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Isospin effects in the photodisintegration of light nuclei

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Using the corpus of data on the (γ,p), (γ,n), $(\gamma,2n)$, and (γ,n_0) cross sections of nine light nuclei (^{13}C, ^{14}C, ^{15}N, ^{17}O, ^{18}O, ^{25}Mg, ^{26}Mg, ^{29}Si, and ^{30}Si), the $T_>$ and $T_<$ isospin components of the giant dipole resonance have been separated. The relative strengths of these components have been extracted, together with the energy differences between the centroids of the components. The ratio of the $T_>$ energy-weighted integrated cross section to the total cross section is somewhat better represented by the simple geometric factor $1/(T_0+1)$, where T_0 is the isospin of the ground state of the excited nucleus, than by a more complete expression which takes into account dynamical effects. If the energy difference between the centroids is represented by $U^*(T_0+1)/A$, the average value of U^* for the three p shell nuclei is found to be 57 MeV, while that for the six s-d shell nuclei is 93 MeV.

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I. INTRODUCTION

Studies of the giant dipole resonance (GDR) of light, non-self-conjugate nuclei have confirmed that the width of the resonance depends on, among other things, the isospin of the ground state of the nucleus. The isospin T_0 of this ground state is characteristic of the nucleus since $T_0=\frac{1}{2}(N-Z)$.

Excited states of the nucleus may have isospin quantum numbers T that are greater than T_0; of particular interest are those with $T=T_0+1$. The configurations of these states are isobaric analogs of low-lying states in adjacent nuclei with the same mass number $A\,(N+Z)$ but different charge number Z. Electric dipole ($E1$) absorption by a nucleus with a ground-state isospin of T_0 ($\neq 0$) leads to population of states with isospin of T_0 or T_0+1 [1]. As a consequence, the GDR is made up of two sets of states with different isospin, which in practice are located at different energies separated by an energy ΔE. One of the earliest cases studied was ^{90}Zr, where an isospin separation of about 5 MeV, predicted by Fallieros, Goulard, and Venter [2], was experimentally confirmed by Berman *et al.* [3].

The relative strengths of the two isospin components and their separation have been the focus of several theoretical calculations, and their experimental resolution is the theme of this paper.

The particle decay properties of the two isospin states are different, a fact which helps us to apportion the total photoabsorption cross section into its components having isospin T_0 ($T_<$) or T_0+1 ($T_>$).

Several theoretical investigations have derived formulas for calculating ΔE and the relative probabilities of the two components. All of these are shell model calculations since collective models are unable to predict isospin effects [4]. Dealing first with the isospin splitting ΔE, Akyuz and Fallieros [5] derived that, for medium and heavy nuclei,

$$\Delta E=\frac{U^*(T_0+1)}{A}\,, \tag{1}$$

where U^* is identified with the quantity U, the nuclear symmetry energy. The experimental quantity U^* is predicted to have a value of about 60 MeV according to Akyuz and Fallieros, but for a light nucleus such as ^{15}N, a value of only 14 MeV is appropriate, according to Leonardi [6].

The relative probability of electric dipole transitions from the T_0 ground state to $T_>$ or $T_<$ states is dominated by the geometric term $1/T_0$. This probability is expressed in terms of the first moment of the integrated cross section σ_{-1}, where

$$\sigma_{-1}=\int\frac{\sigma}{E}dE \tag{2}$$

(integrated to the meson threshold).

When σ_{-1} for transitions to $T_>$ states is compared to the total σ_{-1}, a ratio R can be defined as

$$R=\frac{\sigma_{-1}{>}}{\sigma_{-1}{>}+\sigma_{-1}{<}}=\frac{\sigma_{-1}{>}}{\sigma_{-1}}\,. \tag{3}$$

A simple formulation for this ratio is $R=1/(T_0+1)$. However, more complicated forms of this ratio have been produced, taking into account, for instance, nucleon dynamical effects and nucleon correlations. Hayward, Gibson, and O'Connell [7] derived the formula

$$\frac{\sigma_{-1}>}{\sigma_{-1}<+\sigma_{-1}>}=\frac{1}{T_0+1}\left[\frac{1-1.97T_0R_p^2}{A^{4/3}}(1-\eta)\right], \quad (4)$$

where R_p^2 is the mean square radius of the proton distribution and η a minor correction term never exceeding 5%. Another group (Fallieros *et al.* [2,8]) produced the relationship

$$\frac{\sigma_{-1}>}{\sigma_{-1}<}=\frac{1}{T_0}\frac{1-\frac{3}{2}T_0A^{-2/3}}{1+\frac{3}{2}T_0A^{-2/3}} . \quad (5)$$

In heavier nuclei, where proton emission is inhibited by the Coulomb barrier, neutron emission is the preferred mode of decay unless there is substantial inhibition of that mode. As a result, many authors have assumed that proton emission dominates the decay of the $T_>$ component of the GDR, while the $T_<$ component is identified with the photoneutron cross section. Early work on Zr [3], Ni [9], and medium-weight nuclei [10] indicated a value for U^* of about 60 MeV.

Light nuclei provide powerful tests of predictions about effects of isospin. Neutron and proton emission can be measured from a series of neighboring isotopes such as ^{16}O, ^{17}O, and ^{18}O, whose isospins change from 0 to $\frac{1}{2}$ to 1 and for which correspondingly the T_0+1 component of the photoexcitation cross section may vary from all, to two-thirds, to half the total cross section of the GDR. The complicating factor of the presence of the Coulomb force is minimized in low-Z nuclei.

Wu, Firk, and Berman [11] felt that they had given "the most conclusive evidence to date for isospin splitting" in the light nuclei by showing that for excitation of ^{26}Mg up to 18.9 MeV most photoneutron transitions went to the ground state of ^{25}Mg, whereas excitations above that energy resulted in decays to the first $T=\frac{3}{2}$ state in ^{25}Mg (which is at 18.9 MeV excitation in ^{26}Mg). Ishkhanov *et al.* [12], however, used these same data as evidence of strong configurational splitting of ^{26}Mg. Although both of these splittings are of the same magnitude, the isospin of the decaying states can be identified by the different probabilities of proton and neutron emission. Comparison with theoretical predictions of experimentally measured $T_>/T_<$ strength ratios and energy splitting in light nuclei can quantify the effects of nuclear dynamics.

Over the last decade, much new information has been obtained on the detailed cross sections for photoproton and photoneutron reactions of light nuclei, mainly by groups including one or usually more of the present authors. In particular, the nuclei given in Table I have been studied and the listed reactions measured. Recent, but not all, references are included.

Using the data from these experiments and from other work including deexcitation gamma studies, it is possible to deduce the isospin of various features of the total photon absorption cross section. The data for the nuclei listed in Table I have been analyzed in detail to yield isospin assignments. These details are presented in Ref. [37], and a summary is presented here. The specific study of ^{13}C is included here to illustrate the procedures involved.

TABLE I. Nuclei and reactions examined in this work.

