Q-Value Systematics for Isovector Giant Resonances Excited by (p,n) Reactions on Zr, Nb, Mo, Sn, and Pb Isotopes

W. A. Sterrenburg, Sam M. Austin, R. P. DeVito, and Aaron Galonsky
Cyclotron Laboratory, Michigan State University, East Lansing, Michigan 48824

(Received 7 July 1980)

The (p,n) reaction at 45 MeV is used to study two broad peaks found previously with the target ^{90}Zr. They have now been observed with all but one of seventeen targets from ^{90}Zr to ^{208}Pb. Energy systematics favor the conclusion that these peaks are antianalogs of the giant $M1$ and $E1$ resonances in the target nucleus. The first experimental determinations of T, $T-1$ splittings of the giant $E1$ resonance are reported. Their low values in comparison to T, $T+1$ splittings observed previously can be interpreted as due to a tensor part of the effective isospin potential.

PACS numbers: 25.40.Ep, 24.30.Cz

Many studies with (p,n) reactions have focused on the most prominent feature in the neutron spectra, i.e., on the isobaric analogs of ground states (IAS). In the (p,n) reaction on ^{90}Zr at a bombarding energy of 45 MeV two other features were observed.[1] The first was a peak about 4 MeV wide not far above the IAS which was interpreted as the $T-1$ component (T = target isospin) of the predicted[2] giant Gamow-Teller (GT) or spin-flip transition. Alternatively, this peak may be thought of as the antianalog of a giant magnetic dipole state[1] in the target, ^{90}Zr. The other feature, another cross-section enhancement, located about 10 MeV higher in excitation energy, was observed with the reaction ^{90}Zr(^{3}He,t) at 130 MeV and confirmed in 45-MeV (p,n) spectra[3] and in (p,n) data at higher energies.[4] It was suggested by Marty[5] that this peak is the $T-1$ component of the giant (electric) dipole resonance. A charge-exchange reaction, such as the (p,n) reaction, is the only way to excite such $T-1$ strength.

Thus far these phenomena have been observed only in ^{90}Zr. To determine whether they occur more generally we have obtained[6] (p,n) spectra for seventeen nuclei ($^{90-92,94,96}$Zr, ^{93}Nb, $^{94,96-98,100}$Mo, ^{112,116,120,122,124}Sn, and ^{208}Pb) at E_p = 45 MeV. With one exception we find the two peaks for all nuclei studied. In addition, the systematic variation of the location of these peaks is strong evidence for their interpretation as the antianalogs, with isospin $T-1$, of the giant $M1$ and $E1$ excitations in the parent nuclei. These data represent the first observation of GT $E1$ strength outside of ^{90}Zr and provide for the first time a substantial body of data for testing theories of the location and isospin splitting of these resonances. The relevant states of a target and its isobaric daughter nucleus are illustrated in Fig. 1.

The (p,n) studies were performed with the beam-swinger neutron time-of-flight system at Michigan State University.[7] All targets were isotopically enriched, most to > 95%, and had thicknesses of 1–10 mg/cm^2. The neutron detector was a cylinder (12.7 cm diam × 7.6 cm thick) of NE-213 liquid scintillator placed 7 m from the target.

Figure 2 shows neutron time-of-flight spectra for four Sn isotopes. In addition to the IAS at about 31 MeV neutron energy and the sharp γ-ray peak leaking through the pulse-shape discriminator, two broad peaks are clearly visible in all four spectra. The smooth curves are fits through

