Pb$(n,n'x)$ at 65 MeV and the Isospin Structure of the Giant Quadrupole Resonance Region

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(Received 18 February 1988; revised manuscript received 12 August 1988)

The first Pb$(n,n'x)$ data (at 65 MeV) are compared to earlier (61–66 MeV) $(p,p'x)$ data. The isovector sensitivity of these nucleon probes is used to determine $M_n/M_p \simeq N/Z = 1.54$ for the giant quadrupole resonance (GQR). This result is consistent with other direct GQR measurements, 2_1^+ data connected through core polarization, and several microscopic random-phase-approximation calculations, but in disagreement with a π^-/π^+ study which gives $M_n/M_p = 3.8 \pm 1.2$.

PACS numbers: 24.30.Cz, 21.60.Jz, 25.40.Fq, 27.80.+w

The study of giant resonances (GR's) in nuclei has progressed significantly in recent years.[1,2] This effort has been aided mightily by the availability of a large variety of probes. This variety is essential for obtaining a complete picture of nuclear excitations.[3] The results of the work on GR's are of fundamental importance for understanding both structure and reaction aspects of nuclear dynamics.

Both collective[4] and microscopic[5] nuclear structure models indicate that the giant quadrupole resonance (GQR) in neutron-excess nuclei is consistent with or somewhat more isoscalar than the hydrodynamic limit, i.e., with the ratio of neutron to proton matrix elements $M_n/M_p \leq N/Z$. Nuclear probes which exhibit different sensitivities[3,5] to neutrons and protons can be used to determine the isospin structure of nuclear transitions. For example, pions at energies near the Δ resonance and 60–65-MeV nucleons have $t_{\pi^- n}/t_{\pi^+ n} \approx t_{\pi^+ p}/t_{\pi^- p} \approx 3$ and $t_{pn}/t_{nn} \approx t_{np}/t_{pp} \approx 2$–3, respectively, and so π^-/π^+ and p/n cross-section ratios can be used to obtain a measure of M_n/M_p. Nucleons at these energies, in fact, penetrate the interior of the nucleus better than pions in the Δ region.[6]

Here we report data from the first measurements of $(n,n'x)$ spectra for natural Pb taken at 65 MeV. These are compared with earlier 61–66-MeV ^{208}Pb$(p,p'x)$ data[7,8] to obtain information on M_n/M_p in the region of the GQR. This work is motivated by recent studies of 162-MeV π^- and π^+ scattering on ^{118}Sn (Refs. 9 and 10) and ^{208}Pb (Ref. 11) which have extracted M_n/M_p ratios for the GQR that are far from isoscalar—actually exceeding the hydrodynamic limit. Specifically, Refs. 9–11 report $M_n/M_p = 1.9 \pm 0.4$ and 3.8 ± 1.2 for GQR in ^{118}Sn and ^{208}Pb, respectively. The present nucleon scattering data are found to be consistent with $M_n/M_p \simeq N/Z$ for the GQR as expected from several random-phase-approximation (RPA) calculations, but inconsistent with the pion work. It is also demonstrated that the core polarization implied by the present results is consistent with data on the 2_1^+ transition in ^{208}Pb that have been obtained with several probes. These rather unambiguous data are in serious disagreement with the large pion ratio. In addition, it is noted that there are other experiments exploring the GR region in ^{208}Pb where similar discrepancies with the pion results have been observed. These include $(e,e'n)$,[12] (p,p'),[13] and $(^{17}O,{}^{17}O')$.[14]

