Isovector $E2$ Resonance in ^{208}Pb

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Polarization asymmetries observed in elastic tagged photon scattering at excitations between 16 and 30 MeV were used to identify the isovector giant electric quadrupole resonance in ^{208}Pb through its interference with underlying electric dipole strength. Resonance parameters reflecting the distribution of the $E2$ $(T=1)$ transition strength were extracted in a manner that has minimal sensitivity to uncertainties in the Delbruck amplitudes or in the q dependence of the modified Thomson amplitudes. The isovector $E2$ resonance was found at an excitation of 20.2 ± 0.5 MeV, with a width of 5.5 ± 0.5 MeV, and a strength corresponding to 1.4 ± 0.3 times the isovector quadrupole sum rule.

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The study of collective nuclear excitations dates from the recognition that many of the observed features of giant dipole resonances (GDR) could be described in terms of a simple model in which protons oscillated in bulk against neutrons [1]. This elementary picture of the nucleus also implies the existence of additional higher multipolarity isovector and isoscalar collective excitations. The first experimental evidence for higher multipole resonances came from early (p,p') scattering data which were reinterpreted in 1971 to show the presence of an isoscalar electric quadrupole resonance in ^{40}Ca [2]. Since then, the isoscalar $E2$ giant resonance (ISGQR) has been investigated with a variety of probes in a broad range of nuclei, and knowledge of its properties approaches in detail that of the GDR [3–8].

The problem of measuring the distribution of isovector $E2$ transition strength has not been as tractable as that of the isoscalar. To some extent this situation may be a consequence of the relative insensitivity to $E2$ $(T=1)$ excitations of the hadronic probes which have largely addressed the $E2$ $(T=0)$ [9,10]. Although there is evidence for its existence in a number of nuclei, the systematics of the isovector giant quadrupole resonance (IVGQR) have yet to be well established. This is particularly true in heavier nuclei, and the published reports of measurements of the strength distributions of the IVGQR in the lead region are quite inconsistent [3,11–21]. There is reasonable agreement on the location of the isovector $E2$ resonance at an excitation in the vicinity of 21 to 24 MeV, but reported strengths range between 0 and 1.4 times the isovector quadrupole sum rule (IVQSR), and reported widths between 3.5 and 10 MeV. The experimental techniques that have been employed tend to have either limited multipole selectivity or strong model and theory dependences which make the extraction of quantitative information problematic.

In order to address the question of the IVGQR in ^{208}Pb, we have measured the distribution of electric quadrupole transition strength at excitations between 16 and 30 MeV using highly polarized tagged photons. The present technique avoids many of the difficulties that are inherent in other methods. Photon scattering cannot excite $E0$, and is very insensitive to multipole excitations beyond $E2$; and measured polarization asymmetries permit the separation of the $E1$ and $E2$ contributions to the scattering. In addition, the tagging coincidence requirement ensures that there are no background subtraction problems, and also provides for a substantial enhancement of the photon polarization [22]. A key aspect of the present work is that the polarization asymmetry at a single backward angle is used to measure the interference between the IVGQR and the underlying $E1$ amplitude associated with the high-energy tail of the GDR. The sensitivity of this asymmetry to the $E1$-$E2$ interference is high, while its sensitivity to poorly known Delbruck and Thomson scattering amplitudes is minimal. The forward-peaked Delbruck contribution is expected to be small in the backward direction [23], and the modified Thomson contributions tend to cancel in the asymmetry ratio because the momentum transfer, $q=(2E/\hbar c)\times\sin(\theta/2)$, is constant at a fixed scattering angle. These aspects of the present polarization-asymmetry experiment can be contrasted with the corresponding elements of experiments in which an angular asymmetry in the elastic photon scattering cross section is used to measure the $E1$-$E2$ interference [13,17,19]. In the latter cases, both the rapid fore-to-aft angular variation of the Delbruck amplitudes and the $q(\theta)$ dependence of the exchange contributions to the modified Thomson amplitudes need to be well known. Actual large uncertainties in both tend to preclude reliable quantitative conclusions about the $E2$ transition strength [17].

