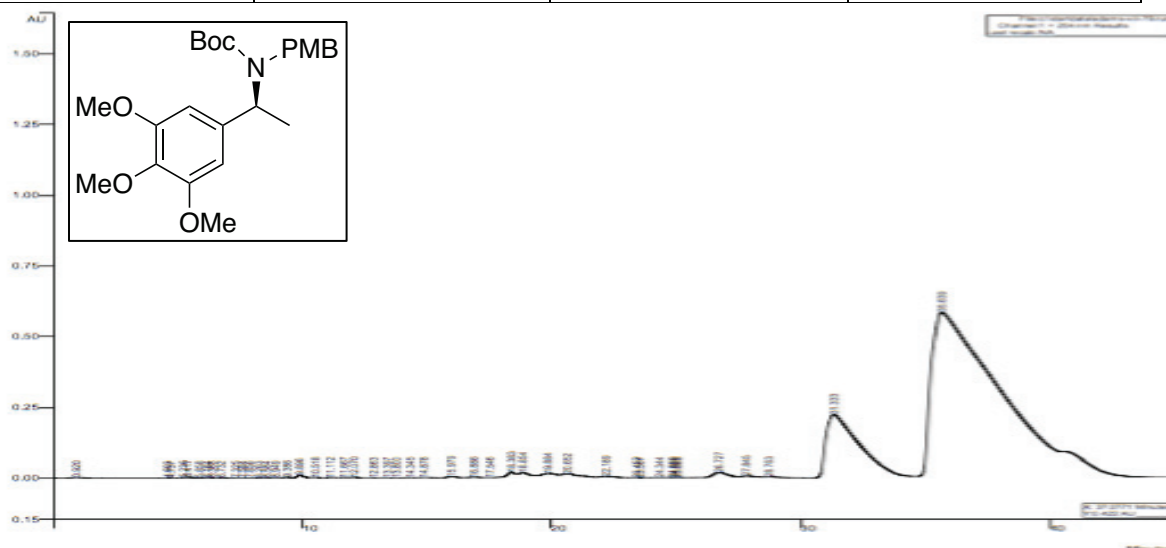
Peak Number	Retention Time	Area Number	Area Percent
1	31.333	210011648	15.6
2	35.639	1138111616	84.4
Total			100

(*S*)-*N*-2,2-Diphenylpropyl-1-(phenyl)ethylamine (3.65):
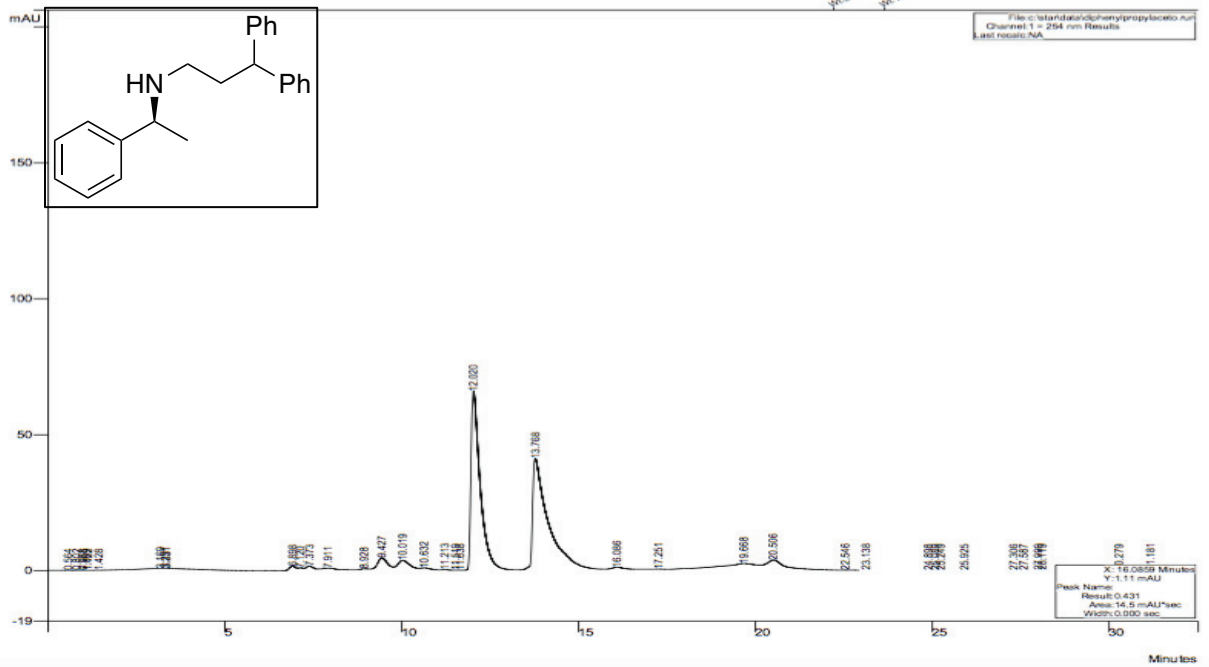
Peak Number	Retention Time	Area Number	Area Percent
1	12.020	12071653	46.7
2	13.768	13760089	53.3
Total			100
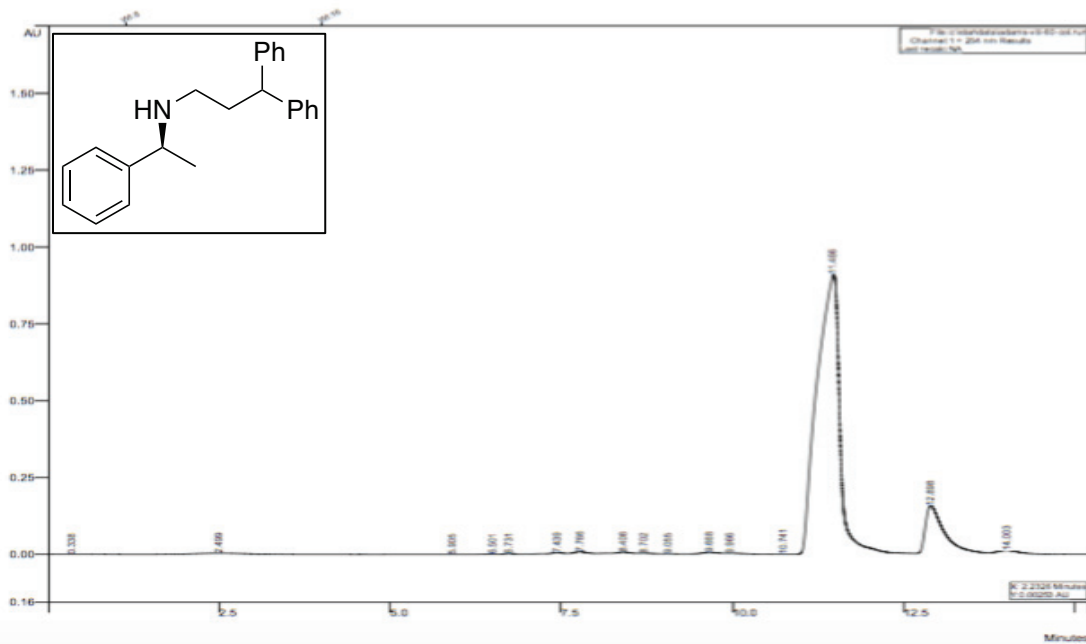
Peak Number	Retention Time	Area Number	Area Percent
1	11.466	212426128	86.4
2	12.898	33514450	13.6
Total			100