^{13}C	γ,p [13]	γ,n [14]	γ,n_0 [15]	$\gamma,2n$ [14]
^{14}C	γ,p [16]	γ,n [17]	γ,n_0 [18]	$\gamma,2n$ [17]
^{15}N	γ,p [19]	γ,n [20]	γ,n_0 [21]	$\gamma,2n$ [22]
^{17}O	γ,p [23]	γ,n [24]	γ,n_0 [25,26]	$\gamma,2n$ [24]
^{18}O	γ,p [27]	γ,n [27]	γ,n_0 [28,29]	$\gamma,2n$ [27]
^{25}Mg	γ,p [30]	γ,n [31]		$\gamma,2n$ [31]
^{26}Mg	γ,p [32]	γ,n [33]	γ,n_0 [11]	$\gamma,2n$ [33]
^{29}Si	γ,p [34]	γ,n [35]		$\gamma,2n$ [35]
^{30}Si	γ,p [36]	γ,n [35]		$\gamma,2n$ [35]

II. PROCEDURES AND CRITERIA

A. Procedures

The procedure for isospin assignment was as follows: (1) General criteria for assigning isospin were laid down as described in Sec. II B below. (2) For each nucleus the energy range from threshold to 30 MeV was subdivided into regions and the effects of isospin in each region, as they relate, for instance, to relative partial cross sections, were delineated. (3) From the data on the partial cross sections, using the criteria, assignments were made of the isospin of each energy region or parts thereof. (4) The total photoneutron and photoproton cross sections were added to give an approximation to the total absorption cross section. In order to parametrize these cross sections and to permit a smooth transition from one energy region to the next, the cross sections were fitted by Gaussian functions. An account of this method is given by Bates *et al.* [20]. Peak energies and total areas of these Gaussians were determined for each nucleus. (5) The areas of the Gaussian functions were then designated $T_<$ or $T_>$, or apportioned between the two. The two isospin components of the total absorption cross section were then extracted. (6) The cross sections integrated to 30 MeV for the two isospin components, $\sigma_i=\int\sigma\,dE$, and their sums were then calculated for each nucleus from the Gaussian parameters, and then the first moments of the areas calculated and appropriately summed. From these values the ratios of the $T_>$ to $T_<$ strengths and the ratios of the $T_>$ strengths to the total strengths were calculated. Also calculated for each nucleus was the difference in energy between the centroids of the two components, defined as

$$\Delta E=\frac{\sigma_i>}{\sigma_{-1}>}-\frac{\sigma_i<}{\sigma_{-1}<} . \quad (6)$$

B. Criteria

The criteria for isospin assignment are discussed below for each of four categories of physical observations.

1. Ground-state transitions and neutron energies

$T_>$ states of a nucleus are forbidden to emit a neutron to $T_<$ states of a daughter nucleus. The presence of neutron transitions to the ground state of a daughter nucleus is strong evidence that the emitting state is a $T_<$ one. However, if the neutron emission channel is the only particle emission channel open, this criterion will not be reliable, as particle emission in the GDR region, even if isospin forbidden, will take place in preference to gamma emission (presumably through isospin mixing).

It follows from the above that isospin assignments can often be based on neutron energies. If neutron transitions are to the ground state or other $T_<$ low-lying states of the daughter, the neutron energies will be high.

2. Ratios of partial cross sections

As Bangert *et al.* point out [38], for decay to $T_0+\frac{1}{2}$ states of the daughter nucleus, the partial cross sections have ratios of

$$\frac{\sigma(\gamma,p)<}{\sigma(\gamma,n)<}=2T_0+1,\quad \frac{\sigma(\gamma,p)>}{\sigma(\gamma,n)>}=\frac{1}{2T_0+1}\,, \tag{7}$$

where $\sigma<$ and $\sigma>$ are the cross sections for decay from T_0 and T_0+1 states, respectively, as is shown in Fig. 1. These formulas come from the appropriate isospin Clebsch-Gordan coefficients. Comparison of the experimental ratios with those from Eq. (7) could indicate the isospin of the emitting levels. This method is, however, complicated by effects of angular momentum on transition probabilities and by the fact that the total $\sigma<$ component of the (γ,n) cross section will have a large component from T_0 to $T_0-\frac{1}{2}$ transitions (e.g., to the ground state of the daughter nucleus). In nearly all cases, these transitions will be more likely than those to $T_0+\frac{1}{2}$ levels on the grounds of the number of available states and the available transition energy.

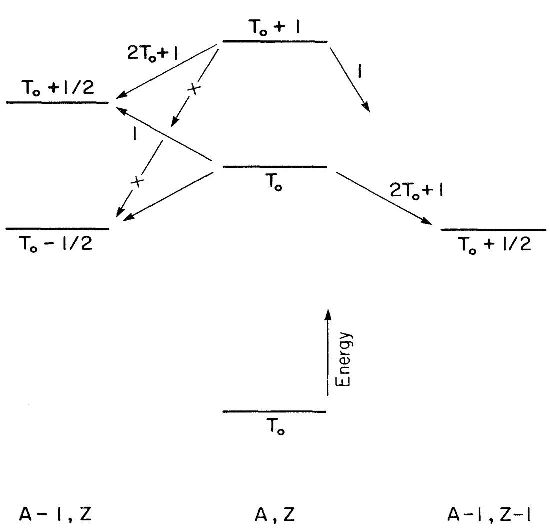

FIG. 1. Nuclei may generally be photoexcited from ground states of isospin T_0 to states of T_0 ($T_<$) or T_0+1 ($T_>$). These states may, if energetically possible, decay to daughter states by neutron or proton emission; the relative probability of decay by n or p emission depends, *inter alia,* on the isospins of the daughter states, as shown in this figure.

3. Sequential nucleon emission

The sequential emission of particles can be indicative of the isospin nature of the intermediate states and thus of states of the parent nucleus. Particle emission is much more likely than gamma emission if both are energetically possible. For example, a high-energy T_0+1 state of the parent nucleus will neutron decay to a $T_0+\frac{1}{2}$ state of the daughter, which may be above the (second) neutron emission threshold. This intermediate state will subsequently emit a second neutron to a low-lying T_0-1 state of the final nucleus, even though such neutron emission is isospin forbidden.

If, however, proton emission be energetically possible, the (γ,np) reaction will take place rather than the $(\gamma,2n)$ reaction, because the emission of a proton to $T=T_0$ low-lying states is allowed. On the other hand, from excited $T_<$ states of some nuclei (such as ^{18}O), sequential neutron emission is allowed. Thus, if both the (γ,np) and $(\gamma,2n)$ reactions are energetically possible, their relative strengths may give information on the isospin nature of the excited parent nucleus.

4. Linewidths

Transitions which are inhibited generally have narrow linewidths. The measured linewidths of discrete resonances far from the collective states of the GDR can therefore give information on the degree of forbiddenness of transitions and, from that, information on isospin.

In summary, the criteria discussed above have been used to assign isospin to resonances and energy regions in the nine nuclei listed in Table I. These general methods have previously been used for the cases of ^{14}C and ^{15}N [16,20]. Much earlier, isospin assignments were made by members of the present authorship and their colleagues for the case of ^{18}O [27].

III. ISOSPIN ASSIGNMENTS OF INDIVIDUAL NUCLEI

The details of the treatment of each of the nine nuclei studied are given in Ref. [37]. Only the results are presented here, except for the representative case of ^{13}C discussed below.

A. ^{13}C

Carbon-13 has a ground state of $T_0=\frac{1}{2}$; electric dipole excitation can lead to states of $T_<=\frac{1}{2}$ or $T_>=\frac{3}{2}$. The ground states of the daughter nuclei after single-nucleon emission, ^{12}C and ^{12}B, have isospin 0 and 1, respectively. An energy-level diagram is shown in Fig. 2.