We have measured C, CH_2, ^{nat}Fe, and ^{nat}Pb elastic and $(n,n'x)$ continuum differential cross sections at 65 MeV. The results for Fe, which indicate $\sigma(n,n'x)/\sigma(p,p'x) \simeq 1$ have been reported earlier.[15] Here we focus on the Pb$(n,n'x)$ measurements. The neutron beam of $\simeq 1.1$ MeV FWHM was produced by ^{7}Li$(p,n)^7$Be and collimated and monitored as has been described elsewhere.[16] The neutron-detection system uses a large-area CH_2 converter and the resultant recoil protons are tracked and measured in a large-area, multiwire-chamber, ΔE-E telescope. The scattered neutron energy is calculated from E_p (proton) and θ_{np}. This arrangement allows continuum measurements over a wide energy (15–65 MeV) and angular range (10°–40°) at one time.[16] The overall energy resolution of $\simeq 2.5$ MeV is determined by the neutron-beam width, and by three roughly 1-MeV contributions from the CH_2 converter thickness, the uncertainty in θ_{np} (determined largely by the beam spot size), and the resolution of the E detector, which in this experiment was a 5-in. by 7-in. NE102 plastic scintillator stopping 70-MeV protons. A CH_2-C converter subtraction is made to subtract out those ^{12}C(n,p) events which cannot be eliminated by time of flight in the telescope. Normalization is provided by n-p scattering from a CH_2 target.

Figure 1 shows 65-MeV ^{nat}Pb$(n,n'x)$ energy spectra, $d^2\sigma/dE\,d\Omega$ (as data points), compared to 66-MeV Pb$(p,p'x)$ data[7] (solid spectra), which have been multiplied by 1.50 and 1.27 at 20° and 28°, respectively (described below) to illustrate the prescription for subtracting the continuum background. For the (n,n'), $\Delta\theta = 8°$, and for the (p,p'), $\Delta\theta = 4°$. [There are more recent cross-section data for ^{208}Pb$(p,p'x)$ at 61 MeV[8] which

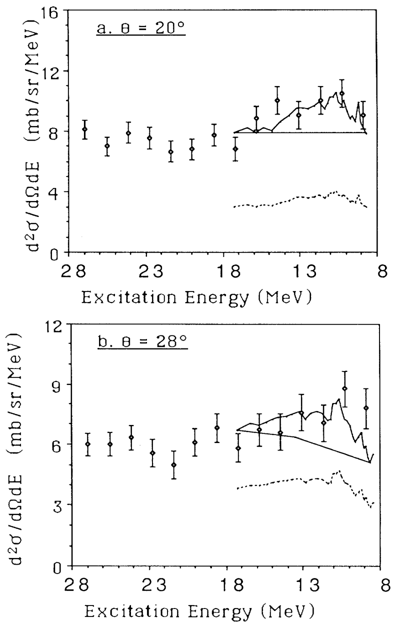

FIG. 1. Comparison of $(n,n'x)$ spectra to (a) $(p,p'x)$ at 20° scaled by 1.50, and (b) $(p,p'x)$ at 28° scaled by 1.27. The points are the $(n,n'x)$ data, the connected points are the $(p,p'x)$ data, and the smooth line is the (scaled) continuum contribution assumed in Ref. 7. The dashed line is the predicted trend of the $(n,n'x)$ GR + continuum cross sections deduced from $(p,p'x)$ data if $M_n/M_p = N/Z = 3.8$ is assumed, as obtained from π^-/π^+ data.

show the same features as the 66-MeV data but appear to be $\approx 20\%$ smaller.] Separating contributions to the different multipoles from the continuum cross sections is not possible for the $(n,n'x)$ data and is difficult for the $(p,p'x)$ data. However, we can compare the $(p,p'x)$ and $(n,n'x)$ cross sections for the continuum and for the GR structure on top of the continuum. Integrating $d^2\sigma/dE\,d\Omega$ over the range $E_x = 8.5$–20 MeV results in $R_{ex} = \sigma(n,n'x)/\sigma(p,p'x) = 1.50 \pm 0.22$ at 20° and 1.27 ± 0.21 at 28° for the total (GR structure plus background) continuum. These are the scale factors applied to the $(p,p'x)$ data. The GR structure in the neutron spectrum centered near $E_x = 11.5$ MeV is assumed, as for $(p,p'x)$,[7] to be sitting on top of a continuum background that is flat at 20° and tilted down toward lower E_x at 28°, as shown by the smooth solid lines in Fig. 1. The R_{ex} ratios for the GR structures above the solid lines are 1.45 ± 0.35 and 1.35 ± 0.35 (all 1 standard deviation) at 20° and 28°, respectively. The uncertainties are statistical, and systematic errors due to the assumed continuum background are comparable.