In the present work, a cw electron beam from the MUSL-2 accelerator was used to produce tagged bremsstrahlung photons. The off-axis linear polarization of the tagged beam was enhanced by means of residual electron selection in a manner previously described [22]. The electron-selection baffle was made from carbon and tungsten to dimensions which provided polarization on the order of 50% for photons with energies in the range of 15 to 30 MeV. The 5-cm-diam scattering target consisted of 10.16 g/cm^{-2} of 98.85% enriched metallic ^{208}Pb. Two large high-resolution NaI detectors were located at 120° on each side of the photon beam. Each detector was well shielded and mounted on a mechanical lift table so that off-axis positions with respect to the beam could be rapidly and accurately established when the sign of the polarization was changed. Photon fluxes were related to the tagging counter rates, and the detector responses were directly measured by placing each detector into the beam at 0°.

The experimental polarization asymmetries at 120° as a function of photon energy are shown in Fig. 1. The dashed curve superimposed on the data corresponds to the asymmetry that one would expect to find in the absence of the IVGQR. At lower energies the experimental asymmetry is consistent with electric dipole scattering, and in the region around 20 MeV it decreases in a manner, illustrated by the solid curve, which is characteristic of the $E1$-$E2$ interference. The curves were derived from ratios of scattering cross sections expressed as the squares of sums of complex scattering amplitudes which included nuclear, Delbruck, and modified Thomson contributions. The real and imaginary parts of the nuclear amplitudes are related to the total photoabsorption via the optical theorem and the Kramers-Kronig dispersion relation [17,24]. In the present case, $E1$, $M1$, and $E2$ contributions were examined. The total photoabsorption of Refs. [25] and [26] was parametrized by a set of four Lorentzians as specified in Table I, and initially assumed to be predominantly $E1$. The inclusion of neither $M1$ [27] nor $E2$ $(T=0)$ [28] strength distributions was found to have much effect on polarization asymmetries in

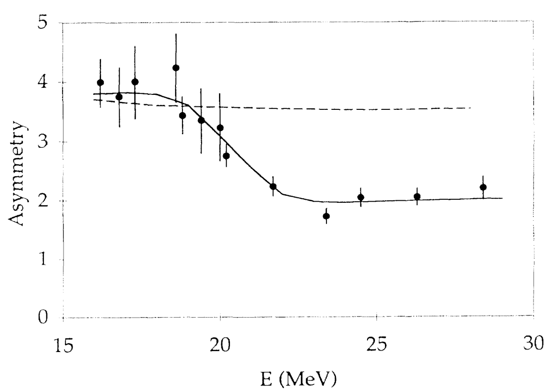

FIG. 1. ^{208}Pb experimental polarization asymmetries at 120°. The asymmetry expected in the absence of an IVGQR is shown by the dashed line. The solid curve indicates the best fit of the $E1$-$E2$ interference to both the polarization asymmetry and the total photoabsorption.

TABLE I. Parametrization of the ^{208}Pb total photoabsorption cross section with four Lorentzians.

E_0 (MeV)	σ_0 (mb)	Γ_0 (MeV)
11.6	99.1	1.88
13.6	627.6	3.43
20.0	15.0	9.0
60.0	14.3	100.0

the energy region of the present experiment. In order to study the gross features of the IVGQR strength distribution, the $E2$ $(T=1)$ contribution to the photoabsorption was parametrized as a single resonance. Several different resonance line shapes were investigated, and the best fit, shown by the solid curve in Fig. 1, to both the polarization asymmetry and the total photoabsorption as parametrized in Table I, was provided by an $E2$ $(T=1)$ Breit-Wigner line corresponding to an energy weighted strength of 1.4 ± 0.3 times the IVQSR, with a 5.5 ± 0.5 MeV FWHM, at an excitation of 20.2 ± 0.5 MeV. We note that a line shape having a relatively smaller high-energy tail, such as that of a Gaussian distribution, would produce a somewhat poorer overall fit to the data. Also, it was found that the quality of the fit was not improved by the inclusion of more than one $E2$ $(T=1)$ resonance. If better total photoabsorption data were available, the present localized distribution of isovector $E2$ strength might be sufficiently large to produce an observable structure in the cross section.