(S)-N-Phenyl-1-(phenyl)ethylamine (3.66):
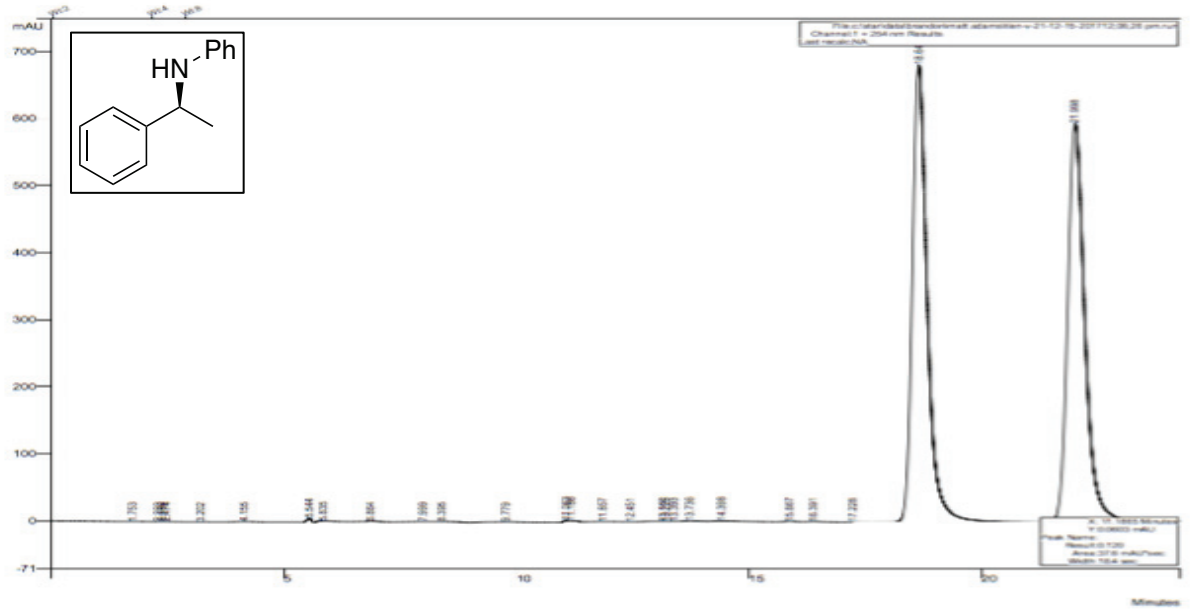
Peak Number	Retention Time	Area Number	Area Percent
1	18.645	151542192	50.0
2	21.998	151795968	50.0
Total			100
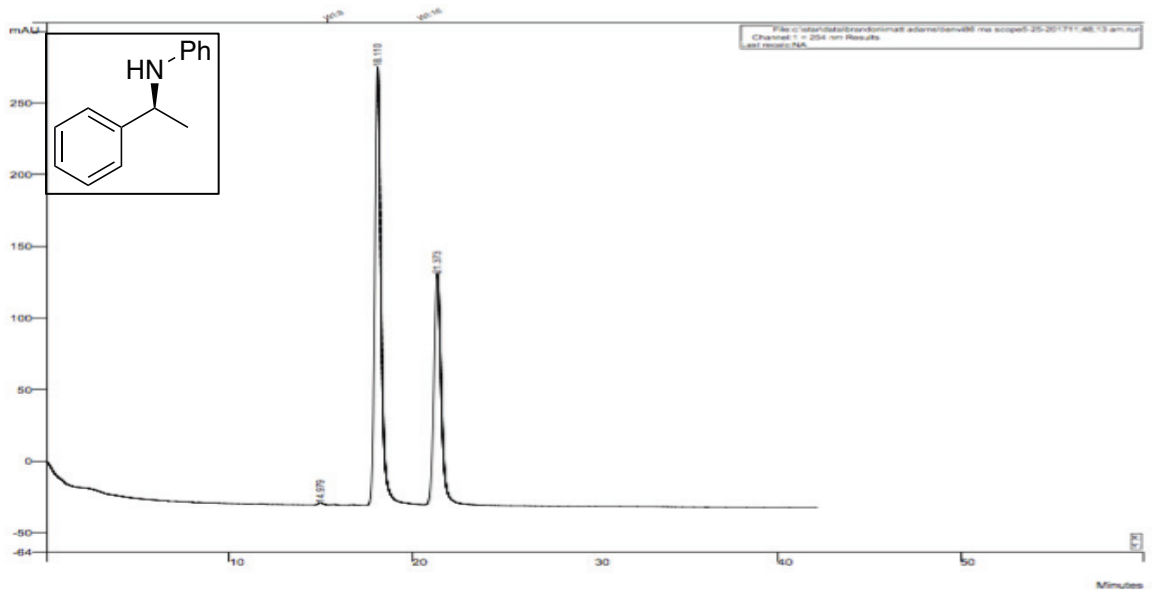
Peak Number	Retention Time	Area Number	Area Percent
1	18.110	72886536	61.8
2	21.373	45066848	38.2
Total			100

338

(*S*)-*N*-Phenyl-1-(4-methoxyphenyl)ethylamine (3.67):
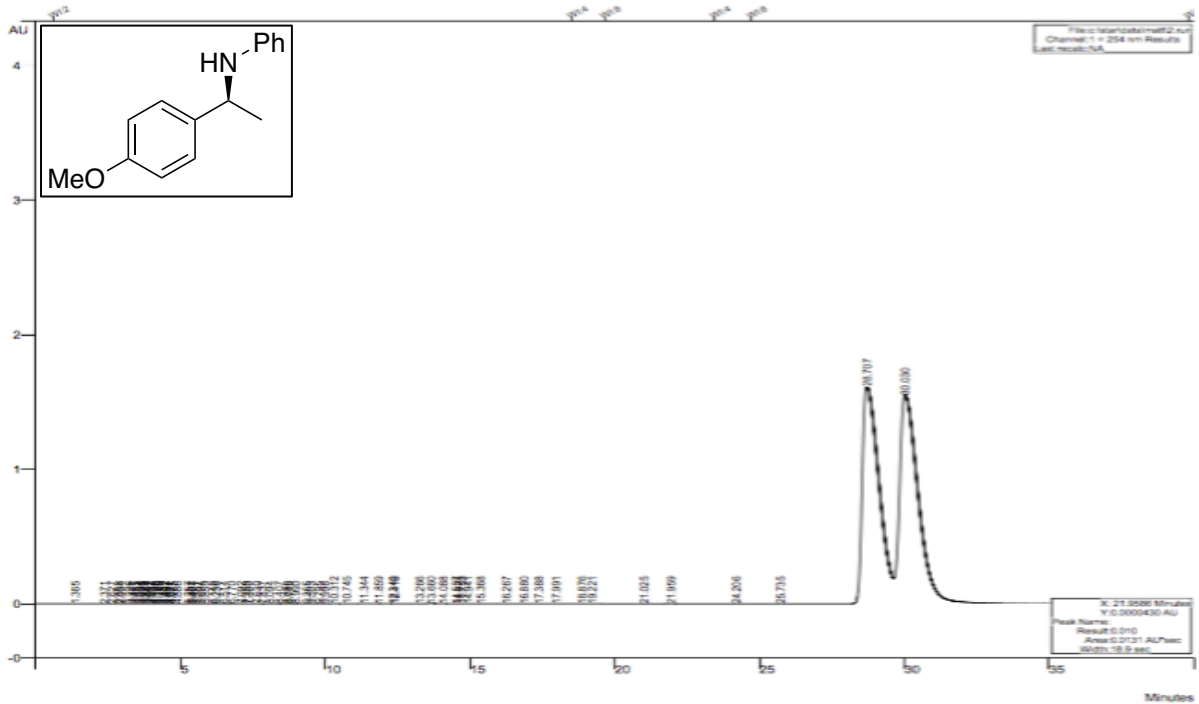
Peak Number	Retention Time	Area Number	Area Percent
1	28.707	646070592	47.9
2	30.030	703743552	52.1
Total			100
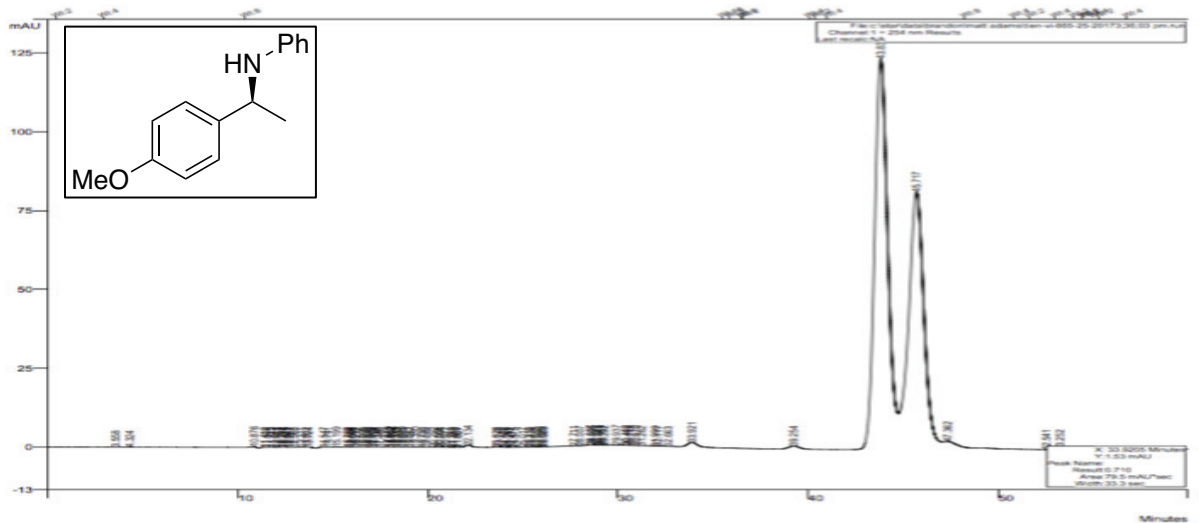
Peak Number	Retention Time	Area Number	Area Percent
1	43.834	58975068	56.1
2	45.717	46076344	43.9
Total			100