The photoproton cross section of ^{13}C is known to 28 MeV [13] and the photoneutron cross section to 42 MeV [14]; the cross sections for neutron decay to the ground state of ^{12}C and to the first excited state have been studied to 35 MeV [15]. In addition, there is information on deexcitation gamma-ray studies [39] which makes possible estimation of cross sections leading to the first $T=1$ state of ^{12}C. From the shape of the photoneutron cross section, it is possible to extrapolate the total cross section to 30 MeV. Very recently [40], there has been work on isospin splitting using meson excitation.

1. Energy region from the photoneutron threshold of 4.95 MeV to the photoproton threshold at 17.53 MeV

In this region proton decay following photon excitation is not energetically possible, nor is any neutron transition to a $T=1$ state of ^{12}C. The fact that neutron decay takes place to $T=0$ states of ^{12}C is therefore not conclusive evidence that the decaying states are $T_<$. The most obvious example of this is the known $T_>$ ($T=\frac{3}{2}$) state in ^{13}C at 15.11 MeV, which shows strongly in (γ,n) and (γ,n_0) cross sections [14,15]. However it is seen as a very sharp resonance, the width being entirely instrumental, indicative of the isospin-forbidden nature of the transitions. It should also be noted that the average neutron energy is low at this excitation energy. The peak at 10.8 MeV has approximately the same full width of half maximum (FWHM) and may also be assigned as having $T_>$ nature. On the other hand, the peak at 16.2 MeV is significantly broader, consistent with a $T_<$ nature.

On the grounds of width, the 10.8- and 15.1-MeV resonances in the (γ,n) cross section, and therefore in the total absorption cross section, are assigned as $T_>$, and the rest of the strength in this region is assigned $T_<$. We note that in the region 16–18 MeV, a region assigned $T_<$ character, the average neutron energy 5 MeV is about one-third the maximum possible energy [14].

2. Energy range 17.53–20.9 MeV [the (γ,pn) threshold]

In this region both neutron and proton emission are energetically possible. If a state of ^{13}C in this region is $T_>$, proton emission from it will be favored as neutron emission is forbidden until 20.06 MeV, when the first $T=1$ state of ^{12}C becomes available. If the state is $T_<$, neutron emission is favored because of the lack of a Coulomb barrier and the greater number of states available in the daughter nucleus. A neutron from the decay of an excited state in this region to the ground state of ^{12}C would have an energy of about 13 MeV.

Zubanov *et al.* [13] have argued that the resonance generating the 18.6-MeV peak seen in the (γ,p) channel is $T_>$ in nature on the grounds that, although proton emission is inhibited by the Coulomb barrier, the proton reaction is seen strongly. The (γ,p) reaction is isospin allowed from either $T_>$ or $T_<$ states, while the (γ,n) reaction is forbidden from $T_>$ states. If, on the other hand, the resonance at 18.6 MeV were $T_<$, (γ,n) transitions would dominate over Coulomb-inhibited (γ,p) transitions. There is, however, no 18.6-MeV peak in the (γ,n) reaction [14,15].

The $(\gamma,p)/(\gamma,n)$ cross section ratio [13], though strongly peaked at 18.6 MeV, is less than 0.3—that is, if the region be $T_>$, three-quarters of the decays from this region either are via isospin-forbidden transitions or, more likely, are via underlying $T_<$ strength mixed with the $T_>$ resonance. (Figure 7 of Ref. [13] indeed indicates equal strengths of $T_<$ and $T_>$ at this energy.) Consistent with this and taking into account the tails of neighboring Gaussians, we apportion to a peak at this energy $\frac{2}{3}T_>$ strength and $\frac{1}{3}T_<$.

The (γ,n) cross section of Jury *et al.* [14] has an indication of a small peak at 19.8 MeV (4 mb in the peak); at this energy, the average neutron energy is at its lowest value (approximately 3 MeV). There is no obvious peak in the (γ,p) cross section of Zubanov *et al.* [13], but they note a "not well established" one at 19.7 MeV. The $\sigma(\gamma,p)/\sigma(\gamma,n)$ ratio is given as 0.2, similar to that at 18.6 MeV. There is no peak in the (γ,n_0) work of Woodworth *et al.* [15] at this energy, but a level of about 1 mb of cross section is indicated.

With respect to the neutron energy, it is worth noting that even 1 mb of ground-state transitions (which will give neutrons of energy 14 MeV) out of a total of 4 mb of (γ,n) [14] should lead to an average neutron energy of 3.75 MeV even if all the other 3 mb had E_n of zero and that therefore the observed value of an average neutron energy of 3 MeV is not possible with the above values. The explanation almost certainly lies in the nonlinear response of the method of energy determination used at Livermore [14]. The response is such that very-high-energy (ground-state) neutrons have a less than proportionate effect on the estimation of the average neutron energy. This implies that average neutron energies cannot be taken as absolutely correct, even though the relative values are reliable. This is important for light nuclei, where there may be a sharply structured spectrum of neutron energies.

Taking into account the very low neutron energy at 19 MeV, the lack of a peak in (γ,n_0), and the photoproton data, the small Gaussian fitted at 19.5 MeV is assigned $T_>$.

The next major feature is at 20.7 MeV. As at 18.6 MeV, the ratio $\sigma(\gamma,p)/\sigma(\gamma,n)$ reaches a maximum. Zubanov *et al.* [13] have argued that both $T_>$ and $T_<$ components are present. This conclusion was based on their work, that of Jury *et al.* on the total (γ,n) cross section [14], that of Woodworth *et al.* on transitions to low-lying states of ^{12}C [15], and that of Patrick *et al.* on gamma deexcitation of daughter nuclei states [39]. These works taken together show that there is significant cross section (2.7 mb) leading to the $T=1$ state at 15.11 MeV in ^{12}C in addition to 3.8 mb to low-lying ($T=0$) states of ^{12}C. Based on the ratios of the cross sections to the $T=0$ and 1 states of ^{12}C, we assign the Gaussian peak at 20.7 MeV as 60% $T_<$ and 40% $T_>$.

3. Energy region above 20.9 MeV

Jury *et al.* [14] conclude that in this region the isospin of excited ^{13}C nuclei is $T_>$, based on the "absence in this energy region of any appreciable strength in the ground state cross section of Woodworth *et al.*" [15] and on the fact that above 19 MeV the average neutron energy is

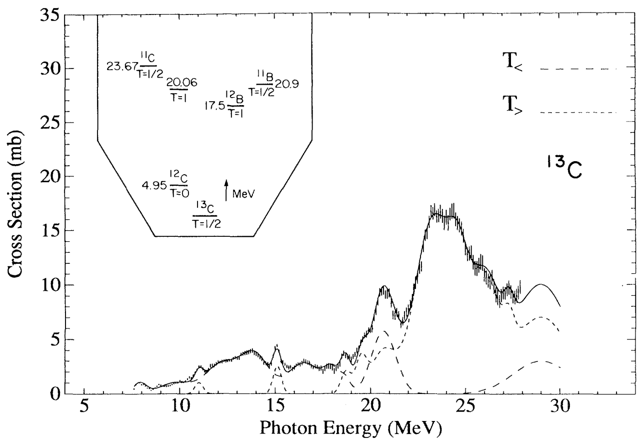

FIG. 2. Total photoabsorption cross section for ^{13}C (solid line), with the deduced $T_<$ and $T_>$ isospin components (dashed and dotted lines, respectively). In the inset is an energy-level diagram indicating energies at which decay channels open.