The errors quoted above for the parameters of the IVGQR, in addition to statistics, include estimates of the uncertainty associated with the determination of the photon polarizations (known to $\pm 5\%$), as well as the uncertainties associated with the contributions of the Delbruck and modified Thomson amplitudes. The greatest uncertainties in the modified Thomson amplitude come from the form of the exchange form factor, $F_{ex}(q)$, and from the degree, related to the GDR energy-weighted sum-rule enhancement κ_{GDR}, to which meson exchange might be considered to contribute to the scattering [29]. The substitution of extremes for the exchange form factor, $1 < F_{ex}(q) < F_{chg}(q)$, and changes in the nominal value of κ_{GDR} by factors of 2 have little effect on the asymmetry. A parametrization of $F_{chg}(q)$ was adopted from Ref. [30]; below 30 MeV, $\kappa_{GDR} \sim 0.29$ [31,32]. There have been several calculations of Delbruck amplitudes for excitation energies of interest in the present experiment [23,33]. The use of these amplitudes alters the backward polarization asymmetry very little from the value it would have with no Delbruck contribution, particularly at excitations below 25 MeV. It has been suggested that Coulomb corrections, not included in current Delbruck calculations, might modify the amplitudes, particularly in the forward direction and at higher energies [34–39]. Such modifications, if they were significant at backward

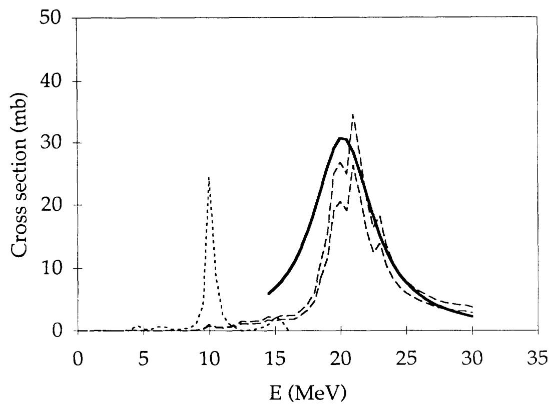

FIG. 2. The distribution of $E2$ transition strength from the present work (solid curve) together with a continuum RPA calculation of isoscalar (dots) and isovector (dashes) $E2$ strength from Ref. [42]. For comparison, the RPA isovector $E2$ is also shown with a 30% enhancement.

angles where the amplitudes are already very small, would affect the present results only if they also introduced a substantial energy dependence in the real amplitude.

Hydrodynamic models, including the simple estimate $E \sim 135A^{-1/3}$, predict IVGQR energies in ^{208}Pb that are typically 1 to 2 MeV higher than what we observe here [40,41]. Width predictions from these calculations are also perhaps a little larger than the present result would indicate. A continuum random-phase-approximation (RPA) calculation by Wambach finds an isovector quadrupole resonance energy, $E = 20.5$ MeV, and a width, $\Gamma \sim 5$ MeV, that are in excellent agreement with our results [42]. Because the RPA calculation does not include exchange effects, the predicted $E2$ $(T=1)$ strength is 1.0 times the IVQSR. Unlike the case of the isoscalar operator which commutes with a wide variety of nuclear potentials, the isovector operator in general does not commute. This results in an enhancement over the RPA value in the computation of the isovector quadrupole sum rule. Lipparini and Stringari have estimated this enhancement to be on the order of 15% for a hydrodynamic potential, and 30% for a Skyrme potential [43]. This degree of enhancement brings the RPA strength into reasonable agreement with our experimental result. Figure 2 shows the distribution of $E2$ transition strength from the present experimental work together with Wambach's continuum RPA calculation of both isoscalar and isovector $E2$ strength. For purposes of comparison, the RPA isovector distribution is also shown with a 30% multiplicative enhancement.