(S)-N-Benzyl-1-(furfuryl)ethylamine (3.68):
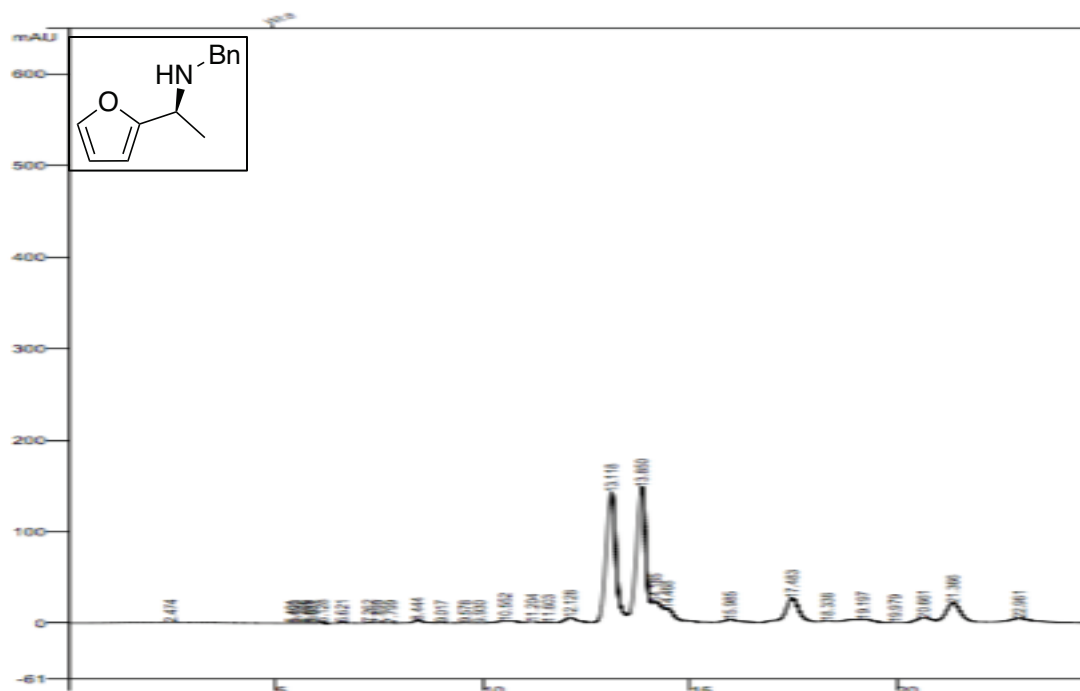
Peak Number	Retention Time	Area Number	Area Percent
1	13.118	24138544	50.2
2	13.850	23921312	49.8
Total			100
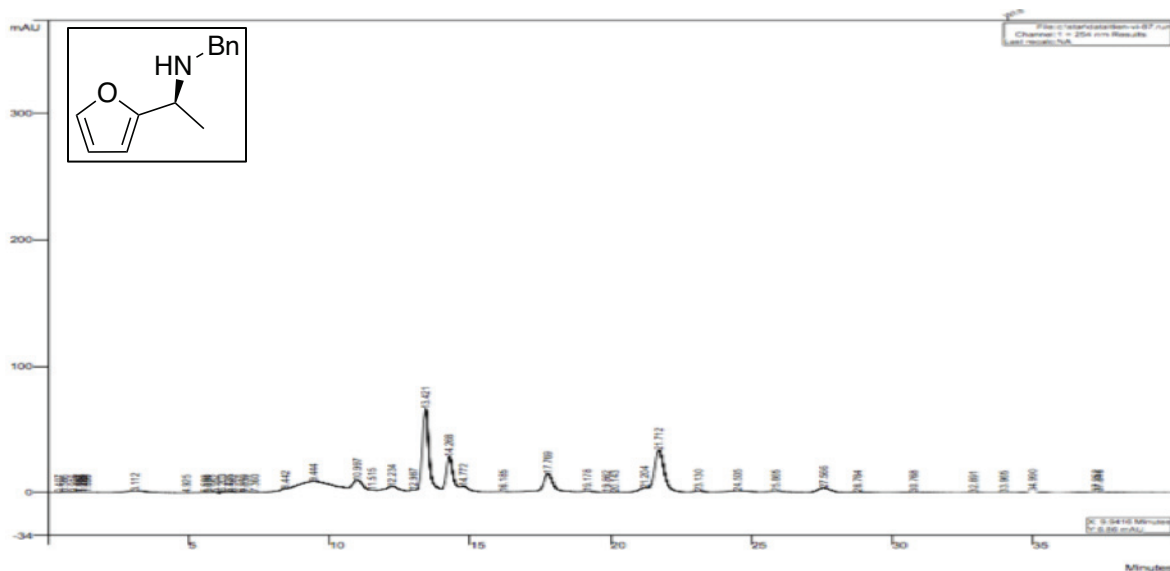
Peak Number	Retention Time	Area Number	Area Percent
1	13.421	11425913	68.6
2	14.268	5231344	31.4
Total			100

340

(S)-N-Benzyl-1-(2'-chlorophenyl)ethylamine (3.69):
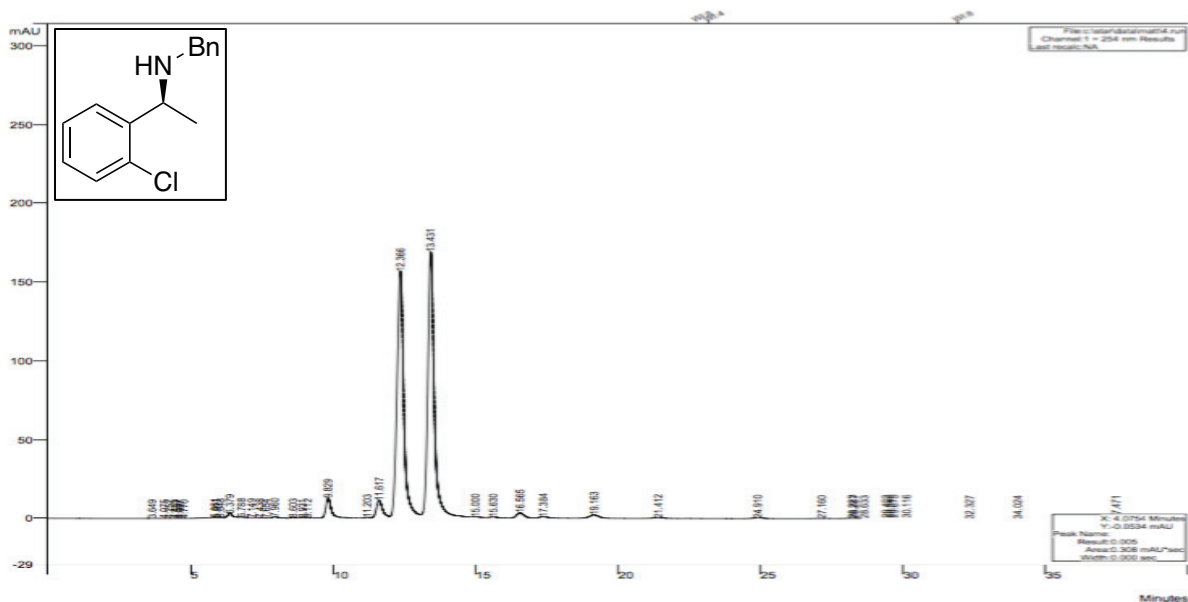
Peak Number	Retention Time	Area Number	Area Percent
1	12.366	25957560	48.2
2	13.431	27895966	51.8
Total			100
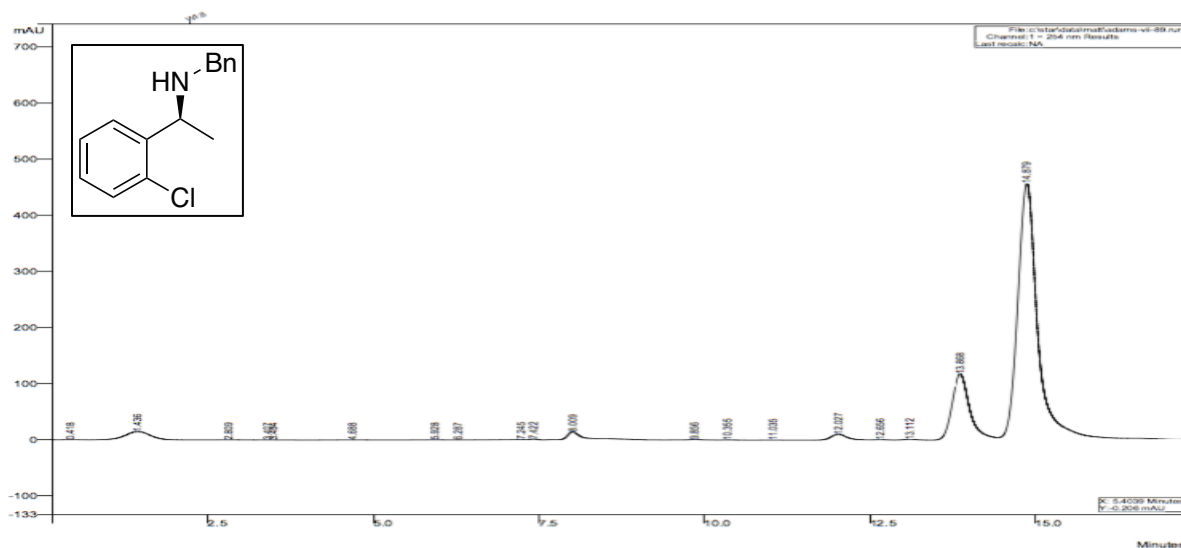
Peak Number	Retention Time	Area Number	Area Percent
1	13.868	22060394	17.8
2	14.879	102067984	82.2
Total			100

