Excitation of the Isoscalar Giant Quadrupole Resonance in $^{118}Sn(\pi^{\pm}, \pi^{\pm\prime})$

J. L. Ullmann, J. J. Kraushaar, T. G. Masterson, R. J. Peterson, R. S. Raymond,[a] and R. A. Ristinen
University of Colorado, Boulder, Colorado 80309

and

N. S. P. King, R. L. Boudrie, C. L. Morris, and W. W. True[b]
Los Alamos National Laboratory, Los Alamos, New Mexico 87545

and

R. E. Anderson[c]
University of North Carolina, Chapel Hill, North Carolina 27514

and

E. R. Siciliano
University of Colorado, Boulder, Colorado 80309, and Los Alamos National Laboratory, Los Alamos, New Mexico 87545

(Received 12 July 1983)

Ths isoscalar giant quadrupole resonance is studied in $^{118}Sn(\pi^{\pm},\pi^{\pm\prime})$ at 130 MeV. It is found that the ratio of π^- to π^+ cross sections at their maximum is 1.9 and that 57% of the energy-weighted sum rule is exhausted in π^- scattering. This large ratio of π^- to π^+ cross sections is not anticipated by conventional models, and may be interpreted as evidence for substantial isovector strength.

PACS numbers: 24.30.Cz, 25.80.Fm, 27.60.+j

The isoscalar giant quadrupole resonance (GQR) is a fundamental mode of nuclear excitation which has been observed as a general property of nuclei with $A \geq 20$. It has been extensively studied by a variety of hadronic and leptonic probes,[1] and is macroscopically pictured as an isoscalar collective vibration of the nuclear shape. On a microscopic level, however, it has been expected for some time that the GQR should not be a pure isoscalar response for $N > Z$ nuclei.[2] In this paper we report experimental evidence for such an isospin impurity. This impurity appears to be significantly larger than anticipated by calculations[3] and should serve to constrain models of the nuclear giant resonances.

Our procedure is to compare π^- and π^+ cross sections for exciting the GQR at a pion kinetic energy near the broad pi-nucleon $\Delta(1232)$ resonance. In this region, the pi-nucleon interaction has the property that the ratio of cross sections $R^{\mp} = \sigma(\pi^-)/\sigma(\pi^+)$ for scattering from a free neutron (proton) is approximately 9 ($\frac{1}{9}$). This qualitative feature is retained in π-nucleus inelastic scattering, and gives us the ability to probe the neutron-proton, or equivalently, isospin degrees of freedom. It has been extensively used to locate various isospin anomalies in light nuclei.[4] The GQR has been previously observed in inelastic π^+ and π^- scattering, but until now only π^+ cross sections have been published.[5]

This measurement was made at the energetic pion channel and spectrometer (EPICS) at the Clinton P. Anderson Meson Physics Facility (LAMPF). An incident pion energy of 130 MeV was chosen for complete pion-muon separation by time of flight. Data were taken on two separate occasions about one year apart. In the second run, a differential range veto was added for redundant muon rejection. The target consisted of 150 ± 5 mg/cm^2 of ^{118}Sn at 97% enrichment for the first run and 270 ± 8 mg/cm^2 for the second. Data were normalized to $\pi^{\pm}p$ scattering from a CH_2 target, measured at one angle, by use of cross sections determined from the phase shifts of Carter *et al.*[6] The total angle-dependent normalization uncertainty was 8% for the first run and 7.5% for the second.