In summary, polarization asymmetries observed in elastic tagged photon scattering at excitations between 16 and 30 MeV were used to identify the isovector giant electric quadrupole resonance in ^{208}Pb through its interference with underlying electric dipole strength. Resonance parameters reflecting the distribution of the $E2$ $(T=1)$ transition strength were extracted in a manner that has minimal sensitivity to uncertainties either in the Delbruck amplitudes or in the q dependence of the modified Thomson amplitudes. The isovector $E2$ resonance was found at an excitation of 20.2 ± 0.5 MeV, with a width of 5.5 ± 0.5 MeV, and a strength corresponding to 1.4 ± 0.3 times the IVQSR.

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[1] M. Goldhaber and E. Teller, Phys. Rev. **74**, 1046 (1948).
[2] M. B. Lewis and F. E. Bertrand, Nucl. Phys. **A196**, 337 (1972).
[3] R. Pitthan, F. R. Buskirk, E. B. Dally, J. N. Dyer, and X. K. Maruyama, Phys. Rev. Lett. **33**, 849 (1974).
[4] A. Schwierezinski, R. Frey, A. Richter, E. Spamer, H. Theissen, O. Titze, Th. Walcher, S. Krewald, and R. Rosenfelder, Phys. Rev. Lett. **35**, 1244 (1975).
[5] D. H. Youngblood, J. M. Moss, C. M. Rozsa, J. D. Bronson, A. D. Bacher, and D. R. Brown, Phys. Rev. C **13**, 994 (1976).
[6] D. J. Horen, J. Arvieux, M. Buenerd, J. Cole, G. Perrin, and de Saintignon, Phys. Rev. C **11**, 1247 (1975).
[7] A. Moalem, W. Benenson, and G. M. Crawley, Phys. Rev. Lett. **31**, 482 (1973).
[8] N. Marty, M. Morlet, A. Willis, V. Comparat, and R. Frascaria, Nucl. Phys. **A238**, 93 (1975).
[9] F. E. Bertrand, Annu. Rev. Nucl. Sci. **26**, 457 (1976).
[10] G. R. Satchler, Nucl. Phys. **A195**, 1 (1972).
[11] M. Nagao and Y. Torizuka, Phys. Rev. Lett. **30**, 1068 (1973).
[12] K. A. Snover, K. Ebisawa, and D. R. Brown, Phys. Rev. Lett. **32**, 317 (1974).
[13] R. Leicht, M. Hammen, K. P. Schelhaas, and B. Ziegler, Nucl. Phys. **A362**, 111 (1981).
[14] D. M. Drake, S. Joly, L. Nilsson, S. A. Wender, K. Aniol, I. Halpern, and D. Storm, Phys. Rev. Lett. **47**, 1581 (1981).
[15] C. Djalali, N. Marty, M. Morelt, and A. Willis, Nucl. Phys. **A380**, 42 (1982).
[16] A. Erell, J. Alster, J. Lichtenstadt, M. A. Moinester, J. D. Bowman, M. D. Cooper, F. Irom, H. S. Matis, E. Piasetzky, U. Sennhauser, and Q. Ingram, Phys. Rev. Lett. **52**, 2134 (1984).
[17] A. M. Nathan, P. L. Cole, P. T. Debevec, S. D. Hoblit, S. L. LeBrun, and D. H. Wright, Phys. Rev. C **34**, 480 (1986).
[18] T. Murakami, I. Halpern, D. W. Storm, P. T. Debevec, L. J. Morford, S. A. Wender, and D. H. Dowell, Phys. Rev. C **35**, 479 (1987).
[19] K. P. Schelhaas, J. M. Henneberg, M. Sanzone-Arenhövel, N. Wieloch-Laufenberg, U. Zurmühl, and B.