(*S*)-*N*-Methyl-*N*'-(*tert*-butyloxycarbonyl)-1-(4-methoxyphenyl)ethylamine (3.70):
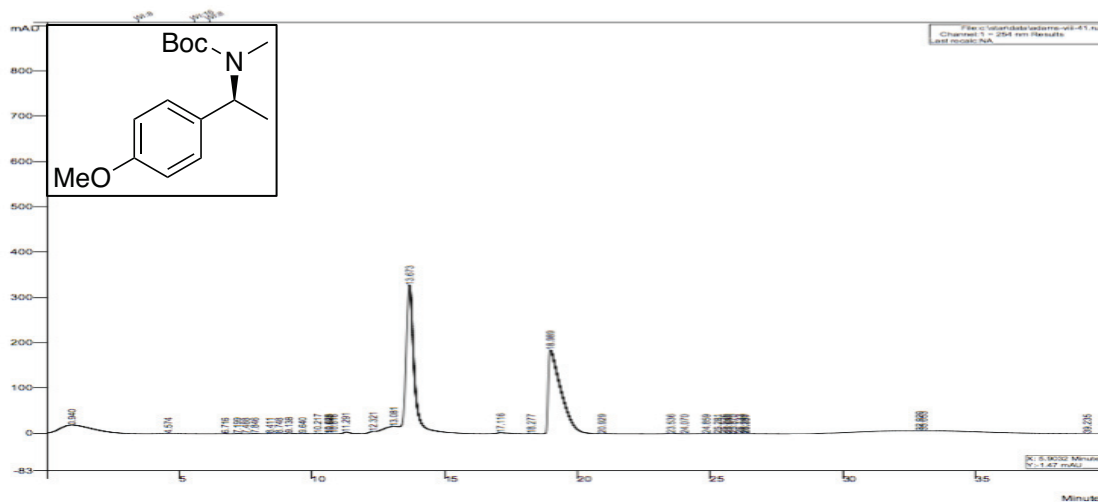
Peak Number	Retention Time	Area Number	Area Percent
1	13.673	71289792	53.4
2	18.989	62092200	46.6
Total			100
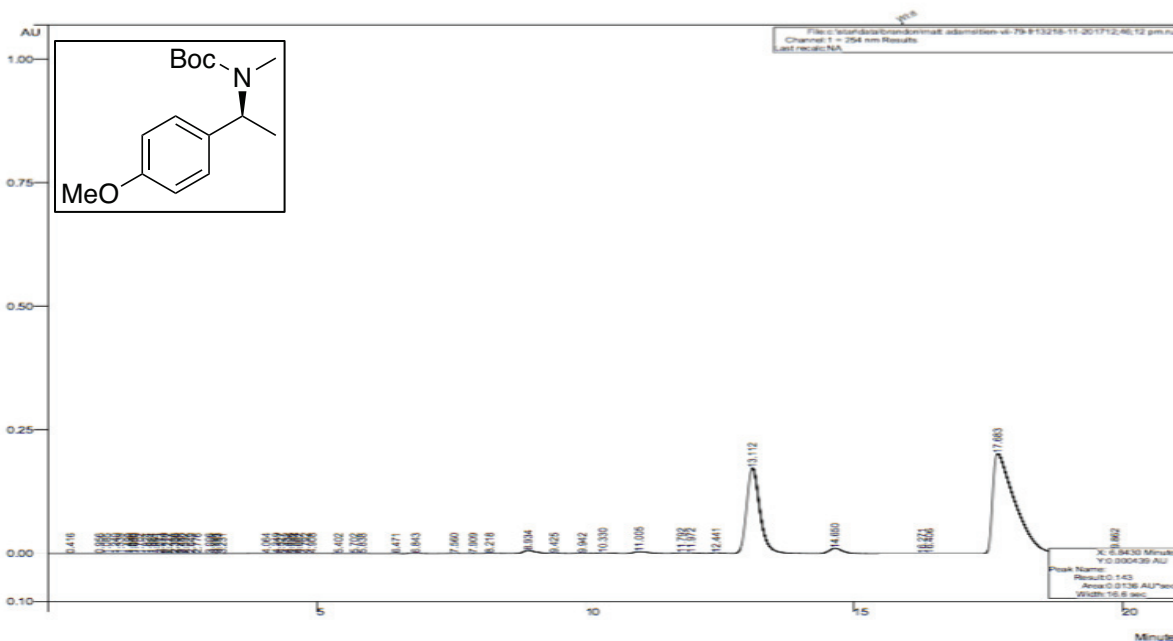
Peak Number	Retention Time	Area Number	Area Percent
1	13.112	30098916	34.0
2	17.683	58315632	66.0
Total			100

(*S*)-*N*-2-Phenylpropyl-1-(4-methoxyphenyl)ethylamine (3.71):
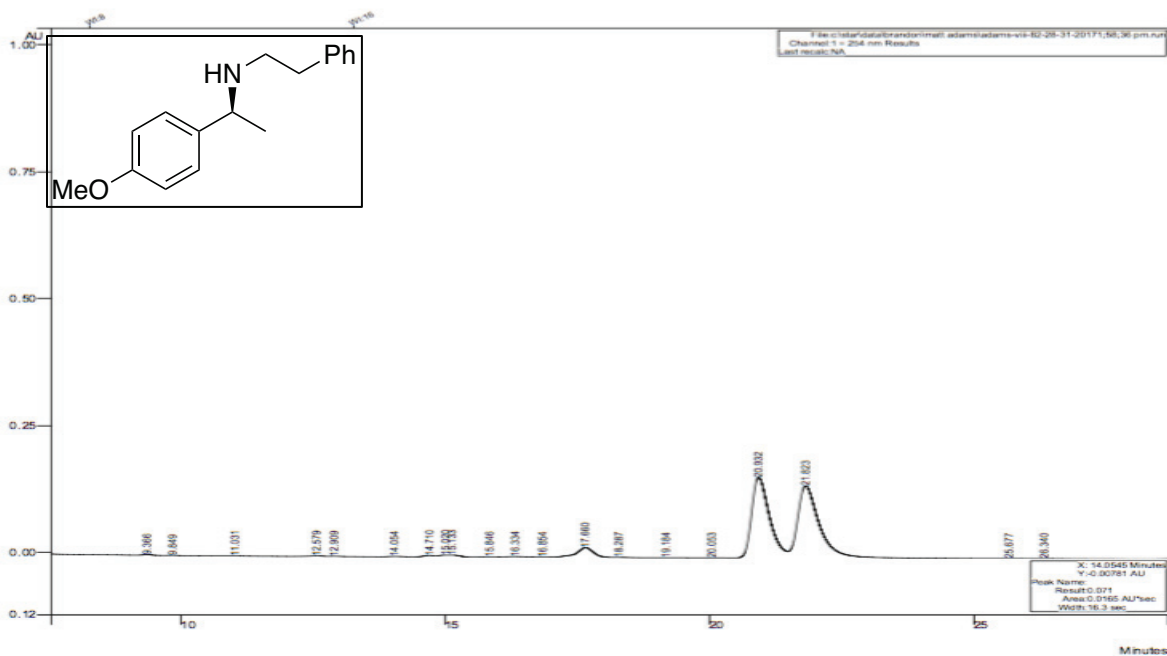
Peak Number	Retention Time	Area Number	Area Percent
1	20.932	37014932	47.5
2	21.823	40895704	52.5
Total			100
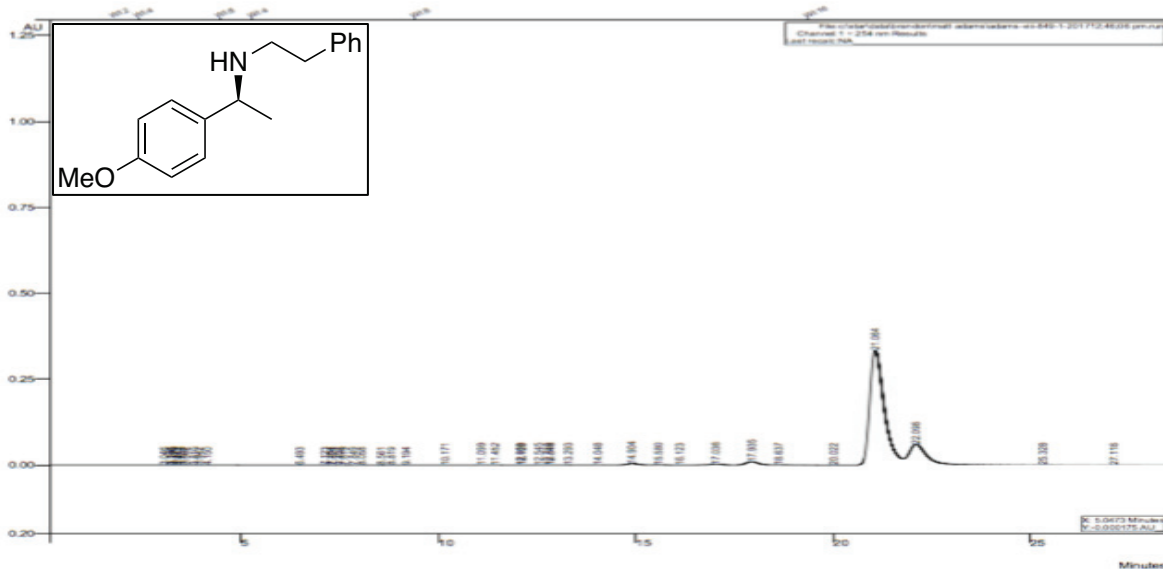
Peak Number	Retention Time	Area Number	Area Percent
1	21.064	85717872	80.5
2	22.096	20713478	19.5
Total			100

