$E2$ Isovector Giant Resonance as Seen through the Capture of Fast Neutrons

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The forward-to-backward asymmetry of high-energy photons emitted in the radiative capture of neutrons with energies up to 20 MeV was measured for ^{208}Pb. The asymmetry increases abruptly from small values to large ones near $E_\gamma \sim 23$ MeV supporting the location in that neighborhood of the $E2$ giant isovector resonance.

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The electric quadrupole ($E2$) isovector giant resonance is not nearly as well established experimentally as the corresponding dipole ($E1$) resonance nor as the isoscalar resonances up to $E3$. The latter, which are oscillations of the nuclear shape, have been extensively studied in recent years by inelastic scattering of various projectiles.[1] To study effectively the isovector resonances (i.e., the charge-separating oscillations of the nucleus) one needs to use a probe that discriminates between neutrons and protons. Almost everything we know about the giant dipole resonance, for example, has been obtained with use of electromagnetic probes in either the entrance or exit channels.

We report here the first observation of the $E2$ isovector resonance in a heavy nucleus by use of the (n, γ) reaction. The basic technique is the same as that used some years ago[2] with (p, γ) to see the $E2$ isovector resonance in lead. Since the $E2$ resonance is much smaller than the $E1$ resonance, it tends to be overshadowed by it. The $E2$ isovector excitation is most easily observed as an interference with the larger $E1$ resonance. This interference produces a front-back asymmetry in the angular distribution of the emitted photons.

The (n, γ) reaction is unquestionably more difficult experimentally than the (p, γ) reaction since it makes use of a secondary beam and is subject to large backgrounds. There are nevertheless two reasons to pursue the (n, γ) reaction in looking for the $E2$ resonance. First, the shape of the resonance that was observed in (p, γ) did not resemble the theoretically expected shape, and second there is a large uncertain background asymmetry in (p, γ) that must be subtracted before one knows how much of the observed asymmetry is due to the $E2$ resonance. This background arises from *direct* or single-particle $E2$ capture. As has been pointed out earlier,[3] there is essentially no such direct component in (n, γ) because the effective charge of a neutron undergoing an $E2$ transition is $\approx 1/A$ times that of the corresponding proton (unlike the case for $E1$ transitions where the effective charges are nearly equal). Thus the observation of a front-back asymmetry in (n, γ) would necessarily imply the existence of a nuclear (collective) $E2$ excitation —i.e., a reaction in which the captured neutron performs a radiationless transition as it excites an $E2$ nuclear resonance which subsequently decays with the emission of radiation.

It is easy to provide a rough framework for the interpretation of the (n, γ) measurement, a framework which mocks up a more detailed calculation and which shows what to expect in an asymmetry measurement and what this expectation depends on. In this skeletal description, the amplitude for dipole plus quadrupole capture leading to a particular residual state with the emission of a photon at θ to the beam can be written

$$F(\theta) = \frac{\sin\theta}{E - E_D + i\Gamma_D/2} + \frac{R\sin\theta\cos\theta}{E - E_Q + i\Gamma_Q/2}.$$

Here E_D, E_Q, Γ_D, and Γ_Q are the dipole and quadrupole energies and widths, and E is the energy of the emitted photon. The angle factors give the classical amplitudes for dipole and quadrupole emissions. (The essential point here is that the second term contains an extra factor of $\cos\theta$.) In simple models, in the high-energy limit, the amplitude ratio R is expected to be real and positive. Its expected magnitude can be very crudely estimated from sum rules and neutron penetration factors. Values $R = \frac{1}{3} \pm \frac{1}{6}$ lie in a reasonable range.

What one typically measures is the asymmetry in fore and aft yields,

$$A(\theta) = [\,Y(\theta) - Y(\pi - \theta)\,]/[(Y(\theta) + Y(\pi - \theta)\,].$$

Because $A(\theta)$ is very nearly linear in $\cos\theta$, one need not measure at many angles. In fact it is customary in capture experiments to use only $\theta = 55°$ (and its supplement). Figure 1 shows the results of a numerical exercise where the resonance parameters for $F(\theta)$ were chosen to match the target in our experiment, ^{208}Pb. The parameters $E_D = 13$ MeV and $\Gamma_D = 5$ MeV give a fair fit to the well-known $E1$ resonance, and $E_Q = 23$ MeV, $\Gamma_Q = 5$ MeV provide reasonable expectations for $E2$. For the different curves in the figure, R was taken to be of the form $R_0 \exp(i\delta)$ with various values for δ and for R_0. (The introduction of δ allows one to see how much any dipole-quadrupole phase difference would influence the asymmetry pattern.) The essential feature of all of these curves is that $A(55°)$ is expected to change dramatically from negative or small values to values approaching the maximum possible value, $+1$, within an interval of width Γ_Q which is roughly centered on E_Q.