We have calculated cross-section ratios for the GQR region using earlier proton work as a guide.[17,18] The calculations of Refs. 17 and 18 show that at 20° there are possible substantial contributions to the resonance region from $E0$, $E1$, $E2$ (the GQR), and even $E4$, with $E2$ ($\sim 50\%$) being the largest. At 28° the prediction is that $E2$ dominates ($\simeq 80\%$) and that $E0$, $E1$, and $E4$ are small. Since at present the resolution is inadequate to distinguish microscopic details, we use a macroscopic model based on isospin-consistent optical-model potentials constructed from the Becchetti-Greenlees proton[19] and Michigan State University (p,n)[20] potentials. Monopole (GMR), dipole (GDR), and quadrupole cross sections were calculated for excitation energies of 13.5, 13.5, and 10.9 MeV, respectively. Transition potentials were derived from the deformed optical potentials assuming $|M_n/M_p| = N/Z$. Our calculation employed the same forms and sum-rule deformation parameters for GMR, GDR, and GQR as used by Satchler.[21] For the GMR, GDR, and GQR,[22] 100%, 100%, and 80% of the energy-weighted sum rule were assumed, respectively. Coulomb excitation of the GDR and GQR was also included as described by Satchler.[23]

The calculated cross sections were integrated from 16° to 24° and from 24° to 32° for each multipole to give $\bar{\sigma}_l$. The ratio of sums

$$R = \sum_{l=0,1,2} \bar{\sigma}_l(n,n'x) \Big/ \sum_{l=0,1,2} \bar{\sigma}_l(p,p'x)$$

are $R(20°) = 1.1$ and $R(28°) = 1.3$, respectively, which are to be compared with the experimental ratios given above. For both the continuum and the GR region the measured cross-section ratios at $\theta = 28°$ (where the GQR dominates) agree (within the substantial uncertainties) with the theoretical prediction which assumes $M_n/M_p = N/Z$. At $\theta = 20°$ the experimental ratio is actually larger than predicted and (assuming scaling for the $E2$) corresponds to $M_n/M_p \simeq 1.2$, which is smaller than N/Z and opposite in direction to the pion results. If we assume that the M_n/M_p from the pion analysis is correct, we can predict $\sigma(n,n'x)$ from $\sigma(p,p'x)$. Using $M_n/M_p = 3.8$ for the GQR yields $\sigma(n,n'x)/\sigma(p,p'x)$ ratios of 0.67 and 0.57 at 28° and 20°, respectively. To obtain results consistent with the pion GQR data, the background for (n,n') (Fig. 1) would have to be moved up nearly 1 mb/sr MeV, which is above the adjacent continuum.

We note that the background subtraction necessary for analysis of the GQR has been performed in the standard way for both the nucleons and the pions. However, the nucleon GQR analysis depends more sensitively on this subtraction. Thus in this paragraph we digress to discuss the implications of the (curious and not yet understood) fact that the ratio of the cross sections in the adjacent continua for both sets of isospin-partner probes is similar to their ratios for the GQR. In the case of the nucleon probes, the continuum ratio is consistent with a one-step quasielastic model with neutron to proton excitations in the reasonable ratio of N/Z. If the continuum for the nucleons were treated with the same one-step quasielastic continuum model, but with the ratio of neutron to proton excitations taken to be 3.8, as found in the pion work, then the $\sigma(n,n'x)$ continuum cross sections would fall much below the measured cross sections as indicated by the dashed curves in Fig. 1. These are based on distorted-wave macroscopic-model calculations with the same isospin interaction and ratio of distortion as in the GQR analysis but scaled by adjusting $\rho_n/\rho_p = 3.8$. We conclude that inconsistency between the nucleon and pion results for the GQR persists in the continua and so the discrepancy between the pion and nucleon results for the GQR is not likely an artifact of the resonance continuum subtraction.