A sample spectrum is shown in Fig. 1. From measurements with other probes, the giant resonance region near 14 MeV is known to consist of the giant quadrupole at 13.2 MeV with a width of 3.8 MeV,[7] the isoscalar monopole at 15.5 MeV with a width of 4.1 MeV,[7] the isovector dipole at 15.6 MeV with a width of about 4.8 MeV,[8] and a

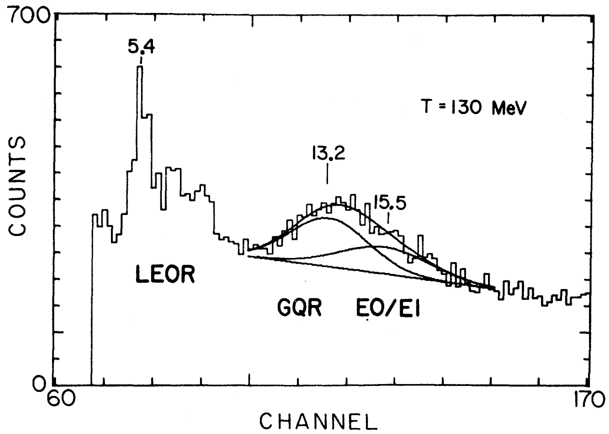

FIG. 1. Sample spectrum of $^{118}Sn(\pi^+,\pi^{+\prime})$ at 30°. The location and width of the GQR and $E0/E1$ were fixed as shown. The assumed straight-line background is also shown. Excitation energies are in megaelectronvolts.

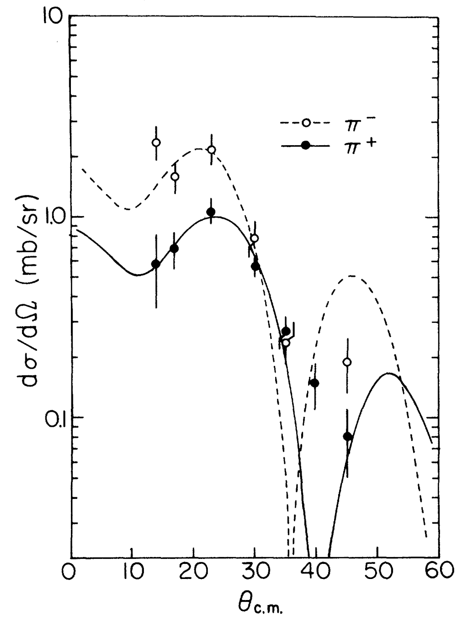

FIG. 2. Angular distribution for the giant quadrupole. The curves are DWIA calculations with magnitudes adjusted to fit the data.

smooth continuum. As shown in Fig. 1, the region was analyzed by fixing the energy and width of two Gaussians: One with the previously observed parameters of the giant quadrupole and the other at 15.5 MeV with a width of 4.4 MeV. Their areas and a straight-line background were then fitted to the data. The extracted areas were insensitive to small changes in the widths. A Gaussian shape was chosen to approximate the macroscopic envelope of the GQR and to be consistent with alpha scattering. A Lorentzian shape, which describes isolated resonances and the giant dipole, did not fit the spectra. A minimum uncertainty of 20% was assumed for most peak areas because of uncertainties in the peak shape and background.

The angular distributions for π^- and π^+ are shown in Fig. 2. The weighted average of the cross sections obtained in the two runs was used at overlap points. The ratio $\sigma(\pi^-)/\sigma(\pi^+)$ of the cross sections at 23° is 1.9 ± 0.4. For comparison, the ratio $R^{\mp}$ for the first 2^+ state in ^{118}Sn was also measured and found to be 1.3 ± 0.1.

Figure 2 also shows $l=2$ curves from configuration-space distorted-wave impulse-approximation (DWIA) calculations.[9] Although the calculations used the complete pi-nucleon interaction, for this discussion we display only the dominant P-wave part of the inelastic transition operator

$$t_{\varphi}(\vec{r}) \simeq \lambda_0 \rho_0(\vec{r}) + \varphi\lambda_1\rho_1(\vec{r}),$$

where $\varphi=\pm1$ for $\pi^{\pm}$, ρ_0 (ρ_1) denotes the isoscalar (isovector) transition density, and λ_0 (λ_1) are the isoscalar (isovector) parameters determined from pi-nucleon phase shifts.[10] We assumed a macroscopic derivative form for the transition densities,

$$\rho_{0(1)} = B_{0(1)}\, \rho_{g.s.}'(r) Y_{l0}(r)(2l+1)^{-1/2},$$

where $\rho_{g.s.}$ is the ground-state density normalized to 1, and B_0 and B_1 are the isoscalar and isovector normalization constants determined from nuclear structure models. The ground-state density was a two-parameter Fermi distribution with parameters taken from electron scattering[11] and corrected for the finite size of the proton.