TABLE III. Gaussians used to fit the ^{14}C photoabsorption cross section. Results from the data: $\sigma_i = 125.36$ MeV mb, $\sigma_{-1} = 6.220$ mb, $\Delta E = 25.6 - 17.3 = 8.3$ MeV, $U^* = 58.1$ MeV, $R = 0.34$.

Energy (MeV)	$\sigma_i <$ (MeV mb)	$\sigma_{-1} <$ (mb)	$\sigma_i >$ (MeV mb)	$\sigma_{-1} >$ (mb)
10.2	0.84	0.083		
11.3	1.19	0.105		
13.0	4.56	0.352		
15.4	27.2	1.777		
18.3	14.85	0.814		
20.5	5.39	0.263		
21.5	6.53	0.304		
22.5			7.17	0.319
23.5	0.50	0.021	2.28	0.097
25.7	7.19	0.280	32.74	1.277
28.4	1.10	0.039	5.02	0.177
30.8	1.58	0.056	7.21	0.255
	70.93	4.093	54.42	2.127

low, indicating that the GDR decays predominantly to highly excited states of ^{12}C rather than to low-lying $T=0$ states. This general conclusion is also reached by Zubanov *et al.* [13], based on a comparison of ^{13}C cross sections and ^{12}C cross sections. They take the ^{12}C cross section as being equal to the $T_>$ component of the ^{13}C GDR and, after subtraction of ^{12}C from ^{13}C, assign the result as $T_<$. This method leaves a significant amount of $T_<$ at high energies, contrary to the conclusions of Jury *et al.* [14]. However, Woodworth *et al.* [15] do in fact show that there are (γ,n_0) and (γ,n_1) strengths which vary little from 26 to above 30 MeV. This work was at only one angle 98°, while the measurement of Woodworth *et al.* [41] for all angles extended only to 23 MeV. At 23 MeV the $(\gamma,n_0)+(\gamma,n_1)$ cross section is about 2 mb, roughly 20% of the total photoneutron cross section. There are presumably transitions to other low-lying states of ^{12}C. Jury *et al.* [14] found a major increase in average neutron energy around 30 MeV, which was taken to be indicative of some $T_<$ strength in this region. We note that ground-state neutrons would have an energy of about 25 MeV, so that a 30% contribution would yield a rise in average neutron energy of 7.5 MeV.

TABLE II. Gaussians used to fit the ^{13}C photoabsorption cross section. Results from the data: $\sigma_i = 140.31$ MeV mb, $\sigma_{-1} = 6.600$ mb, $\Delta E = 24.10 - 16.64 = 7.46$ MeV, $U^* = 64.7$ MeV, $R = 0.62$.

Energy (MeV)	$\sigma_i <$ (MeV mb)	$\sigma_{-1} <$ (mb)	$\sigma_i >$ (MeV mb)	$\sigma_{-1} >$ (mb)
7.9	0.69	0.086		
9.8	2.12	0.218		
11.0			0.532	0.048
12.2	5.75	0.473		
13.9	6.33	0.457		
15.1			1.331	0.088
16.5	5.96	0.362		
18.0	2.13	0.118		
18.7	0.64	0.034	1.277	0.068
19.5			2.235	0.115
20.7	9.10	0.440	6.067	0.293
23.3			37.469	1.611
24.6			8.303	0.338
25.9			21.316	0.824
27.3			1.285	0.047
29.0	8.33	0.294	19.444	0.686
	41.05	2.482	99.260	4.118

TABLE IV. Gaussians used to fit the ^{15}N photoabsorption cross section. Results from the data: $\sigma_i = 156.62$ MeV mb, $\sigma_{-1} = 7.102$ mb, $\Delta E = 23.7 - 19.0 = 4.7$ MeV, $U^* = 47$ MeV, $R = 0.65$.

Energy (MeV)	$\sigma_i <$ (MeV mb)	$\sigma_{-1} <$ (mb)	$\sigma_i >$ (MeV mb)	$\sigma_{-1} >$ (mb)
11.5			1.77	0.151
11.8	0.65	0.054		
13.3	0.93	0.069		
13.9	0.31	0.022		
14.1	0.37	0.026		
14.7	3.11	0.208		
15.4	2.08	0.134		
16.7	1.60	0.095		
17.7	6.31	0.355		
18.9	6.57	0.346		
19.2	1.11	0.057		
19.5			11.55	0.591
20.5			4.52	0.221
21.7	23.95	1.108		
23.2			6.34	0.276
25.4			73.36	2.951
28.5			12.09	0.438
	46.99	2.474	109.63	4.628

TABLE V. Gaussians used to fit the ^{17}O photoabsorption cross section. Results from the data: $\sigma_i=118.4$ MeV mb, $\sigma_{-1}=5.635$ mb, $\Delta E=23.7-15.5=8.2$ MeV, $U^*=92.9$ MeV, $R=0.67$.

Energy (MeV)	$\sigma_i <$ (MeV mb)	$\sigma_{-1} <$ (mb)	$\sigma_i >$ (MeV mb)	$\sigma_{-1} >$ (mb)
5.5	0.51	0.094		
7.0	0.75	0.107		
8.6	1.06	0.124		
10.0	0.95	0.095		
11.3	1.07	0.096		
13.2	5.86	0.447		
15.1	1.19	0.078	1.19	0.078
16.6	2.55	0.154		
18.25			3.99	0.219
19.4	4.79	0.247		
20.3	0.32	0.016	1.28	0.064
22.9	5.78	0.253	51.99	2.277
24.8	0.37	0.015	3.35	0.135
26.2	0.96	0.037	8.64	0.330
28.0	1.62	0.059	15.15	0.531
32.0	1.00	0.036	3.98	0.143
	28.78	1.858	89.57	3.777

On the basis of the above, we assign to the 29.0-MeV resonance 30% $T_<$, 70% $T_>$, with the other Gaussians in this energy region being $T_>$.

For the whole energy range up to 30 MeV, the total absorption cross section and the fit to the cross section are shown in Fig. 2. The parameters of the Gaussians are given in Table II, and the resulting values of σ_i, σ_{-1}, ΔE, U^*, and R are given in the same table.

TABLE VI. Gaussians used to fit the ^{18}O photoabsorption cross section. Results from the data: $\sigma_i=177.2$ MeV mb, $\sigma_{-1}=8.91$ mb, $\Delta E=23.6-14.2=9.4$ MeV, $U^*=84.6$ MeV, $R=0.60$.

Energy (MeV)	$\sigma_i <$ (MeV mb)	$\sigma_{-1} <$ (mb)	$\sigma_i >$ (MeV mb)	$\sigma_{-1} >$ (mb)
9.0	0.63	0.071		
10.2	5.32	0.522		
11.5	6.72	0.585		
13.1	7.18	0.549		
13.9	2.66	0.192		
14.7	8.20	0.558		
15.7	4.31	0.275		
17.2	7.95	0.464	7.95	0.464
19.3	0.88	0.046	7.90	0.410
21.0	0.56	0.027	5.03	0.240
23.5	5.68	0.242	11.36	0.484
26.5			86.41	3.472
30.0			4.26	0.157
36.0			4.20	0.150
	50.09	3.531	127.11	5.377

TABLE VII. Gaussians used to fit the ^{25}Mg photoabsorption cross section. Results from the data: $\sigma=330.54$ MeV mb, $\sigma_{-1}=15.261$ mb, $\Delta E=24.2-18.9=5.3$ MeV, $U^*=88.3$ MeV, $R=0.53$.

