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Isospin Splitting of the Giant Dipole Resonance in ^{60}Ni

T. J. Bowles,[(a)] R. J. Holt, H. E. Jackson, R. D. McKeown,[(b)] A. M. Nathan, and J. R. Specht

Physics Division, Argonne National Laboratory, Argonne, Illinois 60439, and University of Illinois at Urbana-Champaign, Urbana, Illinois 61801

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The most stringent test to date of the concept of isospin splitting of the giant dipole resonance in a medium-weight nucleus has been performed by a study of the (γ, n_0), (γ, p_0), and (γ, γ) reaction channels for ^{60}Ni. The ground-state photoneutron cross section for ^{60}Ni was measured and compared with the already known (γ, p_0) reaction cross section in order to demonstrate isospin splitting. The relative strength and separation of the isospin-dependent components of the resonance were estimated from an analysis of photon scattering data.

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It is widely accepted that in nuclei with a neutron excess $[T \equiv (N-Z)/2 > 0]$, the isovector giant dipole resonance (GDR) is shared between a $T_< \equiv T$ and a $T_> \equiv T+1$ component and that these components are split in energy, primarily by the nuclear symmetry potential.[1,2] Fallieros and collaborators have developed an extended schematic model, which we refer to as the isospin splitting model (ISM), in which the $T_<$ and $T_>$ dipole states are predicted to be separated by an amount[1]

$$\Delta E = 60(T+1)/A \text{ MeV}, \tag{1}$$

and to have dipole matrix elements in the ratio[2]

$$R = \frac{|r_>|^2}{|r_<|^2} = \frac{1}{T}\,\frac{1-1.5TA^{-2/3}+T(T-\frac{1}{2})/NZ}{1+1.5A^{-2/3}-(T-\frac{1}{2})/NZ}, \tag{2}$$

where $A = N+Z$. Although both these predictions are fairly well supported by data on light nuclei,[3] previous experiments on medium-weight nuclei have concentrated primarily on the energy splitting.[4] There has not yet been a quantitative test of Eq. (2) in a medium-weight nucleus. In this Letter we reinvestigate the question of isospin splitting in ^{60}Ni. We will show that a new measurement of the ^{60}Ni(γ, n_0) cross section and a reanalysis of the ^{60}Ni(γ, γ) data provide confirming evidence for the predictions of the ISM.

Diener *et al.*[5] already have considered the question of isospin splitting in ^{60}Ni and have measured the ^{59}Co$(p, \gamma_0)^{60}$Ni cross section throughout the giant-resonance region. These data [see Fig. 1(a)] indicate two peaks located near 17 and 20 MeV. At that time, the total (γ, n) data of

Min and White[6] indicated only one peak near 17 MeV. Since isospin conservation forbids neutron decay from the $T_>$ component, these data were taken as confirming evidence that the 17- and 20-MeV peaks had isospin $T_<$ and $T_>$, respectively, and the ~3 MeV splitting was in excellent agreement with Eq. (1). This simple picture was upset by subsequent and more accurate total (γ, n) measurements by Fultz *et al.*,[7] in which considerable photoneutron strength was found in the region of the supposed $T_>$ resonance [Fig. 1(b)]. The difficulty is partially resolved if one realizes that the decay of the GDR in medium and heavy nuclei is largely dominated by the statistical decay of the compound nucleus. Thus a small amount of isospin mixing in the underlying compound nuclear levels will result in the decay of the GDR being totally dominated by neutron emission, regardless of the isospin. If one is to learn about the isospin of the GDR by a study of its decay modes, one must investigate channels in which the decay is nonstatistical. We report here a study of the ground-state neutron decay of the GDR in ^{60}Ni, which *a posteriori* is nonstatistical and which establishes the isospin assignments suggested by Diener *et al.*

The ground-state photoneutron cross section was measured by exploiting the Argonne National Laboratory high-current electron accelerator and the associated high-resolution time-of-flight spectrometer. The accelerator was operated in a mode that produced ~35-ps-wide pulses with a peak current of 200 A and a repetition rate of 800 Hz. The electron beam was energy analyzed so that $\Delta E/E = 1\%$ (full width at half maximum) and was focused onto a 1.5-mm-thick Ag bremsstrahlung radiator. The photons then irradiated a sample of ^{60}Ni (enriched to $\gtrsim 99\%$) in the form of a powder. The sample was encased in a thin-walled Al container of dimensions $1.0\times2.5\times5.1$ cm^3. Neutrons from reaction ^{60}Ni$(\gamma, n)^{59}$Ni traveled through a well-collimated 25-m flight path which was at an angle of 90° with respect to the photon beam axis. The neutrons were detected in a scintillator 5.1 cm thick $\times$ 10.2 cm $\times$ 20.3 cm. A more detailed description of the photoneutron method is given by Holt *et al.*[8] The central problem in the present work is to ensure that the observed neutrons are due to ground-state photoneutron decay. The first excited state in ^{59}Ni is only 340 keV above the ground state. The resolution of the time-of-flight spectrometer varied from 9 keV at $E_n = 3$ MeV to 26 keV at $E_n = 9$ MeV, the energy range of the present measurement.