All calculations used $B_0 = Z(\beta R)_p + N(\beta R)_n$, where (βR) is the proton or neutron deformation length. In order to understand the observed cross-section ratio, calculations based on three models were tried. For the first two models we set $(\beta R)_p = (\beta R)_n = (\beta R)$, determined from an isoscalar linear energy-weighted sum rule with uniform mass distribution. Initially, we considered the GQR to be a pure isoscalar response and set $B_1 = 0$. This implies that $R^{\mp}$ can differ from unity only through a difference in π^- and π^+ distorted waves, which we calculated to be less than 5% in the region of the cross-section maximum. This is far less than our observed ratio. Next, we assumed a hydrodynamic model and set B_1

$=Z(\beta R)_p - N(\beta R)_n$. This yielded a ratio of 1.4 at 23° which is greater than unity but still less than the observed ratio.

Finally, we used the schematic model calculations of Brown and Madsen[3] which allow $(\beta R)_p$ and $(\beta R)_n$ to differ. Briefly, their calculations predict that for a closed-proton-shell nucleus the low-lying $0\hbar\omega$ 2^+ proton vibrations should be damped compared to the neutron vibrations because of the shell closure, while the $2\hbar\omega$ GQR should not be subject to this blocking. Their results include core polarization and are given in terms of the ratio of neutron to proton matrix elements, $M_n/M_p = N(\beta R)_n/Z(\beta R)_p$. For the first 2^+ state in ^{118}Sn, their calculation is in reasonable agreement with our measured experimental ratio[12] of 1.3. However, for the GQR their model predicts[13] $M_n/M_p = 1.23$, which yields a cross-section ratio, $R^{\mp}$, at 23° of about 1.2, which is quite different from the experimental value.

We can obtain a measurement of M_n/M_p directly from the data by noting that at 130 MeV, $\lambda_0/\lambda_1 \approx 2$ and at 23° the effects of π^+ and π^- distortions are nearly equal. In this situation we obtain the approximate result $M_n/M_p \approx \sigma(\pi^-)/\sigma(\pi^+)$. This implies that $M_n/M_p \approx 1.9 \pm 0.4$. This is consistent with the value of $M_n/M_p = 2.08$ obtained by Kailas *et al.* from inelastic medium-energy alpha and proton scattering to the GQR in ^{120}Sn.[14]

For comparison with other probes, we can express our results as a fraction of the linearly energy-weighted sum rule, $F_{\rm SR} = \sigma(\text{measured})/\sigma(100\%)$, with the cross section calculated using the hydrodynamic model. The sum-rule fraction was determined by a least-squares fit of the data by the calculation over the entire angular range. $(57 \pm 6)\%$ of the sum rule is exhausted in π^- scattering, which is consistent with the 60% strength observed in inelastic alpha scattering,[2] but only $(37 \pm 3)\%$ of the sum rule is exhausted in π^+ scattering. Similar behavior is observed in the low-energy octupole and monopole/dipole regions. The complete results for these states will be reported elsewhere.[12] This result is different from that of Arvieux *et al.*[5] who found that the sum-rule fraction for the GQR excited in ^{89}Y$(\pi^+, \pi^{+\prime})$ was in good agreement with other probes.