Energy (MeV)	$\sigma_i <$ (MeV mb)	$\sigma_{-1} <$ (mb)	$\sigma_i >$ (MeV mb)	$\sigma_{-1} >$ (mb)
11.0	6.33	0.577		
13.4	6.38	0.478		
14.6	2.13	0.146		
17.3	30.60	1.776		
19.5			17.03	0.874
21.0	41.51	1.984		
22.0	49.58	2.272	5.51	0.252
25.0			155.87	6.332
27.5			15.60	0.570
	136.53	7.233	194.01	8.028

B. Other light nuclei

Procedures similar to those described above for the ^{13}C nucleus were applied, *mutatis mutandis,* to the other light nuclei examined. The results for these nuclei are presented in Tables III–X and Figs. 3–10. In addition to the references listed in Table I, information used in making the isospin assignments also was drawn from other references, listed in Table XI.

For ^{14}C and ^{15}N, the present paper makes changes from conclusions reached in Refs. [16] and [20] at the higher energies studied. For ^{17}O, isospin assignments have been made earlier at the lower energies [23] and this

TABLE VIII. Gaussians used to fit the ^{26}Mg photoabsorption cross section. Results from the data: $\sigma_i=384.6$ MeV mb, $\sigma_{-1}=17.85$ mb, $\Delta E=24.9-18.7=6.2$ MeV, $U^*=80.6$ MeV, $R=0.46$.

Energy (MeV)	$\sigma_i <$ (MeV mb)	$\sigma_{-1} <$ (mb)	$\sigma_i >$ (MeV mb)	$\sigma_{-1} >$ (mb)
11.7	5.32	0.455		
12.8	5.75	0.449		
13.8	3.83	0.278		
14.8	6.39	0.432		
16.0	5.32	0.332		
16.65	26.11	1.605		
17.6	12.76	0.725		
18.2	21.29	1.172		
20.25	19.96	0.989	19.95	0.989
20.7			4.26	0.206
21.3			10.64	0.500
21.5	8.50	0.396		
22.1	10.65	0.482	10.65	0.482
23.5	53.24	2.269		
25.4			107.23	4.222
28.3			52.79	1.865
	179.12	9.584	205.52	8.264

TABLE IX. Gaussians used to fit the ^{29}Si photoabsorption cross section. Results from the data: $\sigma = 347.82$ MeV mb, $\sigma_{-1} = 16.449$ mb, $\Delta E = 23.50 - 17.85 = 5.65$ MeV, $U^* = 109$ MeV, $R = 0.58$.

Energy (MeV)	$\sigma_i <$ (MeV mb)	$\sigma_{-1} <$ (mb)	$\sigma_i >$ (MeV mb)	$\sigma_{-1} >$ (mb)
9.3	0.85	0.091		
10.3	1.6	0.155		
12.2	10.43	0.872		
14.5	6.38	0.444		
16.1	12.77	0.795		
17.8	32.79	1.847		
19.1	14.47	0.758	14.47	0.758
20.6	24.24	1.182	56.55	2.759
21.4	3.83	0.179	15.32	0.716
22.4	2.38	0.107	21.46	0.959
23.2			8.51	0.367
24.3			19.16	0.789
26.0			38.29	1.476
27.7	0.479	0.017	4.31	0.156
31.0	7.10	0.252	28.40	1.006
	122.15	6.844	225.67	9.605

work has been extended in the present paper. For ^{18}O, a significant change in assignment is made at one energy. For ^{25}Mg, ^{26}Mg, ^{29}Si, and ^{30}Si, the isospin splitting has not previously been evaluated.

IV. SENSITIVITY OF THE RESULTS

As indicated in the preceding text, the strengths of the two isospin components were calculated from the parameters of the Gaussian fits made to the total absorption cross section and the characterization of these Gaussian functions as to their isospin (or, in some few cases, the

TABLE X. Gaussians used to fit the ^{30}Si photoabsorption cross section. Results from the data: $\sigma_i = 310.9$ MeV mb, $\sigma_{-1} = 15.03$ mb, $\Delta E = 24.27 - 17.3 = 7.0$ MeV, $U^* = 105.0$ MeV, $R = 0.48$.

Energy (MeV)	$\sigma_i <$ (MeV mb)	$\sigma_{-1} <$ (mb)	$\sigma_i >$ (MeV mb)	$\sigma_{-1} >$ (mb)
12.0	2.13	0.178		
13.8	17.03	1.237		
15.4	14.90	0.969		
17.2	25.76	1.499		
18.8	51.09	2.714		
20.0	15.97	0.799		
20.8	7.90	0.380	15.95	0.767
21.5			19.16	0.892
22.3			23.42	1.051
23.5			38.32	1.633
24.8			2.66	0.107
26.0			34.72	1.334
28.0			22.75	0.813
30.0			19.14	0.661
	134.78	7.776	176.12	7.258

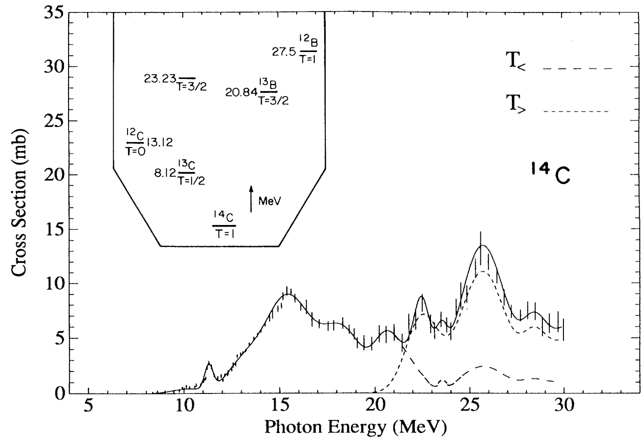

FIG. 3. As for Fig. 2, except that here is illustrated ^{14}C.

fraction of the resonance assigned to a particular isospin). To gain some idea of the "sensitivity" of the determined strengths to this Gaussian-fit procedure, relative strengths of the components were calculated on the basis of taking areas under the total absorption cross section curve between fixed energies, the energy cuts being those used and specified in the detailed consideration of each nucleus. When such an area contained portions of each isospin, recourse was made to Gaussian areas to estimate the proper fraction of each isospin.

When the results of the calculations were compared, it was found that the average relative strengths of the isospin components by the "Gaussian method" differed randomly from those found by the "cuts method" by about 10% and the ΔE values determined by the two methods differed by 3%.