The values of M_n and M_p for the GQR and the 2_1^+ transition in ^{208}Pb from various RPA calculations are summarized in Table I. The Jülich RPA model (a) which includes a discretized continuum is often used in comparing to GR data. The results of Gogny and collaborators (b) and those of Auerbach and co-workers (c) are based on self-consistent RPA models and both include continuum effects. Entries d and e are results of the quasiparticle RPA model[27] of two of the present authors. The results d are obtained with standard-model parameters fixed at physically reasonable values, and the results e are obtained with the model ratio of mean-square neutron to proton radius increased arbitrarily to give M_n/M_p for the GQR closer to that deduced from the pion work of Ref. 11. The results e have been included to illustrate the differences in core-polarization effects implied by the pion results. The RPA models a–d produce similar results for M_n and M_p. The energy splitting between the GQR and the 2_1^+ can be improved by including two-particle–two-hole effects (see, e.g., Wambach[30]) without altering the discussion to follow.

Table I also contains a summary of the available experimental data on M_n and M_p for the GQR and first 2_1^+ transitions in ^{208}Pb. The pion work of Ref. 11 is summarized in entry f. The values of M_p deduced from electromagnetic data[12,28] for these excitations are given in entries g and h, respectively. The value of M_p from 200-MeV (p,p') analyzed[13] with the standard hydrodynamic collective model ($M_n/M_p = N/Z$ for the GQR) is shown in entry i. The result of this careful analysis of the GQR is consistent with the 66-MeV (p,p') used in this paper. The ^{17}O inelastic-scattering results of Ref. 14 (not shown) are also in good agreement with the GQR hydrodynamic collective model. The value of M_n/M_p for the GQR deduced using the present neutron data appears in entry j, and entries k summarize the information of M_n and M_p for the 2_1^+ transition in ^{208}Pb from previous hadronic and electromagnetic studies.[28,29]

Calculations a–d all give M_n/M_p as approximately N/Z for both the GQR and the 2_1^+ transition, in agreement with all the experimental data in Table I except the pion data (f). The isospin structure and sum-rule strength of the GQR and the 2_1^+ are strongly connected through RPA mixing or core polarization. If the M_n/M_p GQR ratio obtained from the pion analysis were correct, it would imply (through core polarization) a similar ratio for the 2_1^+. This effect can be seen by contrasting calculations d and e. For the unrealistic case of e, the resulting M_n/M_p for the 2_1^+ is totally out of line with the value N/Z, which is well established empirically through a variety of probes.[28,29] This result is significant because the 2_1^+ excitation is discrete and the analysis indepen-

TABLE I. Neutron and proton multipole matrix elements M_n and M_p in fm^2 for ^{208}Pb from various RPA calculations. M_n, M_p, and the solution energies E in MeV are given for the GQR and the 2_1^+ transition. Available data are also summarized.

	GQR				2_1^+			
Footnote	E	M_n	M_p	M_n/M_p	E	M_n	M_p	M_n/M_p
a	10.2	112.5	71.5	1.57	4.54	83.4	55.4	1.51
b	12.7	103.6	71.3	1.45	5.19	78.1	54.5	1.43
c	12.0	107.2	74.6	1.44	6.4	71.5	47.3	1.51
d	9.5	116.9	78.3	1.49	4.54	83.4	50.1	1.67
e	9.2	173.0	50.0	3.5	4.4	136.0	37.4	3.6
f	10.6		31.8 ± 9.4	3.8 ± 1.2				
g,h	10.6		68.7 ± 8.6 [g]		4.07		56.4 ± 1.4 [h]	
i,j,k			70.3 ± 5.3 [i]	1.5 ± 0.3 [j]	4.07		57.3 ± 6.3 [k]	1.5 ± 0.3 [k]

[a]Reference 24.

