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ISOSPIN SPLITTING OF THE GIANT DIPOLE RESONANCE IN ^{64}Zn†

B. C. Cook, R. C. Morrison, and F. H. Schamber
Institute for Atomic Research, Department of Physics, Iowa State University, Ames, Iowa 50010
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The (γ, np) reaction is discussed as a probable channel for observation of the $T=T_0+1$ component of the giant dipole resonance, and experimental evidence is presented in support of this conjecture in the case of ^{64}Zn.

Several years ago Fallieros, Goulard, and Ventner[1] predicted that the giant dipole resonance of the nuclear photoeffect should be split into two isospin components in all nuclei with ground state $T>0$. The lower-energy component ($T_<$) has the same isospin as the ground state (T_0), while the second component ($T_>$) has isospin $T=T_0+1$. Several authors[1-3] have reported model-dependent calculations of both the energy splitting and the relative dipole absorption strengths of the two components. Isospin selection rules allow proton decay of both components but prohibit ground-state neutron decay of the $T_>$ states, providing a possible experimental method of identifying the two components. Several experimenters[4-7] have searched for the predicted $T_>$ component by measuring (γ, p), (p, γ_0), and $(\gamma, n)+(\gamma, p)$ cross sections; however, the results of these measurements have not been conclusive. Shoda et al.[5] and Axel et al.[4] found (γ, p) resonances 4-5 MeV above the (γ, n) giant resonance in ^{90}Zr and ^{88}Sr; however, the measured cross section in both cases is much smaller than the predicted strength of the $T_>$ states. Measurements of the photoneutron yield of nickel[6] and the $(\gamma, n)+(\gamma, p)$ cross sections of molybdenum isotopes[7] show anomalous strength in the region above the giant resonance. While these results can be explained by isospin splitting, they do not give direct evidence for states of different T. A conclusive search for the predicted $T_>$ giant resonance requires a direct comparison between isospin-allowed and isospin-forbidden reactions in the energy region just above the $T_<$ giant resonance.

The major cross sections which can be expected to contribute to dipole absorption in this energy region are (γ, n), (γ, p), $(\gamma, 2n)$, (γ, pn), and (γ, np). Decay of the $T_>$ states through either the ground-state (γ, n) or $(\gamma, 2n)$ channels is isospin forbidden, while proton decay (to ground or excited states), as well as neutron decay to $T_>$ states in the residual nucleus, is allowed by the isospin selection rules. In medium and heavy nuclei the Coulomb barrier will strongly inhibit proton emission as long as neutron emission to residual $T_>$ states is energetically possible. In heavy nuclei these residual $T_>$ states are, in general, particle unstable and can decay by isospin-allowed proton decay or isospin-forbidden neutron decay.[8] Since the Coulomb barrier clearly favors the (γ, n) and $(\gamma, 2n)$ processes while selection rules favor (γ, p) and (γ, np), comparison of the relative strengths of these reactions provides a direct test of the strength of isospin selection rules. In particular, these arguments predict that the (γ, np) process should dominate the $T_>$ giant resonance, and in the energy region of expected $T_>$ strength, the (γ, np) cross section should be larger than the Coulomb-barrier favored (γ, n) and $(\gamma, 2n)$ strengths. [The (γ, pn) process is of course also isospin allowed

