Total Photoneutron Cross Sections of Carbon and Magnesium*

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The total photoneutron cross sections of natural carbon and magnesium were measured from thresholds to 30 MeV. The neutron yield curves, determined in 0.5-MeV intervals using a bremsstrahlung beam, were analyzed by the Penfold-Leiss method to obtain two independent sets of cross sections of 1-MeV interval. The carbon cross section exhibits major structure at 18.8, 22.0, and 25.5 MeV, the integrated cross section up to 28 MeV being 39.2 MeV mb. The magnesium cross section indicates levels at 17.0, 19.5, 21.5, 23.5, and 25.5 MeV with the integrated cross section up to 28 MeV, 90.7 MeV mb. The magnesium cross section also shows a small structure at 14.7 MeV due to Mg^{25} and Mg^{26}. The experimental results are compared with the available particle-hole-model calculations of $E1$ levels.

I. INTRODUCTION

THE particle-hole model of the dipole giant resonance[1,2] has been extensively applied to the closed shell nuclei. The detailed calculations made for some light nuclei[2–4] have been successful in describing the major structure observed in experiments.[5–9] For a deformed nucleus such as magnesium, however, relatively few calculations have been made. Even though the semiclassical hydrodynamical model for the deformed nuclei[10,11] successfully predicts the splitting of the giant resonance in deformed nuclei, recent calculations by Nilsson, Sawicki, and Glendenning[12] for C^{12} and Mg^{24} have shown that within each split group, the distribution of dipole strengths forms a rather complex spectrum. As these authors point out, it is not certain whether C^{12} can be properly described as a deformed nucleus. However, since there exist several calculations available for C^{12} which do not assume deformation,[13–15] it is of interest to compare the experimental cross section with both types of calculations.

In spite of its relatively poor energy resolution, bremsstrahlung measurement of photoneutron cross sections has been successfully used to reveal the main structure in light nuclei.[6,8,16] In order to compare the experimental cross sections of C^{12} and Mg^{24} with the predicted structure, the total photoneutron cross sections, $\sigma(\gamma,n)+\sigma(\gamma,pn)+2\sigma(\gamma,2n)+\cdots$, were measured using the bremsstrahlung beam from the University of Virginia 70 MeV electron synchrotron.

II. EXPERIMENTAL PROCEDURE

The details of the experimental procedure used in the present work were reported previously.[6,8,16]

The collimated bremsstrahlung beam from the synchrotron irradiated a cylindrical sample placed along the beam axis at the center of a 4π Halpern-type neutron detector[17] made of paraffin and BF_3 counters. The neutrons from the sample were first slowed down in 13.5-cm thick paraffin layers, and were detected by a system of eight BF_3 counters placed concentric about the beam axis. The paraffin thickness of 13.5 cm was chosen in accordance with the work of Ross and Staub,[18] who found that at this distance the detection efficiency is insensitive to the neutron energy. The energy insensitivity of the detection efficiency was further tested by Halpern *et al.*,[19] who found the photoneutron yield curve from phosphorus by direct neutron detection with paraffin thickness 13.5 cm agrees with the yield curve obtained by counting the residual activity.

The BF_3 counters were shielded against extraneous neutron background by cadmium sheets and borated paraffin. To prevent the registering of electron pile-up pulses, a 20-μsec time delay was inserted between the x-ray pulse and the triggering of a gating circuit. The B^{10} (n,α) pulses were counted during the 700-μsec gating period. An ionization chamber of the National Bureau of Standards type was used to monitor the beam, and a calibrated 10-mCi Ra-Be neutron source was used to calibrate the whole detecting system, which had an

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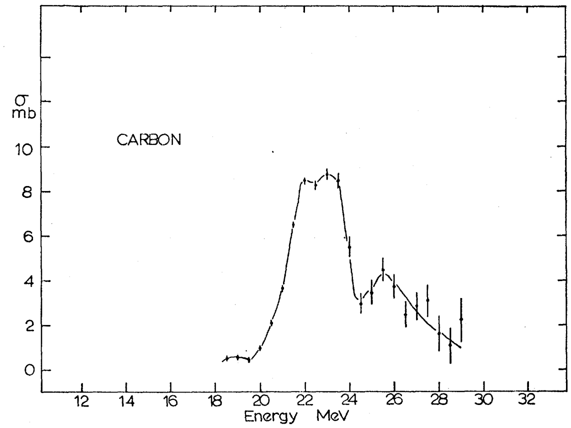