(*S*)-*N*-2,2-Diphenylpropyl-1-(4-methoxyphenyl)ethylamine (3.72):
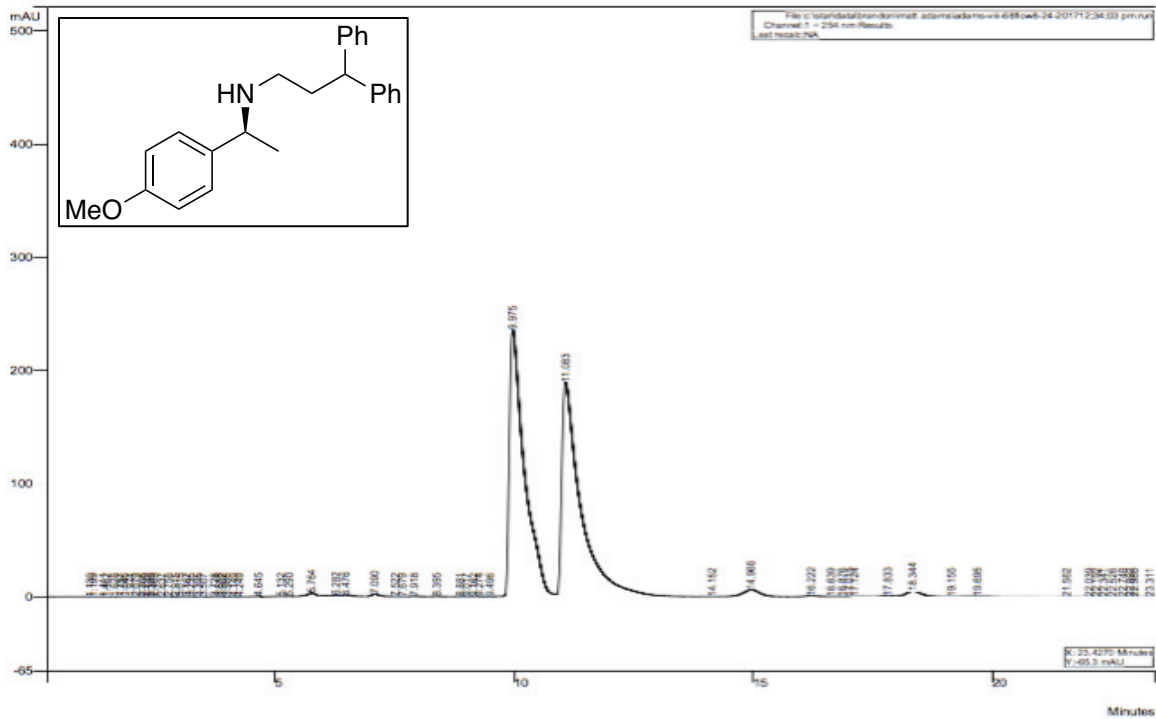
Peak Number	Retention Time	Area Number	Area Percent
1	9.975	51595464	49.3
2	11.038	53115668	50.7
Total			100
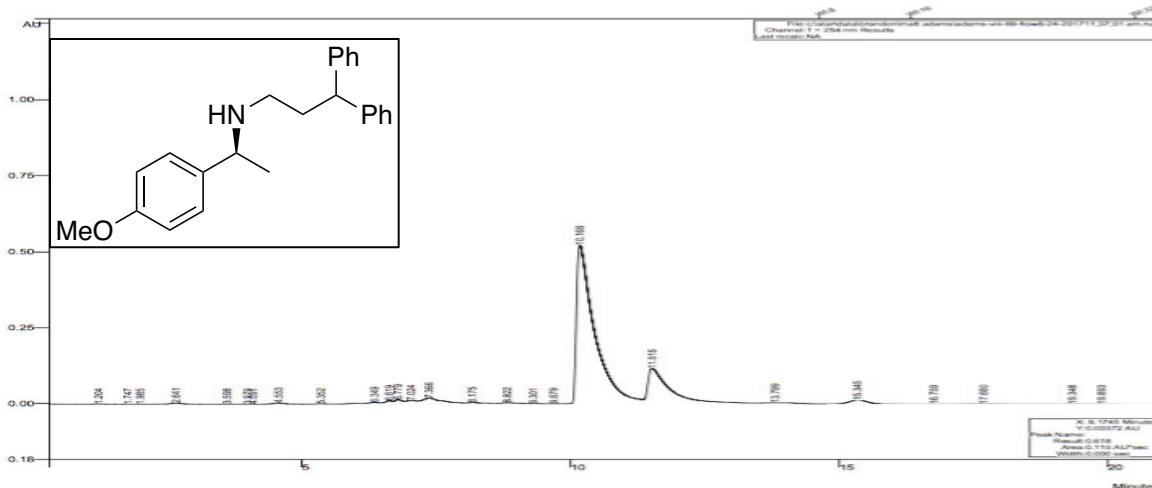
Peak Number	Retention Time	Area Number	Area Percent
1	10.168	123404384	77.8
2	11.515	35200048	22.2
Total			100
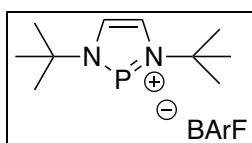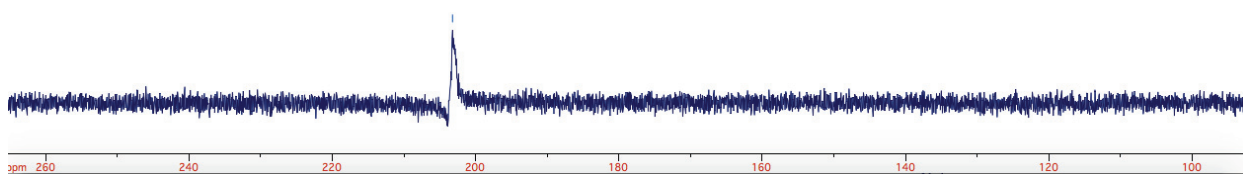
Appendix C: NMR spectra for Chapter 4

1,3-Di-*tert*-butyl-1,3,2-diazaphosphole BArF (4.1):

1,3-Di-mesityl-1,3,2-diazaphosphole BArF (4.2):