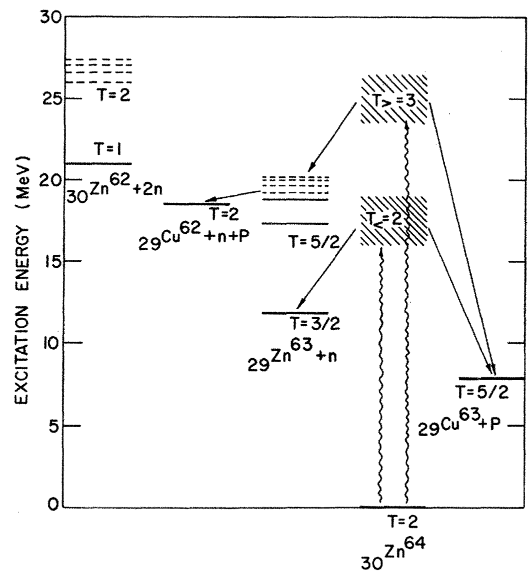

FIG. 1. The predicted $T=2$ and $T=3$ components of the ^{64}Zn giant resonance showing the decay modes allowed by isospin selection rules. The states shown by broken lines represent the expected existence of $T=\frac{5}{2}$ levels in this energy region and do not correspond to any specific known levels.

and hence there is no need to distinguish between (γ, np) and (γ, pn)].

To test this hypothesis, we have measured the (γ, n), $(\gamma, 2n)$, and (γ, np) cross sections in ^{64}Zn. The relevant energy levels and predicted transitions are shown in Fig. 1. Known $T=\frac{5}{2}$ states in ^{63}Zn (analogs to the ground-state and 1.547-MeV level of ^{63}Cu) occur at 5.42 and 6.80 MeV above the ground state, or at 17.3 and 18.7 MeV excitation in the ^{64}Zn system. Since the (γ, np) threshold in ^{64}Zn is at 18.45 MeV, and the $T_>$ giant resonance is certainly above this energy, there will be $T=\frac{5}{2}$ states available in the region between 18.45 MeV and the $T_>$ giant resonance (analogs to all of the low-lying states of ^{63}Cu).

To carry out the measurement, samples of natural zinc (48.9 % ^{64}Zn) were bombarded in the bremsstrahlung beam of the Iowa State University 70-MeV electron synchrotron. The end-point energy was varied in 1-MeV steps from 10 to 40 MeV. Since (γ, n), (γ, np), and $(\gamma, 2n)$ on ^{64}Zn all lead to positron-unstable residual nuclei, it was possible to measure simultaneously the yields for all three processes by half-life separation of the residual radioactivity. Individual yields for each of the three reactions were obtained at each end-point energy by least-squares fit to the decay curves measured for the individual samples. Cross sections were then extracted from the individual yield curves using the "least structure" method of Cook.[9] The resulting relative cross sections for ^{64}Zn(γ, n), ^{64}Zn(γ, np), and ^{64}Zn$(\gamma, 2n)$ are presented in Fig. 2 along with the cross section for the sum of all three processes.

The most important observation is that the (γ, np) cross section is more than 3 times as