Although the data imply the need for a large ratio of M_n/M_p, we must consider the possibility that because the pion is strongly absorbed near resonance, small surface differences in the neutron and proton transition densities, which were assumed to have equal shapes, might strongly affect the calculations. To investigate this, we used the hydrodynamic model and varied the neutron radius from 5.41 to 5.81 fm. The resulting change in the calculated π^-/π^+ cross-section ratio was 4%. We also tried different realistic ground-state neutron and proton densities[15,16] with less than a 2% effect. Of course, realistic transition densities, based on random-phase approximation models instead of the simple derivative model, should be tried. Nonetheless, reasonable differences between the ground-state neutron and proton distributions are not sufficient to explain the observed π^-/π^+ ratio.

A possible approach to understanding the large M_n/M_p ratio is being considered in a valence-nucleon collective picture by True and King.[17] They assume $(\beta R)_p = (\beta R)_n$, but allow the effective number of neutrons and protons to vary, producing a M_n/M_p different from the hydrodynamic value. Their results are encouraging and will be published elsewhere.

To summarize, we have observed a large ratio of $\sigma(\pi^-)/\sigma(\pi^+)$ for the GQR. This represents the first direct observation of a neutron-proton asymmetry in the isoscalar giant resonances, and can be interpreted as implying a value of M_n/M_p significantly larger than predicted. One could also interpret this result as implying the need for a substantial isovector matrix element. This result should help constrain our microscopic understanding of giant resonances and motivate further measurements to define the nature of this asymmetry.

This work was supported in part by the U. S. Department of Energy.

---

[a]Present address: University of Michigan Group, Brookhaven National Laboratory, Upton, N.Y. 11973.

[b]Present address: Rockwell International, Golden, Colo. 80401.

[c]Permanent address: University of California, Davis, Cal. 95616.

[1]F. E. Bertrand, Nucl. Phys. A354, 129 (1981).

[2]A. Bohr and B. R. Mottelson, *Nuclear Structure* (Benjamin, Reading, Mass., 1975), Vol. II, Chap. 6.

[3]V. R. Brown and V. A. Madsen, Phys. Rev. C 11, 1298 (1975).

[4]For example, D. B. Holtkamp *et al.*, Phys. Rev. Lett. 47, 216 (1981); S. Iverson *et al.*, Phys. Lett. 82B, 51 (1979).

[5]J. Arvieux *et al.*, Phys. Lett. 90B, 371 (1980); M. Buenard and J. Arvieux, *Giant Multipole Resonances*, edited by F. E. Bertrand (Harwood, New York,

1980), p. 381.

[6]Program SCATPI by B. Walter and G. A. Rebka [Los Alamos Laboratory Report No. UC34A, 1979 (unpublished)] based on the phase shifts in J. R. Carter *et al.*, Nucl. Phys. B58, 378 (1973).

[7]D. H. Youngblood *et al.*, Phys. Rev. C 23, 1997 (1981).

[8]B. L. Berman and S. C. Fultz, Rev. Mod. Phys. 47, 713 (1975).

[9]Program DWPIES based on the code DWPI; R. A. Eisenstein and G. A. Miller, Comput. Phys. Commun. 11, 95 (1976).

[10]G. Rowe *et al.*, Phys. Rev. C 18, 584 (1978).

[11]C. W. deJager *et al.*, At. Data Nucl. Data Tables 14, 479 (1974).

[12]J. L. Ullmann *et al.*, to be published.

[13]V. A. Madsen, private communication.

[14]S. Kailas *et al.*, in *Proceedings of the International Conference on Nuclear Structure, Amsterdam, 1982*, edited by A. van der Woude and B. J. Verhaar (European Physical Society, Petit-Lancy, Switzerland, 1982), p. 93.

[15]M. Beiner *et al.*, Nucl. Phys. A238, 29 (1975).

[16]J. W. Negele and D. Vautherin, Phys. Rev. C 5, 2472 (1972).

[17]W. W. True and N. S. P. King, to be published.