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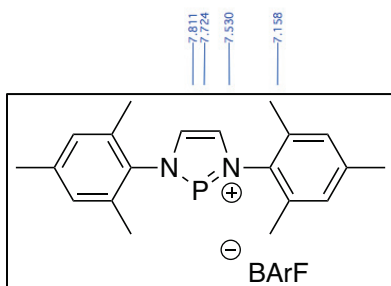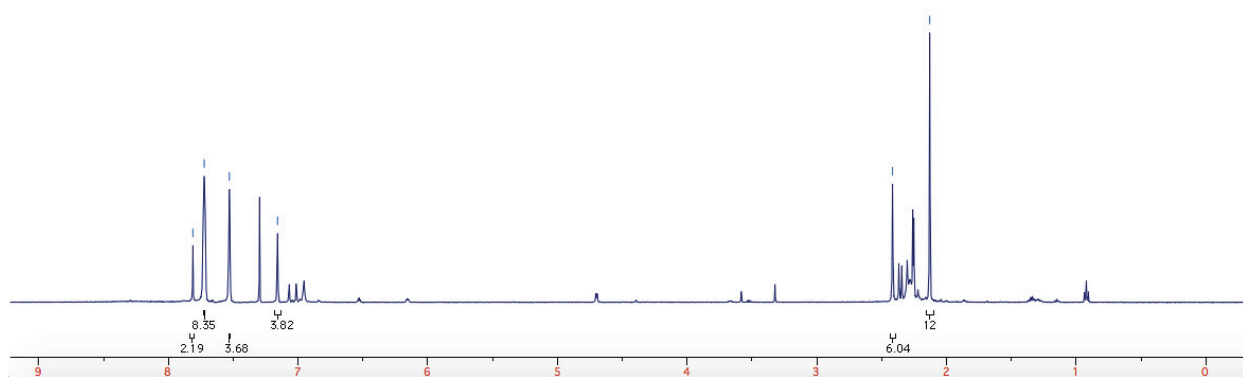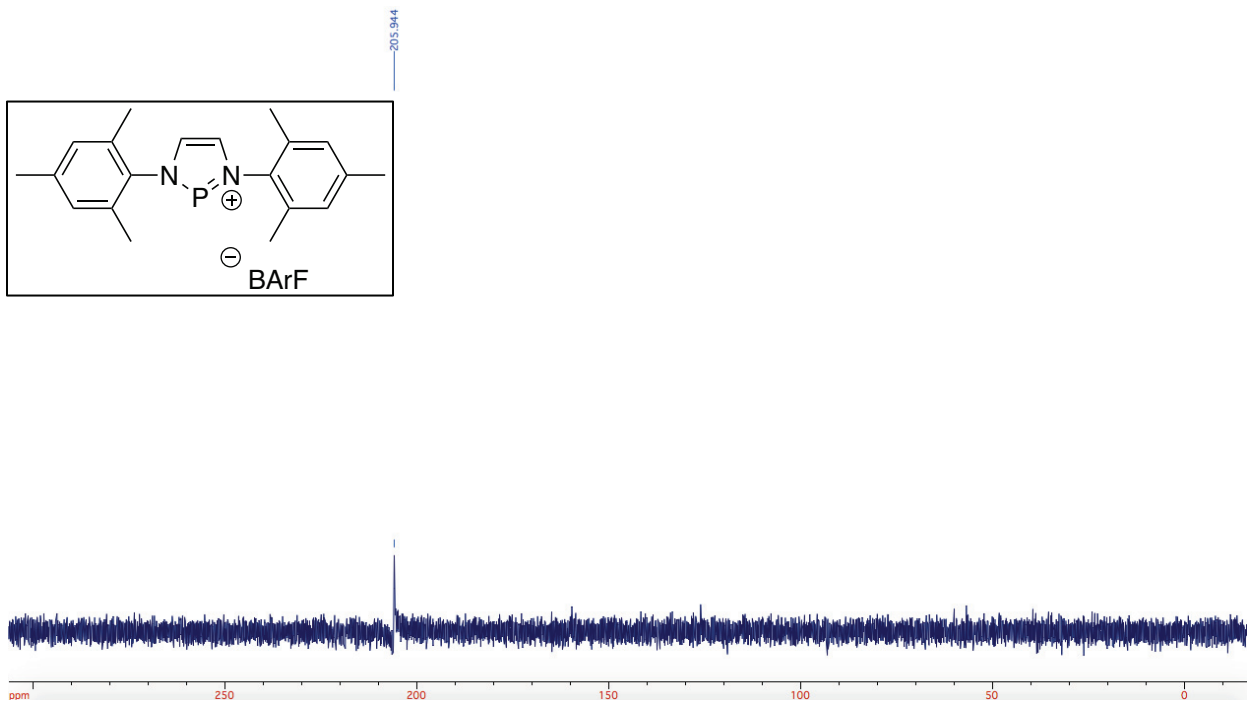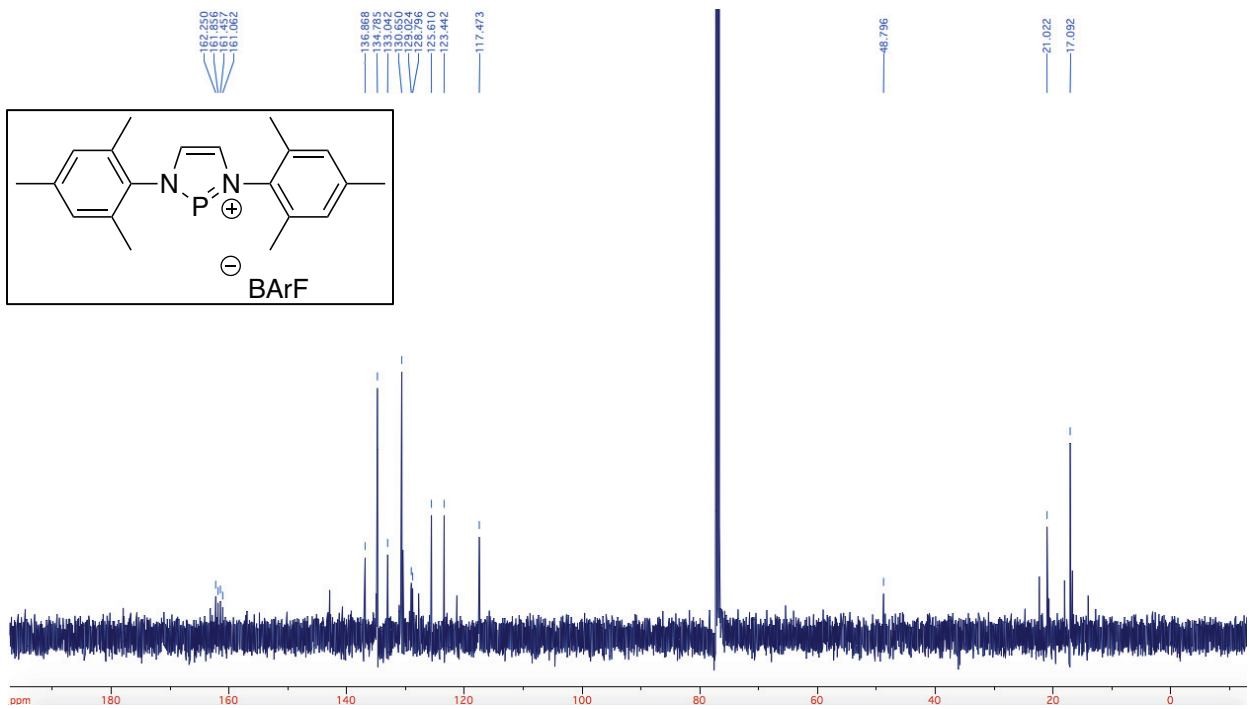
N-Benzyl-1-phenylethanamine (4.3):
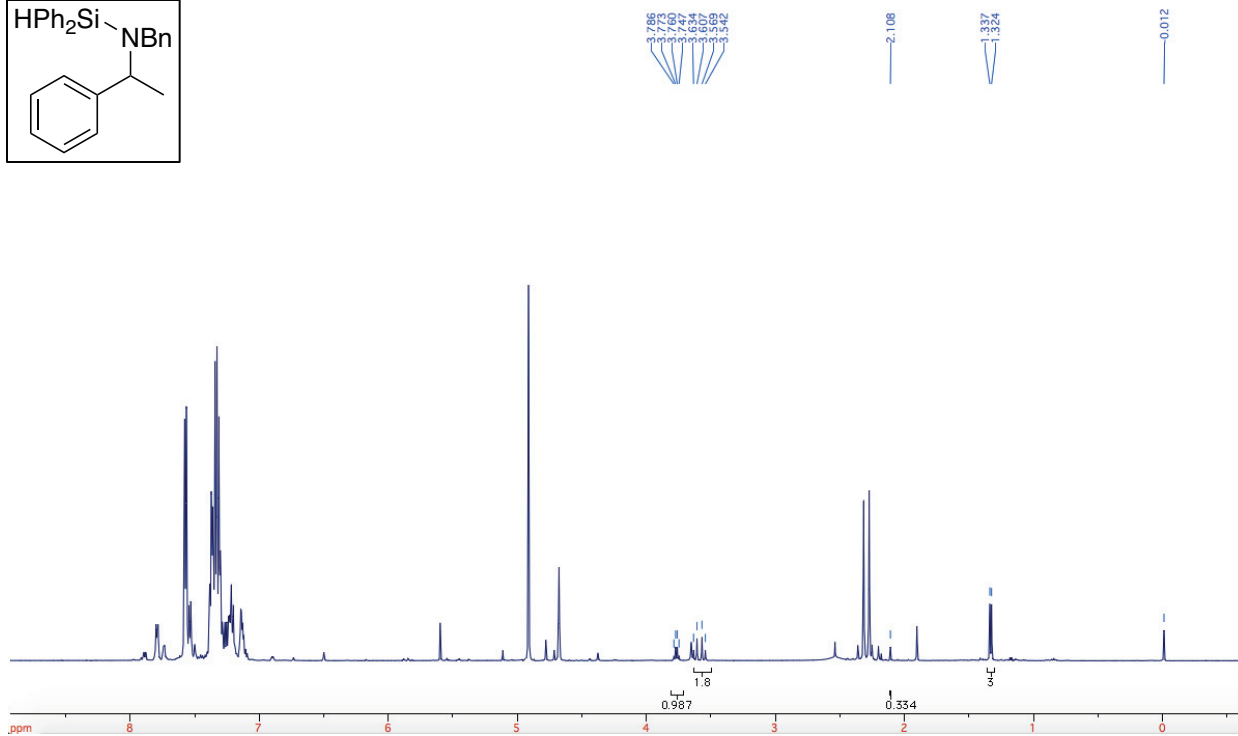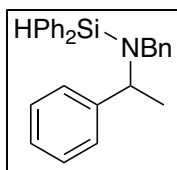
Phenethanol (4.4):
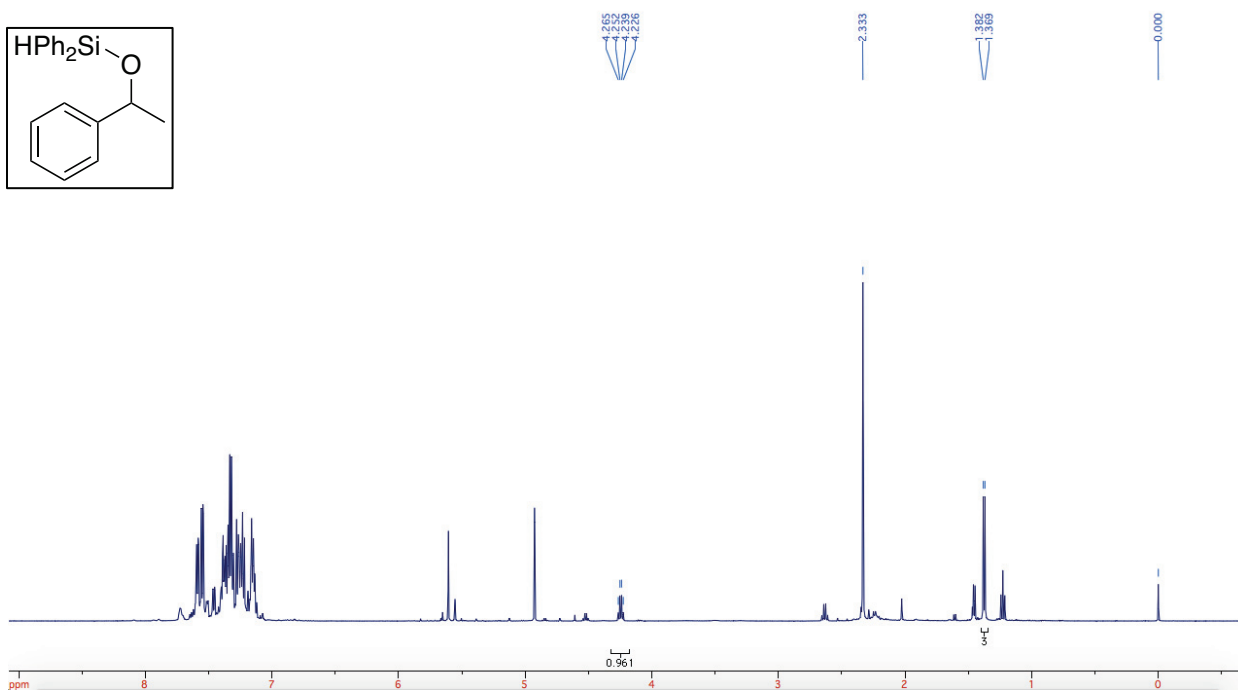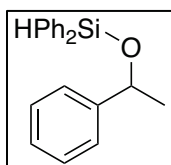
