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*The E2 Isovector Giant Resonance
As Seen Through
The Capture of Fast Neutrons*

Los Alamos Los Alamos National Laboratory
Los Alamos, New Mexico 87545

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THE E2 ISOVECTOR GIANT RESONANCE AS SEEN THROUGH THE CAPTURE OF FAST NEUTRONS

by

D. M. Drake

and

K. Aniol, I. Halpern, S. Joly, L. Nilsson, D. Storm, and S. A. Wender

ABSTRACT

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.

The electric quadrupole (E2) isovector giant resonance is not nearly as well established experimentally as the corresponding dipole (E1) resonance and the isoscalar resonances up to E3. The latter, which are oscillations of the nuclear shape, have been studied extensively in recent years by inelastic scattering of various projectiles.¹ To study the isovector resonances effectively (that is, the charge-separating oscillations of the nucleus), a probe that discriminates between neutrons and protons must be used. Almost everything we know about the giant dipole resonance, for example, has been obtained using electromagnetic probes in either the entrance or exit channels.

We report here the first observation of the E2 isovector resonance in a heavy nucleus using the (n,γ) reaction. The basic technique is the same as that used several years ago² with (p,γ) to see the E2 isovector resonance in lead. Because the E2 resonance is much smaller than the E1 resonance, it tends to be overshadowed by it. The E2 isovector excitation is observed most easily 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 to study experimentally than the (p,γ) reaction because it uses 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 observed in (p,γ) did not resemble the expected theoretical shape; and second, there is a large uncertain background asymmetry in (p,γ) that must be subtracted before we know how much of the observed asymmetry is the result of the E2 resonance. This background arises from *direct* or single-particle E2 capture. As 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 $\sim 1/A$ 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—that is, 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.

Providing a rough framework for the interpretation of the (n,γ) measurement is easy—a framework that mocks up a more detailed calculation and 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 emission. (The essential point here is that the second term contains an extra factor, $\cos \theta$.) In simple models, in the high-energy limit, the amplitude ratio, R , is expected to be real and positive. Its expected magnitude can be estimated very crudely from sum rules and neutron penetration factors. Values of $R = 1/3 \pm 1/6$ lie within a reasonable range.

Typically we measure the asymmetry in fore and aft yields,

$$A(\theta) = \frac{Y(\theta) - Y(\pi - \theta)}{Y(\theta) + Y(\pi - \theta)}$$

Because $A(\theta)$ is very nearly linear in $\cos \theta$, we need not measure at many angles. In fact, customarily in capture experiments we use only $\theta = 55^\circ$ (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 ^{208}Pb experiment. 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 of δ and for R . (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 $A(55^\circ)$ 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 calcu-

lations 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. (We can show that the addition of such a third amplitude must have the same effect as a positive phase shift.)

Longo and Saporetti 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 found 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 purpose, 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 such a worthwhile 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 tandem accelerator at Los Alamos. A 1- μA deuteron beam of variable energy up to 18 MeV produced the neutrons in a cell 3 cm long containing up to 8.5 atm of deuterium. The high neutron energies (<20 MeV) required improving the already extensive shielding around the NaI photon detection system. In the final arrangement, the singles rates and associated dead times were very nearly the same at 55° and 125° . 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 target was a 350-gm cylinder of ^{208}Pb with axis perpendicular to the reaction plane. A hole was drilled along the cylinder 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 $\sim 3\%$ after correction for attenuation and Doppler shift.

The photopeak events (full energy deposited in the NaI detector) were supplemented with one-escape events. This doubled the effective counting rate and was made

Fig. 1. Expected asymmetries, $A(55^\circ)$, 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 amplitudes was taken as $R_0 e^{i\delta}$. For a large range of values of R_0 and δ , the expected asymmetry increases substantially in the neighborhood of the E2 giant resonance.

possible by the fast coincidence between the NaI detector and the surrounding (NaI) annular shield. The beam was pulsed at $2.5 \times 10^6 \text{ s}^{-1}$. Good events were accepted in a 2.5-ns interval and were corrected for random events observed with a displaced time gate.

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

The measured asymmetries of 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 Fig. 4. 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.

Fig. 2. The high-energy photon (photopeak) spectra measured at 55 and 125° when ^{208}Pb is bombarded with 20-MeV neutrons. These spectra were corrected for attenuation in the target and for Doppler shift but were not in any other way renormalized. The measured line shape is shown for $E_\gamma = 24$ MeV.

To obtain $A(55^\circ)$ 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 $A(55^\circ)$ is shown in Fig. 4. It is seen from this curve, and from the plot of Fig. 3, that $A(55^\circ)$ in both representations increases abruptly when the photon energy reaches ~ 23 MeV. In addition, the curve in Fig. 4 shows a suprisingly 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 conclude from a match of the data at the upper

Fig. 3. Asymmetries computed from the unfolded spectra of Fig. 2 and similar one-escape spectra. The energies for the five points of lowest excitation correspond to known states, or doublets, in ^{209}Pb . The highest points were arbitrarily placed 1/2 MeV apart. The unfolding was terminated at 18.8 MeV.

ends of Figs. 3 and 4 to the curves of Fig. 1, that the center of the E2 isovector giant resonance lies within an MeV of 23-1/2 MeV. Unfortunately, the present data are 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 using the (n,γ) reaction should encourage the design of experiments, which can use higher neutron energies that better define the properties of this important resonance.

Fig. 4. The measured fore-aft asymmetry $A(55^\circ)$ for photons emitted to the ground state of ^{209}Pb when neutrons of energy E_n are captured in ^{208}Pb .

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