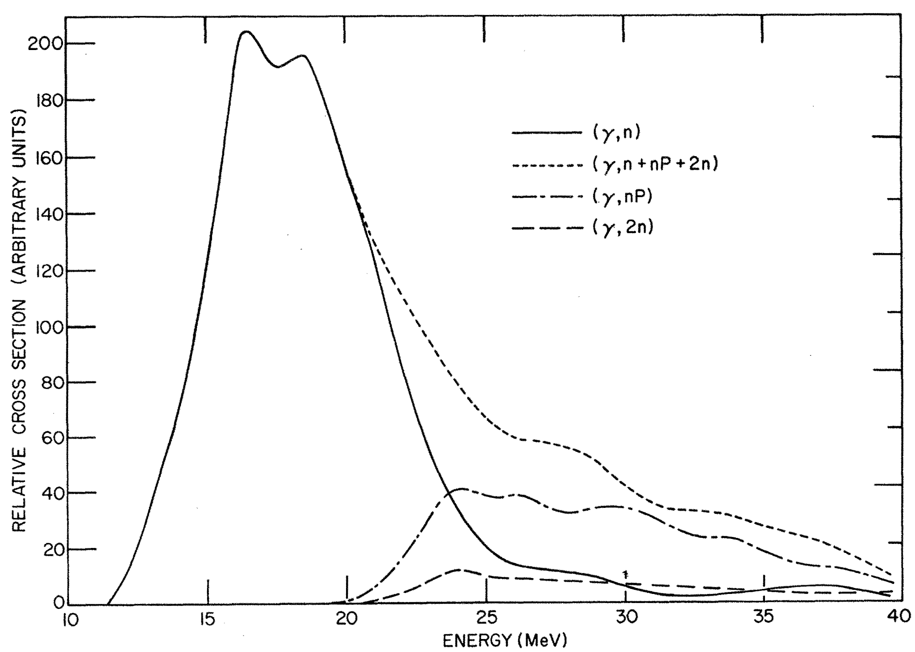

FIG. 2. The relative cross sections for ^{64}Zn(γ,n), (γ,np), and $(\gamma, 2n)$, along with the sum cross section for all three reactions.

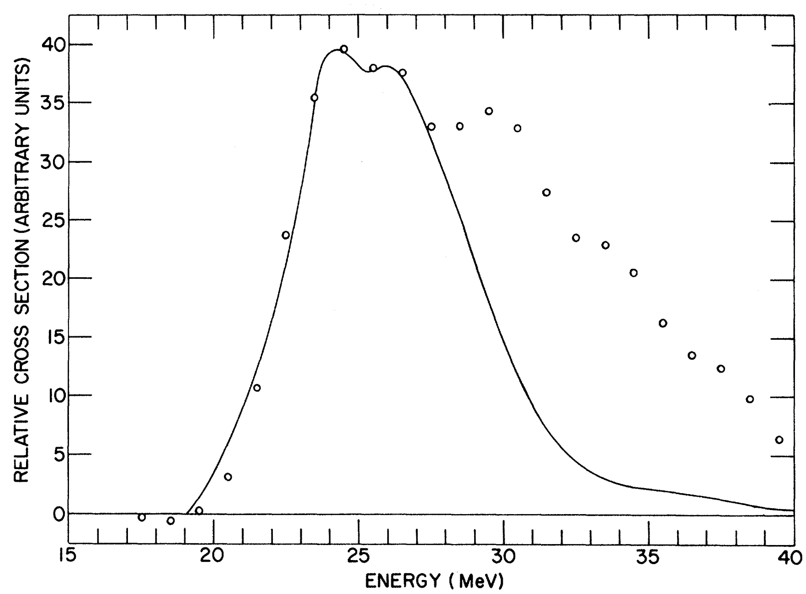

FIG. 3. The measured cross section for $^{64}Zn(\gamma,np)^{62}Cu$ (points). The solid curve is the measured (γ,n) cross section shifted up in energy by 7.7 MeV and multiplied by 0.196.

strong as the $(\gamma, 2n)$ process. From statistical considerations alone one would expect $(\gamma, np) < (\gamma, 2n)$ unless a selection rule is operative. Since $(\gamma, 2n)$ and ground-state (γ, n) are isospin forbidden from $T=3$ states, the observed enhancement of (γ, np) is consistent with the assumption of dipole absorption predominantly to $T=3$ levels in this energy region.

It is also important to examine the strength, shape, and peak energy of the (γ, np) resonance. While these certainly cannot be used as direct evidence for a $T_>$ giant resonance, these features obviously must be consistent with this interpretation if it is valid. The (γ, np) cross-section envelope indicates a strong resonance centered near 25 MeV which is similar in overall shape and about 20% of the amplitude of the 18-MeV (γ, n) resonance. Figure 3 illustrates this similarity for the detailed (γ, n) and (γ, np) curves. While it is difficult to draw conclusions concerning the apparant structure in the (γ, np) cross section, it is worth noting that the structure shown in Fig. 3 was consistently reproduced in three independent measurements of the cross section. Indentifying the portion under the smooth cruve of Fig. 3 with the $T_>$ giant resonance implies a splitting energy of 7.7 MeV and a ratio of $T_>/T_<$ strength of the order of 20% considering only the (γ, n) and (γ, np) channels. It is interesting to note that population of the lowest-lying (particle-stable) $T=\frac{5}{2}$ levels in ^{63}Zn must result in (γ, n) cross-section strength, and considerable (γ, n) strength is indeed observed in the proper energy region. The broad shelf extending to 30 MeV in the (γ, n) cross section of Fig. 2 may thus account for an additional 5-10% of the total $T_>$ strength.