***N*-Benzyl-2-methylpropan-2-amine (4.5):**
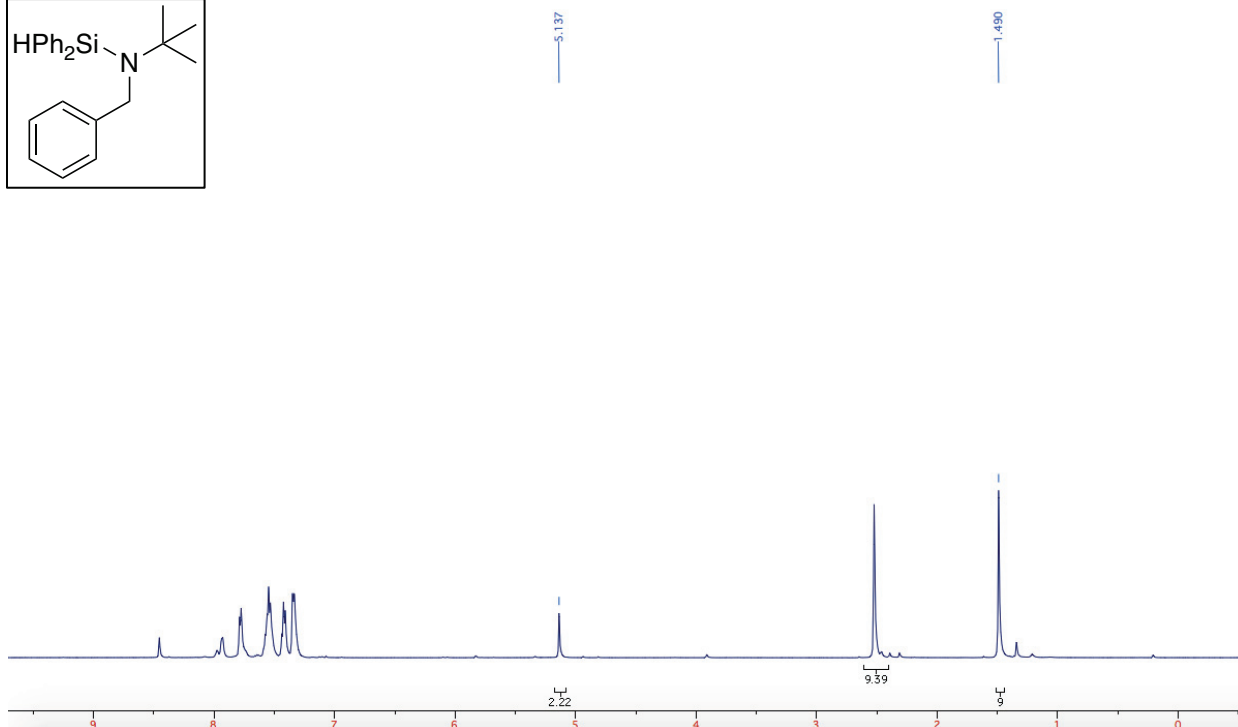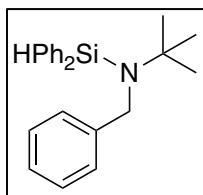
***N*-(Prop-2-ynyl)-2,3-dihydro-1*H*-inden-1-amine (4.6):**
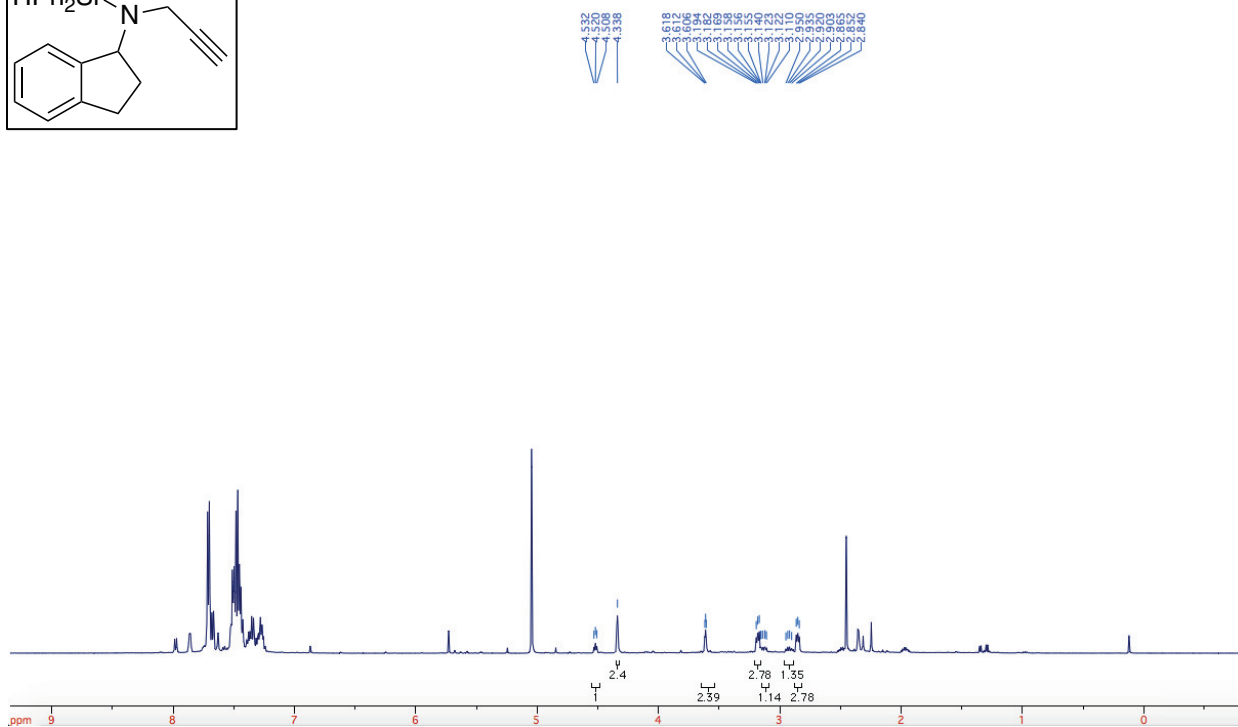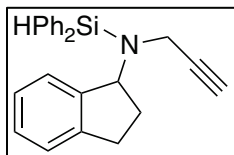
N-Benzyl-1-(pyridin-2-yl)ethanamine (4.7):
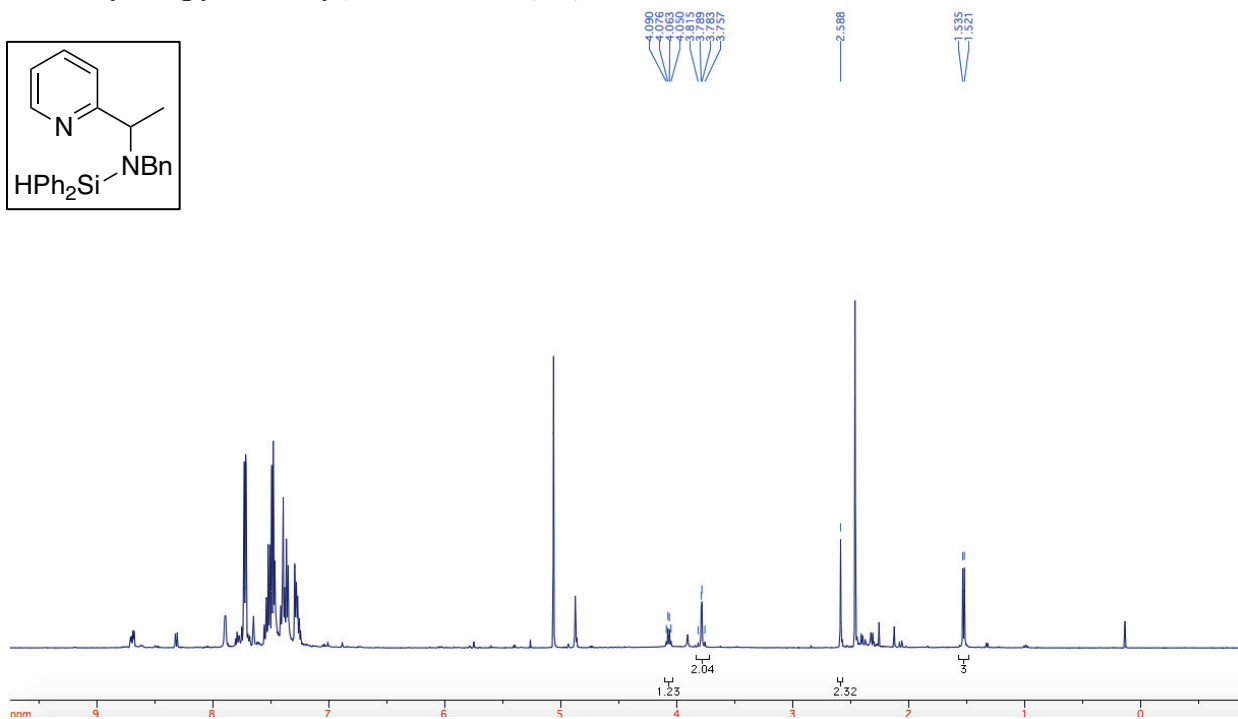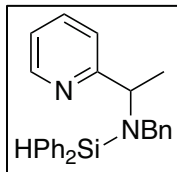
N-Benzyl-1-phenylethanamine (4.8):
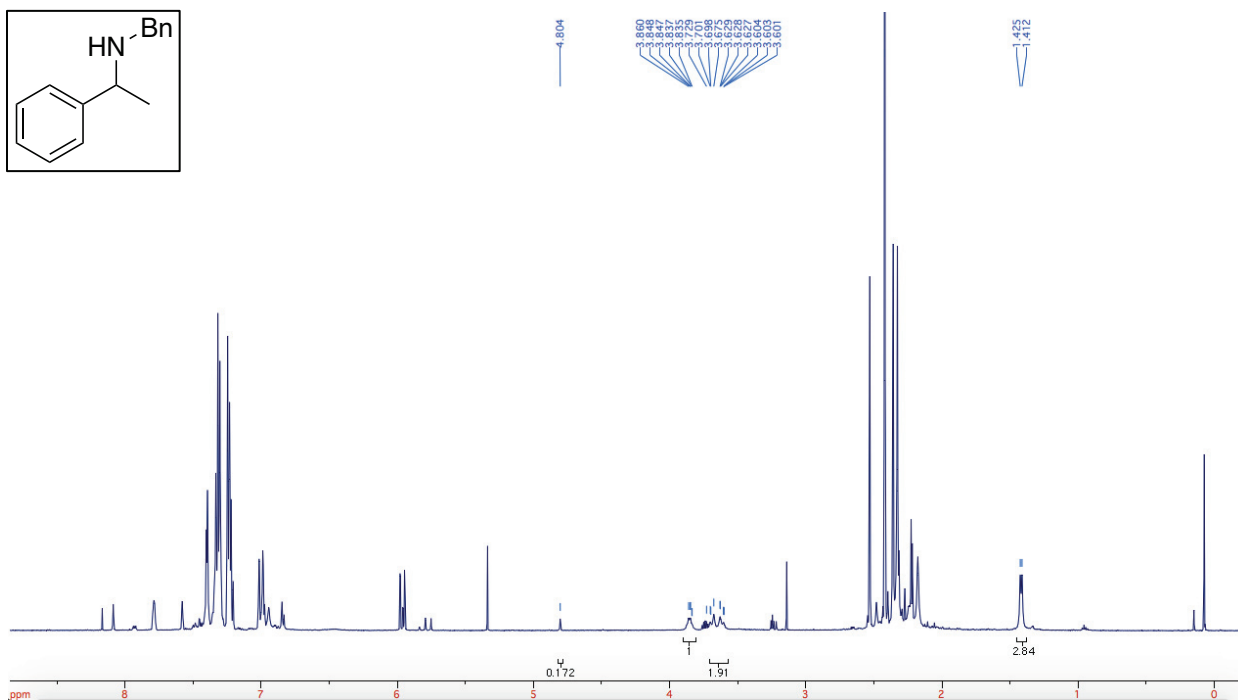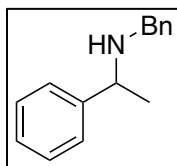
Appendix D: X-Ray Crystallography Data