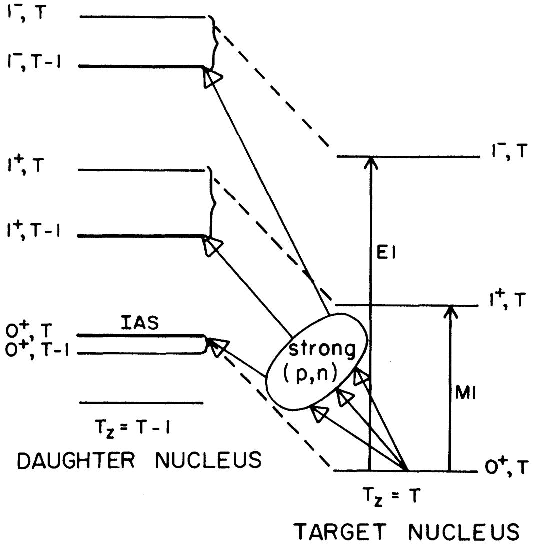

FIG. 1. Some states of the target nucleus ($T_z = T$) and their analogs (isospin = T) and antianalogs (isospin = $T-1$) in the $T_z = T-1$ nucleus resulting from a (p,n) reaction. The target states are the ground state and the $M1$ and $E1$ giant resonant states. Isospin geometry strongly favors the three transitions indicated.

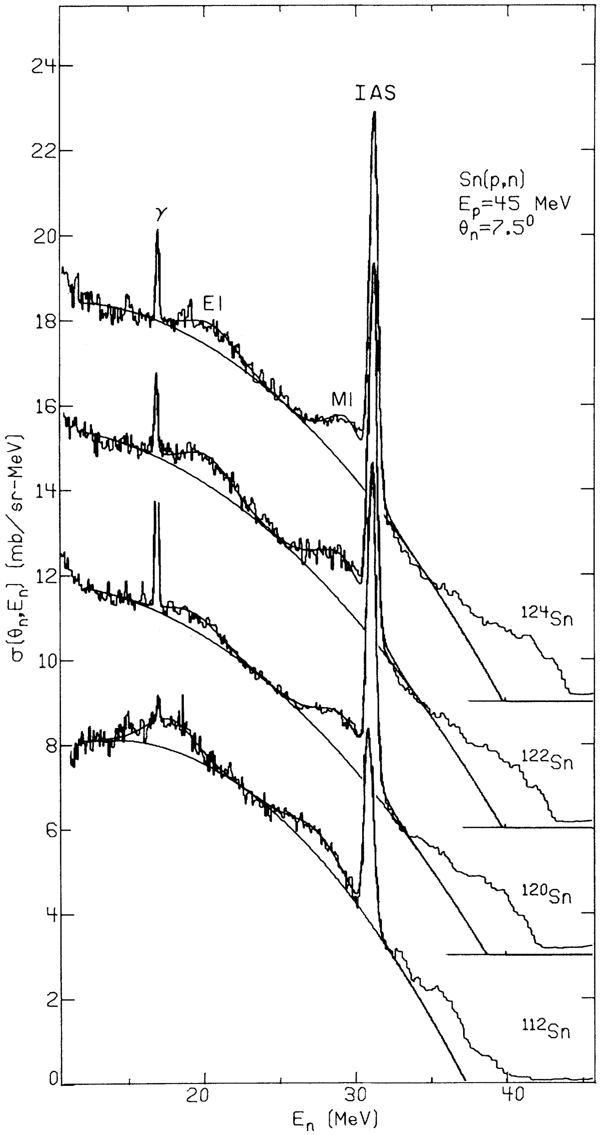

FIG. 2. Neutron spectra for ^{112,120,122,124}Sn(p, n) measured at 7.5°. The baselines for ^{120}Sn, ^{122}Sn, and ^{124}Sn are shifted for display purposes. The solid curves are fits to the data if we assume quadratic backgrounds and Gaussian peak shapes.

the data if we assume quadratic backgrounds and Gaussian peaks. The widths for both broad peaks were fixed at 3.6 MeV for all Sn isotopes, and a search was made only for the centroids and the heights. As one can see, both broad peaks shift towards the IAS as the neutron excess increases. This effect is even more visible in Fig. 3 where the neutron spectra are shifted in energy so that the IAS peaks all fall on the same vertical line, thereby graphically correcting for the Coulomb displacement energies.[8] Hence, points in a vertical line correspond to the same excitation energy (E_x) in every target. For ^{208}Pb the peak at lower E_x lies nearly under the IAS. In this case we show an additional result of the fitting in which the sharp IAS is neglected. Compared to the Sn targets in which the broad peaks had widths of 3.6 MeV, in ^{208}Pb the widths were only 2.9 MeV,