Ziegler, Nucl. Phys. **A489**, 189 (1988).
[20] F. E. Bertrand, J. R. Beene, and D. J. Horen, in *Proceedings of the Third International Conference on Nucleus-Nucleus Collisions, Saint Malo, France, 1988,* edited by C. Detraz *et al.* (North-Holland, Amsterdam, 1988).
[21] A. Håkansson, J. Blomgren, A. Likar, A. Lindholm, and L. Nilsson, Nucl. Phys. **A512**, 399 (1990).
[22] R. M. Laszewski, P. Rullhusen, S. D. Hoblit, and S. LeBrun, Nucl. Instrum. Methods Phys. Res., Sect. A **228**, 334 (1985).
[23] T. Bar-Noy and S. Kahane, Nucl. Phys. **A288**, 132 (1977).
[24] W. R. Dodge, Evans Hayward, R. G. Leicht, Miles McCord, and Richard Starr, Phys. Rev. C **28**, 8 (1983).
[25] A. Veyssiere, H. Beil, R. Bergere, P. Carlos, and A. Lepretre, Nucl. Phys. **A159**, 561 (1970).
[26] A. Lepretre, H. Beil, R. Bergere, P. Carlos, J. Fagot, A. deMiniac, and A. Veyssiere, Nucl. Phys. **A367**, 237 (1981).
[27] R. M. Laszewski, R. Alarcon, D. S. Dale, and S. D. Hoblit, Phys. Rev. Lett. **61**, 1710 (1988).
[28] G. O. Bolme, L. S. Cardman, R. Doerfler, L. J. Koester, Jr., B. L. Miller, C. N. Papanicolas, H. Rothaas, and S. E. Williamson, Phys. Rev. Lett. **61**, 1081 (1988).
[29] P. Christillin and M. Rosa-Clot, Nuovo Cimento **43**, 172 (1978).
[30] J. Heisenberg, R. Hofstadter, J. S. McCarthy, I. Sick, B. C. Clark, R. Herman, and D. G. Ravenhall, Phys. Rev. Lett. **23**, 1402 (1969).
[31] G. E. Brown and M. Rho, Nucl. Phys. **A338**, 269 (1980).
[32] D. S. Dale, A. M. Nathan, F. J. Federspiel, S. D. Hoblit, J. Hughes, and D. Wells, Phys. Lett. B **214**, 329 (1988).
[33] S. Turrini, G. Maino, and A. Ventura, Phys. Rev. C **39**, 824 (1989).
[34] M. Cheng and T. T. Wu, Phys. Rev. **182**, 1873 (1969).
[35] M. Cheng and T. T. Wu, Phys. Rev. D **5**, 3077 (1972).
[36] P. Rullhusen, W. Muchenheim, F. Smend, M. Schumacher, G. P. A. Berg, K. Mork, and Lynn Kissel, Phys. Rev. C **23**, 1375 (1981).
[37] A. I. Milstein and V. M. Strakhovenko, Phys. Lett. **95A**, 135 (1983).
[38] P. Rullhusen, U. Zurmuhl, F. Smend, M. Schumacher, H. G. Borner, and S. A. Kerr, Phys. Rev. C **27**, 559 (1983).
[39] A. I. Milstein, P. Rullhusen, and M. Schumacher, Phys. Lett. B **247**, 481 (1990).
[40] N. Averbach and A. Yeverechyahu, Ann. Phys. (N.Y.) **95**, 35 (1975).
[41] Cai Yanhuang and M. DiToro, Phys. Rev. C **39**, 105 (1989).
[42] J. Wambach (private communication).
[43] E. Lipparini and S. Stringari, Università di Trento Report U.T.F. No. 150, March 1988 (unpublished).