[b]Reference 25.

[c]Reference 26.

[d]Quasiparticle RPA model of Ref. 27. Reference 27 contains results with the interaction adjusted to place the 2_1^+ at the empirical energy 4.07 MeV.

[e]Same as d with the ratio of the mean-square neutron to proton radius increased arbitrarily to yield M_n/M_p closer to that obtained from π^- and π^+ scattering.

[f]Reference 11. The M_p has been determined assuming that the measured $B(E2)\uparrow = (1.01 \pm 0.60) \times 10^3\ e^2\ \mathrm{fm}^4$ is concentrated at $E = 10.6$ MeV.

[g]Reference 12. The GQR M_p has been determined assuming that the measured $B(E2)\uparrow = (4.72 \times 10^3 \pm 25\%)\ e^2\ \mathrm{fm}^4$ is concentrated at $E = 10.6$ MeV.

[h]$B(E2)\uparrow = (3.18 \times 10^3 \pm 5\%)\ e^2\ \mathrm{fm}^4$ for 2_1^+ from Ref. 28.

[i]Reference 13. The GQR M_p has been determined using $M_n/M_p = N/Z$ and 65% of the sum rule quoted by the authors.

[j]Estimate from $(p,p'x)$ measurements and the present work at 28° with resolution insufficient to separate multipoles.

[k]Reference 29.

dent of continuum considerations.

It is also useful to focus on the magnitudes of M_n and M_p, particularly M_p since it can be measured directly by electromagnetic probes. The GQR M_p obtained from the pion analysis is substantially smaller than the value determined directly from the recent ^{208}Pb$(e,e'n)$ experiment.[12] The GQR M_p values obtained indirectly in (p,p') at 200 MeV[13] and $(^{17}O,^{17}O')$[14] are in agreement with the $(e,e'n)$ value. In the unrealistic calculation (e) the GQR M_p has been reduced substantially, but it is still larger than indicated by the pion work, and the corresponding M_p for the 2_1^+ transition is smaller than the electromagnetic values.[28,29] These discrepancies are in opposite directions and cannot easily be resolved since the energy-weighted sum rule is conserved in RPA calculations. The small GQR M_p obtained from pion scattering is mainly associated with the π^+ data. Problems with interpreting the π^+ cross-section data have also been noted in a recent paper[31] on the distribution of quadrupole strength in ^{118}Sn.

In summary, the first $(n,n'x)$ data at 65 MeV have been compared to earlier $(p,p'x)$ data to obtain an estimate of $M_n/M_p \simeq 1.5 \pm 0.3$ for the GQR region in ^{208}Pb. This result, while admittedly rough because of current experimental capabilities, is in reasonable agreement with various theoretical calculations and several other experiments, but in clear disagreement with recent pion work. In addition, the GQR M_p obtained from the pion analysis is substantially smaller than values determined directly by recent $(e,e'n)$,[12] and indirectly by (p,p') at 200 MeV[13] and ^{17}O inelastic scattering.[14] Finally, the core polarization implied by the GQR pion results has M_n/M_p too large and M_p too small compared to data for the well measured 2_1^+ transition. These results suggest that there is a problem in the interpretation of the pion data (particularly the π^+ data) and not with the nuclear structure models.

We gratefully acknowledge the support of the National Science Foundation under Grant No. NSF 84-19380, the Associated Western Universities, and the Crocker Nuclear Laboratory, and personnel for support and invaluable assistance. Part of this work was done under the auspices of the U.S. Department of Energy under Contract No. W-74 05-ENG-48 at LLNL.

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