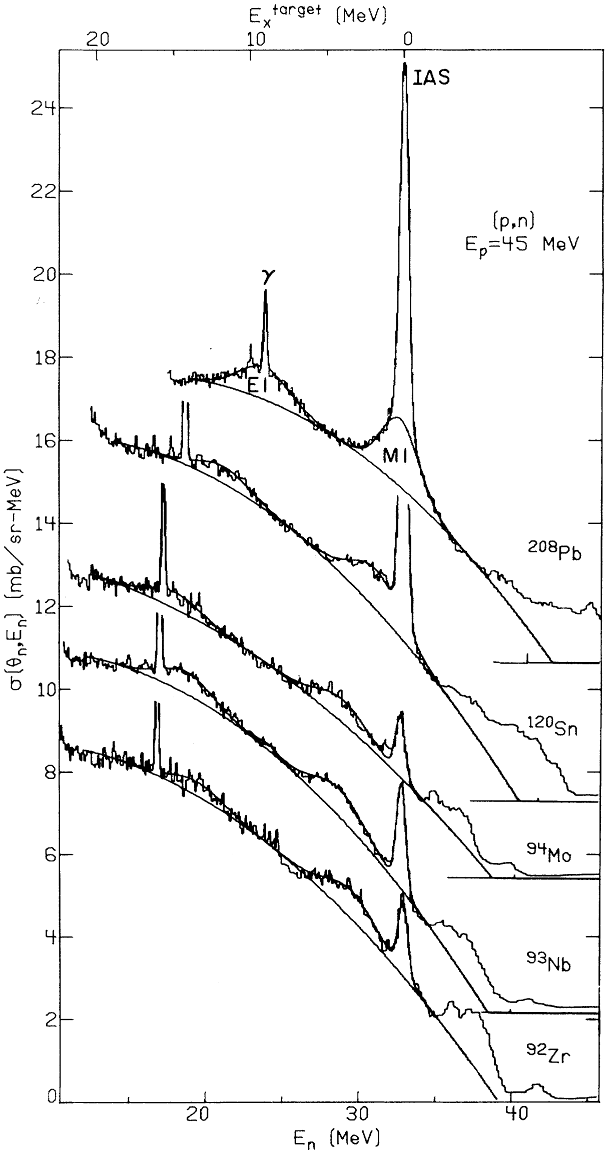

FIG. 3. Neutron spectra for ^{92}Zr, ^{93}Nb, ^{94}Mo, ^{120}Sn, and ^{208}Pb corrected for Coulomb displacement energies. The ^{93}Nb spectrum was measured at 11°, the others at 7.5°. The upper four spectra are shifted for display purposes. The bottom scale gives the neutron energies for ^{92}Zr only; the upper scale gives the calibration for the excitation energies in all the target nuclei.

whereas in Zr, Nb, and Mo they were slightly larger, 3.8 MeV. As for excitation energies, we note that both broad features shift rapidly toward the IAS with increasing $N-Z$.

Since a resonance in the target can be expected to approach the ground state slowly with A, roughly as $A^{-1/3}$, the transitions we observe here cannot be to analogs of target states (isospin T states of the daughter nucleus in Fig. 1). The most natural interpretation is that the observed peaks are $T-1$ antianalogs (see Fig. 1) of target states. Then the rapid shift with A towards the IAS, as illustrated in Figs. 2 and 3, results primarily from a T, $T-1$ isospin splitting whose magnitude increases not with A but with the accompanying increase in $N-Z$. That the observed peaks result from transitions to $T-1$ rather than to T states is consistent with the relative favoring in cross section of the former, because of isospin geometry, by a factor of $N-Z-1$, which is $\gtrsim 9$ for the nuclei studied. Because the peaks are broad and lie atop a large continuum, one would not expect to see the smaller peaks corresponding to isospin T. We then take the higher- (lower-) lying peak to be the $T-1$ antianalog of the $E1$ ($M1$) resonance of isospin T in the parent nucleus. For ^{90}Zr the 120-MeV data[4] confirm these spin assignments. The $E1$ states, having $J^{\pi}=1^-$, can be reached with $L=1$ transfer with or without spin flip. The photonuclear work (to which we will make comparison) proceeds largely without spin flip. We assume that the (p,n) reaction at 45 MeV also proceeds largely without spin flip since the nonflip part of the isospin effective interaction predominates at that low a bombarding energy.[9] This assumption underlies our conclusions on the $E1$ transition.