Estimates of the energy splitting between the $T_<$ and $T_>$ components give 0.5-1.0 MeV per excess neutron; however, Leonardi and Rosa-Clot[2,10] calculate a value of 1-2 MeV for $T=\frac{1}{2}$ nuclei and neglecting exchange terms in the Hamiltonian results in a predicted energy splitting of 7 MeV for ^{64}Zn. In the notation of Ref. 2 this prediction is obtained with $r_s^2 = 2R_0^2 T(T+1)$, $r_v^2 = R_0^2$, $A_v/A_s = -\frac{2}{3}T/A$, and $r_t^2 = A_t = 0$ (no isotensor contribution). This splitting energy is in excellent agreement with the value of 7.7 MeV observed. The matrix elements of the dipole operator in isospin space can be written as

$$\langle bT_bT_z|D|aT_aT_z\rangle$$

$$=(-)^{T_b-T_z}\begin{pmatrix} T_b & 1 & T_a \\ -T_z & 0 & T_z \end{pmatrix}\langle bT_b\|D\|aT_a\rangle,$$

where $T_z = T_a = \frac{1}{2}(N-Z)$. The ratio of the cross sections for $\Delta T=1$ to $\Delta T=0$ is then

$$\frac{\sigma(T_a \to T_a+1)}{\sigma(T_a \to T_a)} = \frac{1}{T}\frac{\sigma_{T+1}}{\sigma_T},$$

where the factor $1/T$ comes from the 3-j symbols, and the reduced cross sections (σ_T and σ_{T+1}) are proportional to the squares of the reduced matrix elements. The isospin sum rule developed by O'Connell,[3] when evaluated for ^{64}Zn in the harmonic-oscillator model, yields an integrated cross-section ratio

$$\frac{\int\sigma(\Delta T=1)}{\int\sigma(\Delta T=0)}=0.47.$$

If one uses experimental values for the total integrated cross section and peak energy, this ratio is reduced to about 0.27. The normalization of cross sections used in Fig. 3 is certainly consistent with these estimates.

An alternative explanation of the observed enhancement of the (γ, np) cross section is the quasideuteron effect. However, quasideuteron absorption is expected to be important only at higher energies and while this process may contribute below 40 MeV, it would be most surprising to see a number as large as 20% of the giant resonance at 26 MeV. Also, the quasideuteron picture is not consistent with the clearly observed resonance in the cross section shown in Fig. 3, and while the similar shapes of the (γ, n) and (γ, np) resonances are expected from isospin splitting, this agreement would be purely accidental in the quasideuteron model. However, the yield in excess of the smooth curve shown in Fig. 3 may very well be dominated by this process.

We would conclude then, that in certain nuclei the (γ, np) channel is available for decay of the $T_>$ component of the giant dipole resonance, and would be expected to compete favorably with the (γ, p) channel. The data presented support this conclusion for the case of ^{64}Zn, and hence give convincing evidence for the existence of the $T_>$ resonance and the validity of the isospin selection rules in medium-A nuclei. The relative strengths and energy splitting of the two components are consistent with theoretical prediction. Additional experiments would be of great value, and could provide a conclusive test of this interpretation. In particular, it would be most desirable to measure the (γ, n) and (γ, np) cross sections for several isotopes of a given element. The analysis presented here would predict a systematic decrease in strength of the (γ, np) peak with increased neutron excess, while the quasideuteron model would lead to an essentially constant (γ, np) strength. Such a measurement could then clearly select the correct explanation.

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