Further tests of sensitivity were made by changing isospin assignments arbitrarily—for example, in ^{17}O, if the 16.6- and 15.1-MeV peaks were both assigned $T_>$ (instead of $T_<$ and 50:50 $T_>:T_<$), the relative isospin

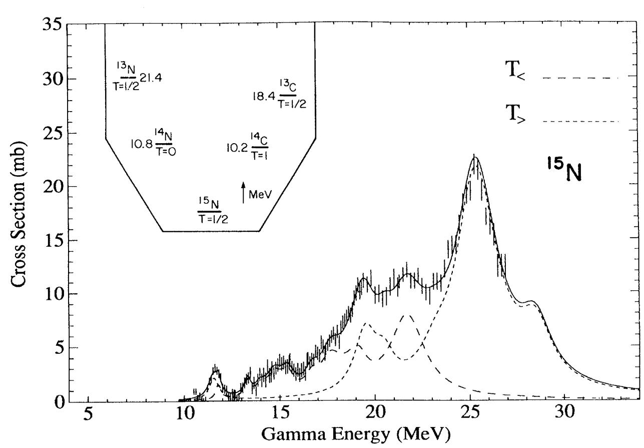

FIG. 4. As for Fig. 2, except that here is illustrated ^{15}N.

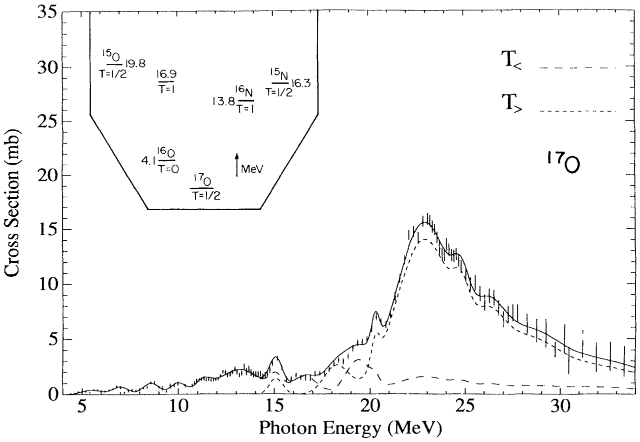

FIG. 5. As for Fig. 2, except that here is illustrated ^{17}O.

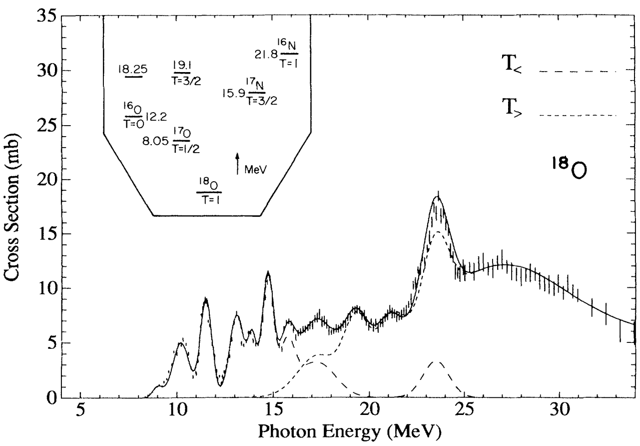

FIG. 6. As for Fig. 2, except that here is illustrated ^{18}O.

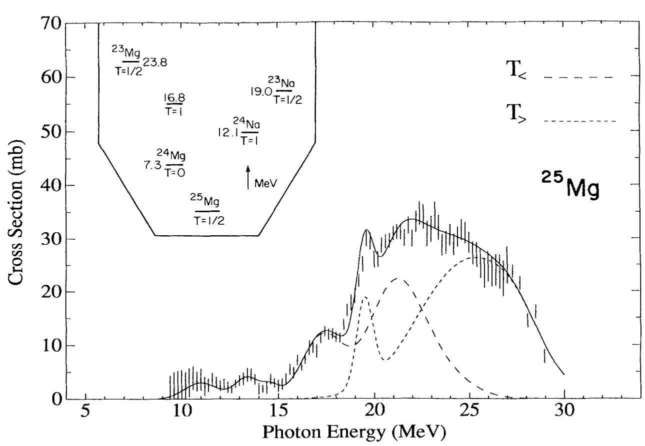

FIG. 7. As for Fig. 2, except that here is illustrated ^{25}Mg.

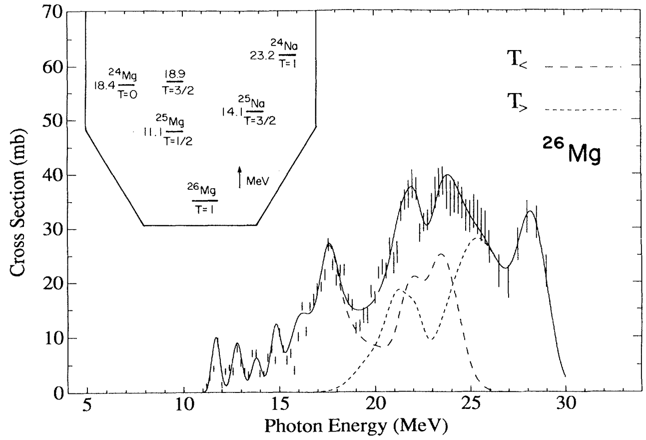

FIG. 8. As for Fig. 2, except that here is illustrated ^{26}Mg.

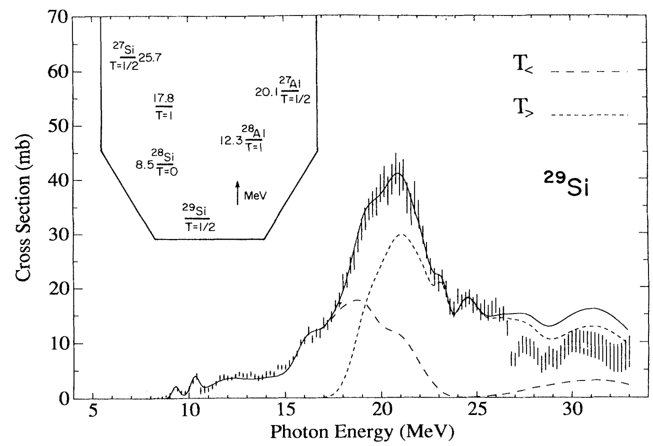

FIG. 9. As for Fig. 2, except that here is illustrated ^{29}Si. At 27 MeV and above, the data points shown are for the photoneutron reaction. The total cross section (solid line) is based on the assumption that the ratio of the photoproton to the photoneutron components remains constant.

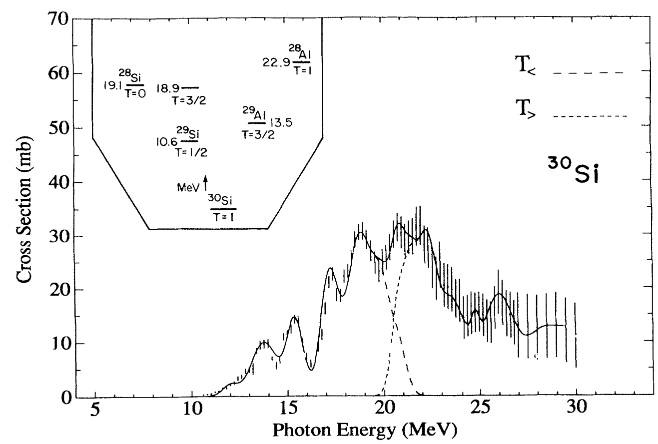

FIG. 10. As for Fig. 2, except that here is illustrated ^{29}Si.

TABLE XI. Additional references.