Now the actual expectations for $A(\theta)$ in ^{208}Pb have been studied in great detail by Longo, Saporetti, and their collaborators.[4] They have done extensive calculations using the so-called direct-semidirect model for nucleon capture with carefully chosen optical-model parameters for the incoming projectile. The $A(\theta)$'s they find for different residual states all resemble those shown in Fig. 1. Longo and Saporetti also show that if one includes a third capture amplitude in the $E2$ isovector region, namely one for the tail of the lower-lying $E2$ isoscalar resonance, then the negative undershoot in the curves of Fig. 1 tends to get filled in. (One can show that the addition of such a third amplitude must have the same effect as a positive phase shift, δ).

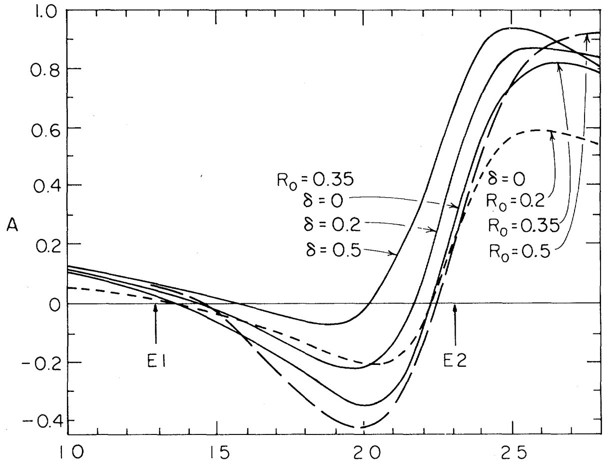

FIG. 1. Expected asymmetries, $A(55°)$, for photons emitted in radiative capture by ^{208}Pb. The centers of the $E1$ and $E2$ isovector giant resonances were assumed to lie at the energies indicated by arrows. Both resonances were assumed to be 5 MeV wide and the ratio of $E2$ to $E1$ amplitude was taken as $R_0 e^{i\delta}$. It is seen that for a large range of values of R_0 and δ, the expected asymmetry increases substantially in the neighborhood of the $E2$ giant resonance.

Longo and Saporetti have also investigated how the curves for $A(\theta)$ are expected to depend on the spin and parity of the residual states in ^{209}Pb. They find curves of the standard shape (Fig. 1) for all J^π but with the amount of negative undershoot increasing with residual angular momentum. For our present purposes, the important point is that spin and parity do not make a very great difference. The curves for $A(\theta)$ all rise abruptly toward unity in the neighborhood of the $E2$ resonance.

It is this dramatic and unmistakable signature that makes the (n,γ) reaction so worthwhile a probe for the $E2$ isovector resonance despite its low counting rates and high backgrounds.

The measurements were performed with the (n,γ) detection system at the Los Alamos tandem accelerator. A 1-μA deuteron beam of variable energy up to 18 MeV was used to produce the neutrons in a cell 3 cm long containing up to 8.5 atm of deuterium. These neutrons irradiated a 350-gm ^{208}Pb target placed 10 cm downstream from the deuterium cell. The target was a cylinder with axis perpendicular to the reaction plane. A hole was drilled along its axis to minimize neutron and photon attenuation. The calculated attenuation for the highest energy photons was 9% greater at 55° than at 125°. The attenuation corrections were checked by observing the 2.6-MeV $(n,n'\gamma)$ line in Pb and the corresponding 15.1-MeV line in a carbon target. These photons showed (the expected) fore-aft symmetry to within $\approx 3\%$ after correction for attenuation and Doppler shift.

The capture photons were detected in a 15-cm-diam by 25-cm-long NaI detector 120 cm from the target. This detector was surrounded by a two-section NaI annulus which was in turn surrounded by 10 cm of lead and 40 cm of borated paraffin. The collimator to the detector through the shielding was filled with a 50-cm column of ^{6}LiH. Additional shielding was added on the up-