We now consider these enhancements in more detail beginning with that at higher E_x which we assume is the antianalog of the giant ($E1$) dipole resonance in the target nucleus. The E_x of the $E1$ resonance, E_x(target), is well known in many nuclei[10] and can be found by interpolation where measured values do not exist. The difference between this energy and the E_x (above the IAS) of the broad peak is $\Delta E^- = E(T) - E(T-1)$, the amount of the isospin splitting. Formally, $\Delta E^- = E_x(\text{target}) - [Q(\text{IAS}) - Q(T-1)]$. The splitting ΔE^- is plotted (labeled $E1$) in Fig. 4 for all the cases measured. The uncertainties are principally those of $Q(T-1)$, the quantities measured here.

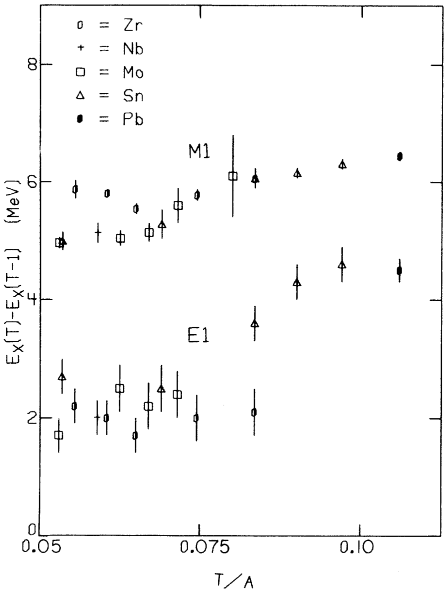

FIG. 4. Isospin splitting between the T and the $T-1$ components of $M1$ and $E1$ states vs $T/A=\frac{1}{2}(N-Z)/A$.

Several calculations[11,12] have yielded values of ΔE^+, the isospin splitting between the $T+1$ and T components of the giant resonance, and some measurements[13,14] have been reported. The results, correlated through a Lane-type, or isovector, potential give

$$\Delta E^+ = (T+1)E_v, \tag{1}$$

with $E_v = V/A$ and $V \cong 60$ MeV.[12] This model predicts that $\Delta E^- \cong 60T/A$; our results are all smaller than this prediction. In a more general treatment[15,16] the isotensor contributions may not be neglected, and one obtains

$$\begin{aligned}\Delta E^+ &= (T+1)[E_v + (2T-1)E_t],\\ \Delta E^- &= T[E_v - (2T+3)E_t].\end{aligned} \tag{2}$$

Both parameters, E_v and E_t, may be determined for a nucleus in which both ΔE^+ and ΔE^- have been measured. Such a nucleus is ^{90}Zr: $\Delta E^+ = 3.9 \pm 0.5$ (Ref. 12) and $\Delta E^- = 2.2 \pm 0.3$. Equations (2) yield $E_v = 0.56 \pm 0.05$ and $E_t = 0.010 \pm 0.005$. Inclusion of the tensor contribution has reduced AE_v from 58 to 51 MeV. These values and like values for the other nuclei having published values of ΔE^+ to use with our ΔE^- measurements are given in Table I. The differences, $\Delta E^+ - \Delta E^-$, are consistent with lower-limit estimates of Leonardi[16] of 2 and 4 MeV for ^{120}Sn and ^{208}Pb, respectively.

Unlike the status of the $E1$ resonance, little is known of the location of $M1$ strength for heavier nuclei. We adopted the common assumption[17]

TABLE I. Isospin splittings of the giant $E1$ resonance and values of the vector and tensor contributions (all in megaelectronvolts) according to Eqs. (2). Values of ΔE^- are from the present work.