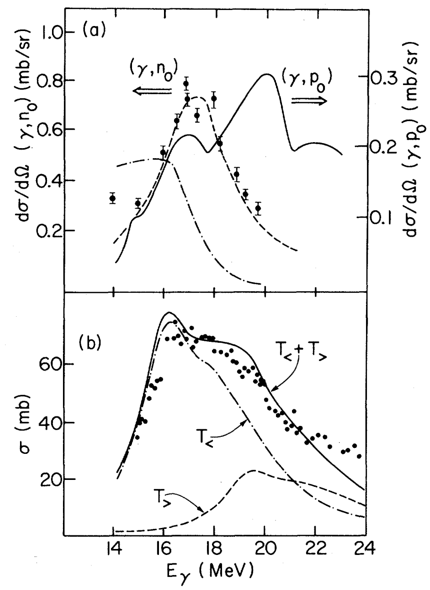

FIG. 1. (a) Ground-state photoneutron (points) and photoproton (solid line) cross sections for ^{60}Ni. The data points are the results of the present measurement. The solid line is from Ref. 5. The dashed curve is a Lorentizian of width 3.4 MeV and peak cross section adjusted to fit the (γ, n_0) data. The dash-dotted curve is a Hauser-Feshbach statistical calculation of the (γ, n_0) cross section. (b) Total photoneutron cross sections for ^{60}Ni from Ref. 7 (circles) and the calculated photoabsorption cross section σ_γ for ^{60}Ni (solid line). The dashed and dash-dotted lines are the calculated $T_>$ and $T_<$ components, respectively, of σ_γ. The calculation was performed in the framework of the dynamic collective model with parameters adjusted to fit the elastic photon scattering data.

The energy of the electron beam was varied between 14 and 20 MeV in 0.5-MeV steps. In order to ensure that only ground-state neutron decay was detected only the top 250 keV of each spectrum was analyzed. The cross sections were determined relative to the reaction ^{2}H(γ, n)H by substituting a container of ^2H_2O in place of the ^{60}Ni sample. Background was measured by performing the measurements with a container of H_2O and an empty container.

The final results are represented by the points in Fig. 1(a). The nonstatistical nature of this decay mode was established with a Hauser-Feshbach calculation, which produced a (γ, n_0) cross section which did not resemble the observed results [dash-dotted curve in Fig. 1(a)]. The solid curve represents the (γ, p_0) cross-section measurements of Ref. 5. The dashed curve is merely a Lorentzian shape with a width of 3.4 MeV, the same as the width of the 17-MeV resonance dis-

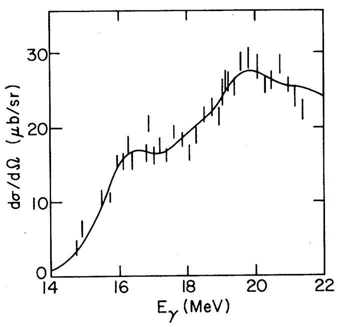

FIG. 2. The elastic photon scattering data on ^{60}Ni from Ref. 9. The solid line is the best fit to these data with use of the dynamic collective model. The relevant parameters are given in Table I.

cussed in Ref. 5. The peak height of the Lorentzian was arbitrarily adjusted to give the peak cross section of the present (γ, n_0) data. Clearly, there are two distinct peaks in the (γ, p_0) cross sections, whereas there is only the lower-energy one in the (γ, n_0) data. This is exactly the pattern that one would expect from the ISM.

Ideally, in order to test quantitatively the predictions of the ISM, one must determine the isospin dependence of the total photoabsorption cross section σ_γ. It is not sufficient to study the isospin dependence of the (γ, p_0) and (γ, n_0) decay channels, since these channels do not reflect necessarily the total distribution of $T_<$ and $T_>$ dipole strength. We have used a new technique, based upon an analysis of our previously published photon scattering data.[9,10] Since the photon scattering cross section is constrained through the optical theorem and a dispersion relation[11] to σ_γ, this analysis is equivalent to an analysis of σ_γ. Therefore, unlike the analysis of the (γ, p_0) data in Ref. 5, the present treatment does not require a knowledge of partial decay widths.