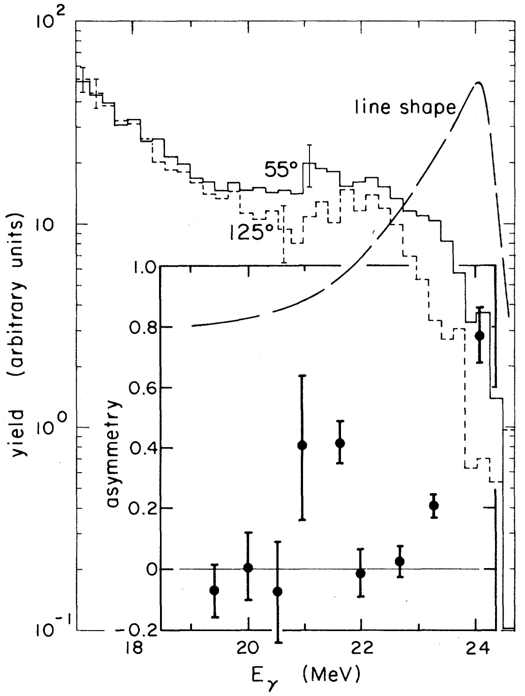

FIG. 2. The high-energy photon (photopeak) spectra measured at 55° and 125° when ^{208}Pb is bombarded with 20-MeV neutrons. These spectra have been corrected for attenuation in the target and for Doppler shift, but were not in any other way renormalized. The two spectra were individually unfolded with use of the measured line shape (shown in the figure for $E_\gamma = 24$ MeV) and the asymmetries $A(55°)$ were computed as a function of photon energy. These asymmetries were combined with the results obtained from the one-escape spectra and are plotted in the lower portion of the figure. The energies for the five points of lowest excitation correspond to known states or doublets in ^{209}Pb. The higher points were arbitrarily placed $\frac{1}{2}$ MeV apart. The unfolding was terminated at $E_\gamma = 18.8$ MeV.

stream side of the detector and between the detector and background sources like the deuterium cell and collimators in the beam line. In the final arrangement, the singles rates and associated deadtimes were very nearly the same at 55° and 125°.

Time of flight was used to distinguish target photons from background events. For this purpose the beam was pulsed at 2.5×10^6 sec^{-1}. Good events were accepted in a 2.5-ns time interval and were corrected for random events observed with a displaced time gate. To provide phototube stability in the presence of high singles counting rates, the resistor string carried 7 mA and the phototube assembly was water cooled.

The photopeak events (full energy deposited in the NaI detector) were supplemented with one-escape events. This increased the effective counting rate by a factor of ~2 and was made possible by the fast coincidence between the central NaI detector and the surrounding NaI shield.

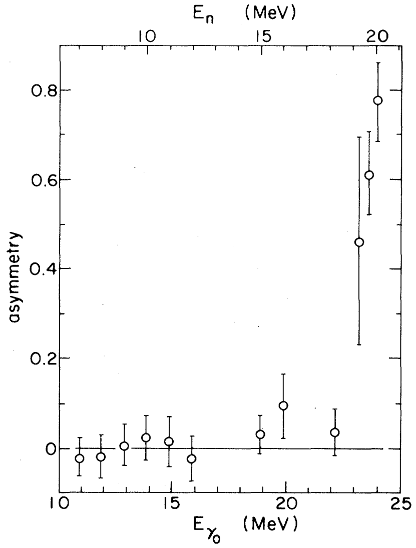

FIG. 3. The measured fore-aft asymmetry $A(55°)$ for photons emitted to the ground state of ^{209}Pb when neutrons of energy E_n are captured in ^{208}Pb.

The observed pulse-height spectra $P(55°)$ and $P(125°)$ for the run with 20-MeV neutrons are plotted in Fig. 2. It is seen that these spectra cut off reasonably sharply above the highest possible capture photon energies, showing that there is no significant pileup in the measurements.

The measured asymmetries for γ_0, the photons to the ground state, are plotted as a function of neutron energy in Fig. 3. To complement these values, we also obtained values of the asymmetry for different energy photons at the fixed neutron energy of 20 MeV (the maximum we could reach). This asymmetry, again for 55°, is plotted as a function of E_γ in the lower portion of Fig. 2. One would expect it to be exactly the same curve as that for γ_0 as a function of E_n [with the abscissae displaced by the 3.9-MeV Q value of (n, γ_0)] if giant resonances built upon excited states (1) were all identical and (2) had negligible photon widths to states other than the one they are built on. These conditions are expected to hold only qualitatively.

To obtain $A(55°)$ as a function of E_γ at $E_n = 20$ MeV, it was necessary to unfold the measured spectra with the measured detector response function shown in Fig. 2. The resulting $A(55°)$

is shown in the lower portion of Fig. 2. It is seen from this curve and from the plot of Fig. 3 that $A(55°)$ in both representations increases abruptly when the photon energy reaches ~23 MeV. In addition, the curve in Fig. 2 shows a surprisingly large asymmetry at ~2.5 MeV below the location of γ_0. This does not appear to be an artifact because it is also present to some extent in the spectra for $E_n = 19.8$ and 19.3 MeV.

We would conclude from a match of the data at the upper ends of Figs. 2 and 3 to the curves of Fig. 1 that the center of the $E2$ isovector giant resonance lies within 1 MeV of $23 - \frac{1}{2}$ MeV. The present data are unfortunately not precise enough to provide useful information about the strength and width of the $E2$ isovector resonance, but they do provide striking evidence for its existence and location. The specificity of the signature for this resonance in the (n, γ) reaction should encourage the design of experiments at neutron energies above those that could be reached in this experiment in order to define better the properties of this important resonance.

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