1,3-Di-*tert*-butyl-2-(neopentyloxy)-1,3,2-diazaphospholene (2.10):

A. Crystal Data

formula	$C_{15}H_{31}N_2OP$
formula weight	286.39
crystal dimensions (mm)	0.40 ´ 0.20 ´ 0.14
crystal system	monoclinic
space group	$P2_1/n$ (an alternate setting of $P2_1/c$ [No. 14])
unit cell parameters^a	
a (Å)	6.3186 (3)
b (Å)	29.6193 (12)
c (Å)	9.6890 (4)
b (deg)	92.8854 (5)
V (Å^3)	1811.02 (14)
Z	4
r_{calcd} (g cm^{-3})	1.050
μ (mm^{-1})	0.149

B. *Data Collection and Refinement Conditions*

|	
diffractometer	Bruker PLATFORM/APEX II CCD^b
radiation (l [Å])	graphite-monochromated Mo Ka (0.71073)
temperature (°C)	–80
scan type	w scans (0.3°) (20 s exposures)
data collection $2q$ limit (deg)	53.23
total data collected	14894 (-7 ≤ h ≤ 7, -37 ≤ k ≤ 37, -12 ≤ l ≤ 12)
independent reflections	3789 (R_{int} = 0.0261)
number of observed reflections (*NO*)	3044 [$F_o^2 \geq 2s(F_o^2)$]
structure solution method	intrinsic phasing (*SHELXT-2014^c*)
refinement method	full-matrix least-squares on F^2 (*SHELXL–2014^d*)
absorption correction method	Gaussian integration (face-indexed)
range of transmission factors	1.0000–0.9361
data/restraints/parameters	3789 / 0 / 172
goodness-of-fit (*S*)^e [all data]	1.036
final *R* indices^f	
R_1 [$F_o^2 \geq 2s(F_o^2)$]	0.0397
wR_2 [all data]	0.1140
largest difference peak and hole	0.256 and –0.201 e Å^{-3}

^{a}Obtained from least-squares refinement of 9206 reflections with 4.42° < $2q$ < 42.20°.

^{b}Programs for diffractometer operation, data collection, data reduction and absorption correction were those supplied by Bruker.

[c]Sheldrick, G. M. *Acta Crystallogr.* **2015**, *A71*, 3–8. (*SHELXT-2014*)

[d]Sheldrick, G. M. *Acta Crystallogr.* **2015**, *C71*, 3–8. (*SHELXL-2014*)

[e]$S = [\mathrm{S}w(F_o^2 - F_c^2)^2/(n - p)]^{1/2}$ (n = number of data; p = number of parameters varied; w = $[s^2(F_o^2) + (0.0547P)^2 + 0.5116P]^{-1}$ where $P = [\mathrm{Max}(F_o^2, 0) + 2F_c^2]/3$).

[f]$R_1 = \mathrm{S}||F_o| - |F_c||/\mathrm{S}|F_o|$; $wR_2 = [\mathrm{S}w(F_o^2 - F_c^2)^2/\mathrm{S}w(F_o^4)]^{1/2}$.

2-Neopentoxy-1,3-*bis*{(*R*)1-(naphthalen-1-yl)ethyl}-1,3,2-diazaphosphole (3.32):

A. Crystal Data

formula	$C_{31}H_{35}N_2OP$
formula weight	482.58
crystal dimensions (mm)	0.53 ´ 0.12 ´ 0.09
crystal system	orthorhombic
space group	$P2_12_12_1$ (No. 19)
unit cell parameters[a]	
a (Å)	9.0755 (2)
b (Å)	10.5045 (3)
c (Å)	28.7228 (7)
V (Å^3)	2738.25 (12)
Z	4
r_{calcd} (g cm^{-3})	1.171
μ (mm^{-1})	1.072

B. Data Collection and Refinement Conditions

diffractometer	Bruker D8/APEX II CCD[b]
radiation (l [Å])	Cu Ka (1.54178) (microfocus source)
temperature (°C)	–100
scan type	w and f scans (1.0°) (5 s exposures)
data collection $2q$ limit (deg)	148.16
total data collected	19504 (-11 ≤ h ≤ 10, -13 ≤ k ≤ 13, -35 ≤ l ≤ 35)
independent reflections	5539 (R_{int} = 0.0280)
number of observed reflections (*NO*)	5315 [$F_o^2 \geq 2s(F_o^2)$]
structure solution method	direct methods/dual space (*SHELXD*[c])
refinement method	full-matrix least-squares on F^2 (*SHELXL–2014*[d])
absorption correction method	Gaussian integration (face-indexed)
range of transmission factors	0.9410–0.7084
data/restraints/parameters	5539 / 24[e] / 347
extinction coefficient (x)[f]	0.0018(4)
Flack absolute structure parameter[h]	0.00(3)

goodness-of-fit $(S)^i$ [all data]   1.040

final R indices[j]

    R_1 $[F_o^2 \geq 2s(F_o^2)]$ 0.0417

    wR_2 [all data]   0.1187

largest difference peak and hole   0.611 and –0.344 e Å^{-3}

[a]Obtained from least-squares refinement of 9034 reflections with $6.16° < 2q < 147.32°$.

[b]Programs for diffractometer operation, data collection, data reduction and absorption correction were those supplied by Bruker.

[c]Schneider, T. R.; Sheldrick, G. M. *Acta Crystallogr.* **2002**, *D58*, 1772-1779.

[d]Sheldrick, G. M. *Acta Crystallogr.* **2015**, *C71*, 3–8.

[e](i) The following pairs of bond distances were constrained to be equal (within 0.03 Å) during refinement: d(O1–C3A) = d(O1–C3B); d(C3A–C4) = d(C3B–C4). (ii) The following distances were constrained to be equal (within 0.03 Å) to a common refined value during refinement: d(C4–C6A), d(C4–C7A), d(C4–C6B), d(C4–C7B). (iii) The anisotropic displacement parameters (six U_{ij} terms per atom) for the following pairs of atoms were constrained to be equal (within 0.03 Å) during refinement: U_{ij}(C3A) = U_{ij}(C3B); U_{ij}(C6A) = U_{ij}(C6B); U_{ij}(C7A) = U_{ij}(C7B).

[g]$F_c^* = kF_c[1 + x\{0.001F_c^2 l^3/\sin(2q)\}]^{-1/4}$ where k is the overall scale factor.

[h]Flack, H. D. *Acta Crystallogr.* **1983**, *A39*, 876–881; Flack, H. D.; Bernardinelli, G. *Acta Crystallogr.* **1999**, *A55*, 908–915; Flack, H. D.; Bernardinelli, G. *J. Appl. Cryst.* **2000**, *33*, 1143–1148. The Flack parameter will refine to a value near zero if the structure is in the correct configuration and will refine to a value near one for the inverted configuration.

[i]$S = [Sw(F_o^2 - F_c^2)^2/(n - p)]^{1/2}$ (n = number of data; p = number of parameters varied; $w = [s^2(F_o^2) + (0.0727P)^2 + 0.4889P]^{-1}$ where $P = [\text{Max}(F_o^2, 0) + 2F_c^2]/3$).

[j]$R_1 = S||F_o| - |F_c||/S|F_o|$; $wR_2 = [Sw(F_o^2 - F_c^2)^2/Sw(F_o^4)]^{1/2}$.

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