The analysis was performed in the framework of the dynamic collective model,[12] in which the basic dipole state is split into several satellite peaks as a result of the coupling to collective surface vibrations. The details of the calculations are described in Ref. 10. Briefly, we assumed two unperturbed dipole states separated by an energy ΔE and with squared dipole matrix elements in the ratio R. These two dipole states are assumed to add incoherently, since there are a considerable number of neutron decay channels open. The distribution of dipole strengths was found by allowing each of these states to couple in an identical way to the surface vibrations. Rather than using the ISM to constrain ΔE

TABLE I. Isospin splitting parameters obtained from the analysis of the reaction ^{60}Ni$(\gamma,\gamma)^{60}$Ni.

ΔE (MeV) Present analysis[a]	ISM[b]	R Present analysis[a]	ISM[c]
3.7	3.0	0.29 ± 0.10	0.37

[a]With use of the notations of Ref. 10, the other parameters of the calculation are $E_1 = 17.22$, $E_2 = 1.332$, $\beta_0 = 0.21$, $\Gamma_0 = 2.6$, and $\delta = 0$.
[b]Eq. (1).
[c]Eq. (2).

and R as in Ref. 10, these parameters were determined from a least-squares fit to the elastic scattering data. These data and the best fit are shown in Fig. 2, and the results are summarized and compared to the ISM in Table I. It is interesting that the present results are in such good agreement with the ISM predictions, since a small amount of isospin mixing can produce a large change in R. In fact, with use of the formalism of Barker and Mann,[13] the observed intensity ratio corresponds to an isospin mixing coefficient of only ~3% in amplitude (or 0.1% in intensity). In Fig. 1(b) we show the corresponding photoabsorption cross section σ_γ and the $T_<$ and $T_>$ components. We see that σ_γ tracks quite well with the total (γ, n) data; whereas, the $T_<$ component has a much different shape than that of the (γ, n_0) data. Therefore, one must proceed with caution in extracting quantitative information, for example ΔE, from (γ, p_0) and (γ, n_0) comparisons. We note that because the coupling to the surface vibrations redistributes the dipole strengths, a simple two-Lorentzian analysis of the photonuclear cross sections is not appropriate.

In summary, we have provided the most stringent test of the isospin splitting model for the giant dipole resonance in medium-weight nuclei. From the viewpoint of (γ, n_0), (γ, p_0), and (γ, γ) reactions for ^{60}Ni, we find that the concept of isospin splitting of the GDR in ^{60}Ni is valid.

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[a]Present address: Los Alamos National Laboratory, Los Alamos, N. Mex. 87545.
[b]Present address: California Institute of Technology, Pasadena, Calif. 91125.

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Energy Dependence of the Small-Angle Differential Cross Sections to Isobaric Analog States in $^7Li(\pi^+, \pi^0)^7Be$ and $^{13}C(\pi^+, \pi^0)^{13}N$

A. Doron, J. Alster, A. Erell, S. Gilad,[(a)] and M. A. Moinester
Department of Physics and Astronomy, Tel Aviv University, Tel Aviv 69978, Israel

and

R. A. Anderson, H. W. Baer, J. D. Bowman, M. D. Cooper, F. H. Cverna, C. M. Hoffman, N. S. P. King, M. J. Leitch, and J. P. Piffaretti[(b)]
Clinton P. Anderson Meson Physics Facility, Los Alamos National Laboratory, Los Alamos, New Mexico 87545

and

P. R. Bevington[(c)] and E. Winkelmann[(d)]
Physics Department, Case Western Reserve University, Cleveland, Ohio 44106

and

C. D. Goodman
Indiana University Cyclotron Facility, Bloomington, Indiana 47401
(Received 16 September 1981)

The forward-angle differential cross sections of pion single charge exchange on ^{7}Li and ^{13}C were measured at 70, 100, 150, 165, and 180 MeV. The cross sections rise steeply up to 150 MeV and remain almost constant between 150 and 180 MeV. Comparisons with theoretical calculations and with the free charge-exchange cross sections are presented. There is poor agreement with the data. Only phenomenological calculations can fit the resonance region. The isobaric analog excitation functions rise more steeply than the continuum single-charge-exchange cross sections.

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In the last few years much attention has been given to pion single-charge-exchange (SCE) reactions.[1] The measurements of the reactions to the isobaric analog states (IAS), $^7Li(\pi^+, \pi^0)^7Be$(IAS)[2,3] and $^{13}C(\pi^+, \pi^0)^{13}N$(IAS),[3] provided the first excitation functions of angle-integrated cross sections for SCE to a single state. Much theoretical effort has been devoted to understanding these results.[1] Distorted-wave impulse-approximation (DWIA) calculations, using first-order optical potentials,[1] produced a dip in the excitation functions at the (3,3) resonance, with cross sections too low by as much as a factor of 5. Higher-order calculations reduced the discrepancies to a factor of 1.5 and produced flatter excitation functions.[1] Recently, there have been