Target	ΔE^+	ΔE^-	E_v	E_t	AE_v
^{90}Zr	3.9[a]	2.2	0.56	0.010	51
^{116}Sn	4.0[b]	2.5	0.38	0.0039	44
^{120}Sn	5.5[b]	3.6	0.44	0.0032	53
^{124}Sn	6.3[b]	4.6	0.43	0.0020	54
^{208}Pb	11.2[b]	4.5	0.35	0.0031	73

[a] Ref. 13. [b] Ref. 14, Fig. 13.

$E_x(M1) = 40A^{-1/3}$ and proceeded as with the $E1$ data to compute isospin splittings. The results are given in Fig. 4 (labeled $M1$). All the points fall within a fairly small region around 6 MeV. The average splitting [$\Delta E^-(M1) = 5.3$ MeV] between $T/A = 0.05$ and 0.075 corresponds to an optical-model symmetry potential of about 85 MeV, close to the expected value.

In conclusion, we can say that the phenomena first observed in the reactions $^{90}\mathrm{Zr}(p,n)$ and $^{90}\mathrm{Zr}(^3\mathrm{He},t)$ appear to be much more general; they are not restricted to ^{90}Zr. For the peak at the lower E_x, the energy systematics and the earlier information that its angular distribution[1,18] is similar to that of known 1^+ states strongly favor the identification as an antianalog of the giant $M1$ state. For the peak at the higher E_x, the energy systematics point strongly to the interpretation of that peak being the antianalog of the famous $E1$ giant resonance. This identification leads directly to a determination of the T, $T-1$ isospin splitting of that resonance. For the first time there are data (in sixteen nuclei) for the testing of theories of this splitting. Our data already indicate that the splitting has an important isotensor component.

We gratefully acknowledge the loan of some of the targets by C. H. Poppe of Lawrence Livermore Laboratory and the support of the National Science Foundation under Grant No. Phy-78-22696.

---

[1] R. R. Doering *et al.*, Phys. Rev. Lett. 35, 1691 (1975).

[2] K. Ikeda, S. Fujii, and J. I. Fujita, Phys. Lett. 3, 271 (1963).

[3] A. Galonsky *et al.*, Phys. Lett. 74B, 176 (1978).

[4] D. E. Bainum *et al.*, Phys. Rev. Lett. 44, 1751 (1980).

[5] N. Marty, private communication.

[6] W. Sterrenburg *et al.*, Bull. Am. Phys. Soc. 24, 649 (1979).

[7] R. Bhowmik *et al.*, Nucl. Instrum. Methods 143, 63 (1977).

[8] W. J. Courtney and J. D. Fox, Nucl. Data Tables 15, 141 (1975).

[9] W. Sterrenburg *et al.*, Phys. Lett. 91B, 337 (1980); S. M. Austin *et al.*, Phys. Rev. Lett. 44, 972 (1980).

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

[11] R. Leonardi, Phys. Rev. Lett. 28, 836 (1972).

[12] R. O. Akyuz and S. Fallieros, Phys. Rev. Lett. 27, 1016 (1971).

[13] P. Paul, J. F. Amann, and K. A. Snover, Phys. Rev. Lett. 27, 1013 (1971).

[14] K. Shoda, Phys. Rep. 53, 341 (1979).

[15] S. Fallieros, in *Proceedings of the International Conference on Photonuclear Reactions and Applications, Pacific Grove, California, 1973*, edited by B. L. Berman (Lawrence Livermore Laboratory, Livermore, Cal., 1973), Report No. CONF-730301, p. 401.

[16] R. Leonardi, Phys. Rev. C 14, 385 (1976).

[17] L. W. Fagg, Rev. Mod. Phys. 47, 683 (1975).

[18] D. Ovazza *et al.*, Phys. Rev. C 18, 2438 (1978). $\sigma(\theta)$ for $^{90}\mathrm{Zr}(^3\mathrm{He},t)$ at 80 MeV suggested a mixture of multipolarities, the major one being consistent with a 1^+ assignment.