Nucleus	Table and figure number	Additional references
^{14}C	III,3	[42]
^{15}N	IV,4	[43,44]
^{17}O	V,5	[45,46]
^{18}O	VI,6	[47,48]
^{25}Mg	VII,7	[49–52]
^{26}Mg	VIII,8	[52–54]
^{29}Si	IX,9	[55,56]

strength R [defined by Eq. (3) in Sec. I] would change from 0.67 to 0.72. In the analysis of ^{14}C, we noted [37] that a change of the assignment of the 22.5-MeV peak made a 15% change in R, but that the different approaches of McLean *et al.* [16] and the present work did not alter ΔE significantly.

V. DISCUSSION

A. Relative strengths of isospin components

Table XII gives the measured values of $R = \sigma_{-1}^{>}/\sigma_{-1}$, together with those calculated from the work of Hayward, Gibson, and O'Connell [7] and Fallieros, Goulard, and Venter [2]. Figure 11 illustrates the results.

The most obvious result of this work is that, on average, the relative strength $R = \sigma_{-1}^{>}/\sigma_{-1}$ is somewhat better fitted by the geometric factor $1/(T_0+1)$ rather than by the full expression of Hayward, Gibson, and O'Connell [7] given in Eq. (4) above. We do not know the reason for this discrepancy, but we raise some questions.

First, we question whether it is justifiable for Hayward, Gibson, and O'Connell to assume that the $T_>$ component for Pb is zero. Assuming that a very small fraction does exist decreases the amount by which the $T_>$ component of the GDR is reduced by dynamical effects.

Second, we question whether the assumption that neutron and proton radii are equal can be justified, particularly in the light nuclei and particularly in the context of the present work where we are examining what happens when one or two nucleons are being added to closed (sub)shells. Specifically, if the proton distribution radius is assumed to be 10% greater than that of the neutron distribution radius, for the nucleus ^{18}O, for example, the predicted value for the ratio R is 0.48. This represents a significant change from the value of 0.35 obtained with the assumption of equal mean square radii for neutron and proton distributions.

Third, we question whether it is justifiable to assume that σ_{-1} is proportional to $A^{4/3}$ [their Eq. (4.8) [7]] while at the same time [their Eqs. (4.5), (4.6), and (4.7)] assuming that it is proportional to A^2 (that is, T_0 times the mean square proton radius with T_0 roughly proportional to $A^{1.4}$ over the range of A from 20 to 200). Table XIII shows that, in the nuclei we have studied, the ratio $\sigma_{-1}/A^{4/3}$ is nearly constant and equal to ~ 0.19 mb, considerably less than the value of 0.244 mb estimated by Hayward, Gibson, and O'Connell, but reasonably consistent with the values for other nuclei plotted in their Fig. 1. The present value of 0.19 is in very good agreement with the value of 0.186 ± 0.013 mb quoted in the review by Berman and Fultz [57] for nuclei of $A > 60$. Hayward, Gibson, and O'Connell suggest that the reason for the discrepancy between experimental results and their predictions may be that there is more strength above 30 MeV, the usual upper limit for integration. Although this is certainly true, it is likely that much of this strength will be $T_>$ in nature, and as we already find that our proportion of $T_>$ is greater than the prediction of Hayward, Gibson, and O'Connell, further deviation will occur if the integration is taken to higher energies.

B. Isospin splitting

One of the questions posed in Sec. I was whether there were separable isospin components of the GDR and if, in particular, the work of Wu, Firk, and Berman [11] on ^{26}Mg showed such existence. We believe that we have

TABLE XII. Values of $R = \sigma_{-1}^{>}/(\sigma_{-1}^{<} + \sigma_{-1}^{>})$. For $T=\frac{1}{2}$, average $R = 0.61$ (H gives 0.56, F gives 0.62); $1/(T_0+1) = 0.67$. For $T=1$, average $R = 0.47$ (H gives 0.36, F gives 0.40); $1/(T_0+1) = 0.50$.

Nucleus	T_0	Expt. (E)	Hayward, Gibson, and O'Connell [7] (H)	Fallieros, Goulard, and Venter [2] (F)	E/H	E/F
^{13}C	$\frac{1}{2}$	0.62	0.53	0.60	1.17	1.03
^{14}C	1	0.34	0.32	0.37	1.06	0.92
^{15}N	$\frac{1}{2}$	0.65	0.55	0.61	1.18	1.07
^{17}O	$\frac{1}{2}$	0.67	0.56	0.61	1.20	1.10
^{18}O	1	0.60	0.35	0.39	1.71	1.54
^{25}Mg	$\frac{1}{2}$	0.53	0.59	0.63	0.90	0.84
^{26}Mg	1	0.46	0.38	0.42	1.21	1.10
^{29}Si	$\frac{1}{2}$	0.58	0.59	0.63	0.98	0.92
^{30}Si	1	0.48	0.40	0.43	1.20	1.12

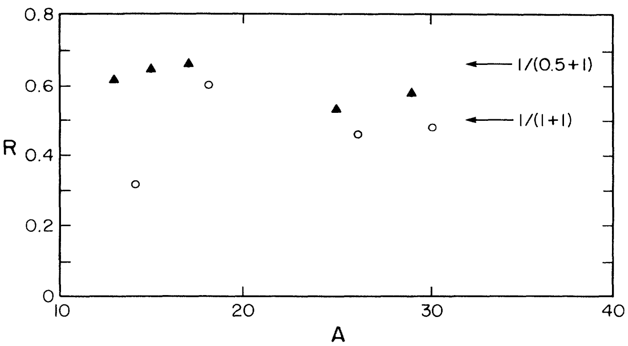

FIG. 11. Values of $R=\sigma_{-1}>/(\sigma_{-1}<+\sigma_{-1}>)$ for the nuclei analyzed here. $T_0=\frac{1}{2}$ nuclei are shown as ▲, $T_0=1$ nuclei by ○. The values expected from $1/(T_0+1)$ for $T_0=0.5$ and 1 are shown by the arrows.

shown that indeed there are separable isospin components in the GDR of the p and s-d light nuclei. In particular, we have examined the case of ^{26}Mg [37] and conclude that different resonances in the total photon absorption cross section have significantly different decay modes, differences attributable to different isospin, and that the resonance characterized by the $T_<$ and $T_>$ isospins tend to be grouped into two parts, although a complete separation is clearly not the case (see Table VIII and Fig. 8).

C. Symmetry energy

We noted that one formulation [5] of the isospin splitting energy in MeV was $\Delta E=60(T_0+1)/A$. The values of $U^*=\Delta EA/(T_0+1)$ are given in Table XIV and plotted in Fig. 12. For the three lightest nuclei ^{13}C, ^{14}C, and ^{15}N, the discrepancy between U^* and 60 MeV is very small (average $U^*=57$ MeV). However, for the six heavier nuclei analyzed in this work, the values of U^* are consistently much larger than 60 MeV, with an average of 93 MeV. Also shown in Table XIV and Fig. 12 are values of U^* for nine nuclei reviewed by Thompson [10]. For these, the average value of U^* is 57 MeV. None has $U^*>65$ MeV. The three lightest nuclei in the present series (^{13,14}C and ^{15}N) are in the p shell, the six heavier ones in the present series are all in the s-d shell, and of the nine nuclei from Ref. [10], six are in the $f_{7/2}$ shell.

It is doubtful that the effect seen in the present work is caused by $T_<$ strength above the cutoff energy of 30 MeV in the s-d shell nuclei, as we note that the prediction of high-energy $T_<$ strength is not confined to this shell (Pywell *et al.* [35] refer to "the onset of additional $T_<$ strength . . . [in silicon] . . . as has been seen previously in the lighter $4N\pm1$ nuclei ^{13}C, ^{15}N, and ^{17}O").

In order to examine the apparent change in the symmetry energy U^* from 60 to 90 MeV from p shell to s-d shell nuclei, we have attempted to express the measured U^* values in terms of the value of the dipole symmetry energy U_D used in Ref. [5]. U_D is the difference between the traditional symmetry energy (e.g., as appears in the Lane potential) and the dipole excitation energy (less the single-particle transition energy). Using relations estab-

TABLE XIII. Integrated cross sections.

Nucleus	σ_i (MeV mb)	σ_{-1} (mb)	$\sigma_{-1}A^{-4/3}$ (mb)	$\sigma_i/(60NZ/A)$
^{13}C	140.3	6.60	0.216	0.72
^{14}C	125.4	6.22	0.184	0.61
^{15}N	156.6	7.10	0.192	0.70
^{17}O	118.4	5.64	0.129	0.47
^{18}O	177.2	8.91	0.189	0.66
^{25}Mg	330.5	15.26	0.209	0.88
^{26}Mg	384.6	17.85	0.226	1.00
^{29}Si	347.8	16.45	0.184	0.80
^{30}Si	310.9	15.03	0.161	0.69
	Averages		0.188	0.73

TABLE XIV. Values of isospin splitting.

Nucleus	T_0	ΔE (MeV)	$U^*=\Delta EA/(T_0+1)$ (MeV)
^{13}C	$\frac{1}{2}$	7.5	65
^{14}C	1	8.2	58
^{15}N	$\frac{1}{2}$	4.7	47
^{17}O	$\frac{1}{2}$	8.2	93
^{18}O	1	9.4	85
^{25}Mg	$\frac{1}{2}$	5.3	88
^{26}Mg	1	6.2	81
^{29}Si	$\frac{1}{2}$	5.7	109
^{30}Si	1	7.0	105
^{44}Ca	2	4.4	65.0
^{48}Ca	4	5.5	52.8
^{46}Ti	1	2.5	57.5
^{48}Ti	2	4.1	65.6
^{50}Ti	3	4.9	61.3
^{54}Cr	3	2.8	37.8
^{54}Fe	1	2.0	54.0
^{90}Zr	5	3.8	56.7
^{92}Mo	4	3.5	64.4

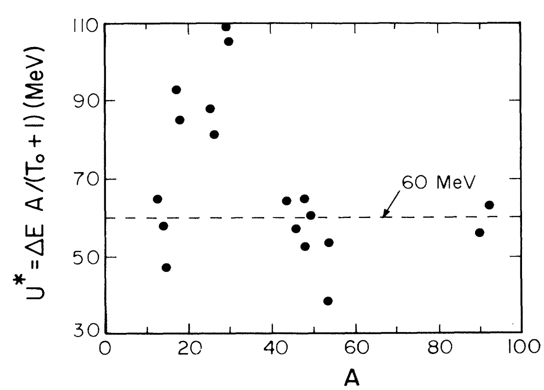

FIG. 12. Values of $U^*=\Delta EA/(T_0+1)$ for the nine nuclei considered here ($A=13$–30) and for nine nuclei with $A=44$–92. The six nuclei in the s-d shell ($A=17$–30) have significantly higher values than the rest.

lished in Ref. [5], we have calculated for the p shell nuclei discussed in this paper an average value of $U_D = 2.9$ MeV.

For the s-d shell nuclei, an average value of $U_D = 1.9$ MeV is found by ignoring shell effects. If extra energy is required for the $T_>$ excitations by elevating nucleons from the underlying p shell, then the observed value of $U^* = 90$ MeV yields an average value of $U_D = 4.2$ MeV, or 2.3 MeV greater than the value obtained from the usual interpretation of U_D. This energy difference can be thought of as an enhancement to U_D by the energy gap between the p and s-d shells.

We attempted a similar analysis on the (mostly f shell) nuclear symmetry energies reported in Ref. [10]. For these nuclei an average symmetry energy U^* of about 57 MeV was measured. By assuming a reasonable energy separation between the s-d and f shells, we were unable to account for a shell effect similar to the p-s-d difference discussed above. We conclude, therefore, that for the f shell the greater number of single-particle excitations making up the $T_<$ and $T_>$ components masks the obvious shell effect seen in the p and s-d region.

Another factor which may be involved in the increased ΔE for s-d shell nuclei derives from the intrinsic (oblate) deformation of the nuclei lying near the middle of this shell. This, together with the expected isospin splitting, may be responsible for the observed increased energy splitting reported here.

It is possible to obtain a crude upper limit on the broadening caused by deformation splitting of the s-d shell nuclei by comparing the total photoabsorption cross sections for ^{28}Si and ^{40}Ca. Both of these nuclei are self-conjugate and therefore only T-upper states are accessible by dipole photon absorption. For ^{28}Si, which lies precisely in the middle of the s-d shell, one might expect a broader GDR than for ^{40}Ca, at the top of the shell and generally considered to be spherical. Such a comparison can be made using the measurements of Ahrens *et al.* [58]; the reported widths of the GDR's of these nuclei are very similar (both near 5 MeV). Therefore it is difficult to assign any significant deformation splitting to the silicon isotopes or to the other s-d nuclei studied in the present work; at the maximum, deformation splitting could not amount to more than 1 or 2 MeV, with the most likely value being near zero.

D. Outliers

Looking at Table XIV and Fig. 12, the outlier of the data is the case of ^{15}N, the value of whose U^* is the lowest of the nine nuclei examined in this work. This peculiarity of ^{15}N does not show up in the relative strengths of the two isospin components (Table XII) or in the fraction of the sum rule satisfied (Table XIII).

In Table XII and Fig. 11, the case of ^{14}C is of interest. It has an R of 0.34, by far the lowest value and well below $1/(T_0+1)=0.50$. However, the predictions of Hayward, Gibson, and O'Connell and Fallieros, Goulard, and Venter are 0.32 and 0.37, respectively. In both cases these low predictions arise from a combination of low A and (comparatively) high T.

An outlier in Table XIII is ^{17}O; the integrated cross section is a lower proportion of the sum rule than is the case for the other nuclei studied. On the other hand, ^{26}Mg has a high value. Again, we can offer no explanation; we refer the reader to the original Refs. [23,33].

VI. SUMMARY

Relative probabilities of proton and neutron emission from photoexcited states have been used to assign isospin to these states. Isospin splitting of the giant dipole resonance has been analyzed for nine light nuclei ($A = 13-30$) using data which have a high degree of self-consistency. We have observed a strong shell dependency of the symmetry energy. For the three nuclei in the p shell, the value of the symmetry energy $U^* = \Delta E A/(T_0+1)$ is near 60 MeV, but for the six nuclei in s-d shell the corresponding value is near 90 MeV. The measured ratios R of the $T_>$ isospin components to the total absorption strengths are in better agreement with the predictions of a simple geometric model for the ratio, namely, $R = 1/(T_0+1)$, than with more detailed predictions.

ACKNOWLEDGMENTS

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