FIG. 1. Total photoneutron cross section of carbon unfolded in 1-MeV intervals.

average detection efficiency of 2.5%. Throughout the experiment, the fluctuation in the detection efficiency remained within 1% of this value. The cylindrical samples used in this experiment were natural carbon graphite and natural magnesium, both 3.2 cm in diameter and 10 cm long.

The contributing isotopes, their abundances in the samples, and the relevant threshold energies are given in Table I.

The neutron yield curves were constructed in 0.5-MeV steps from 17.5 MeV in carbon, and from 10 MeV in magnesium, up to 30 MeV of bremsstrahlung energy. The entire energy range of the experiment was covered in 0.5-MeV steps in 30 separate yield measurements for carbon and 20 for magnesium, with enough neutron counts at each energy to maintain the total counting statistics at less than 1%.

After correcting for the background, the average net yield per unit monitor response was computed for each energy. The net yield curves thus constructed, were analyzed directly through the Penfold-Leiss matrix[20] to unfold two independent and interlacing sets of cross sections in 1-MeV intervals. For carbon, the same yield curve was also analyzed to unfold the cross sections in 0.5-MeV intervals to improve the energy resolution at the expense of statistical errors.

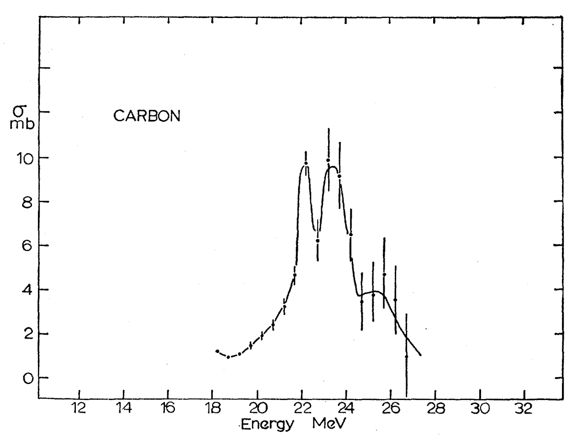

FIG. 2. Total photoneutron cross section of carbon unfolded in 0.5-MeV intervals.

III. RESULTS

The photoneutron cross sections of carbon and magnesium are presented in Figs. 1, 2, and 3. Figure 1 is the carbon data unfolded in 1-MeV intervals. Figure 2 is the same data unfolded in 0.5-MeV intervals. The effect of improving the energy resolution, and the consequent increase in the errors are clearly shown in Fig. 2. This is characteristic of the method used to unfold the cross sections from the bremsstrahlung neutron yield curves.[20] Figure 3 presents the magnesium data unfolded in 1-MeV intervals. The energy positions of the major structure observed in the cross sections are listed in Tables II and III. The integrated cross sections up to 28 MeV, and, for comparison, the energy levels reported in other experiments[9,21–23] are also given.

TABLE I. Isotopic abundance in the samples and threshold energies.

Isotope	Abundance (%)	(γ,n) (MeV)	(γ,pn) (MeV)	$(\gamma,2n)$ (MeV)
C^{12}	98.89	18.7	27.4	32.4
C^{13}	1.11	5.0	20.9	23.7
Mg^{24}	78.60	16.6	24.1	
Mg^{25}	10.11	7.3	19.0	23.9
Mg^{26}	11.29	11.1	23.2	18.4

The important features of the cross sections are discussed below separately:

Carbon

Prominent resonances occur at 22.2, 23.5, and 25.5 MeV. In addition, there is evidence of some structure near the C^{12} threshold (Figs. 1,2), at 18.8 MeV. Even though the separation of 22.2 and 23.5-MeV peaks depends on a single data point in the present poor resolution experiment, they are in excellent agreement with the 22.2- and 23.4-MeV peaks observed in the other (γ,n) experiment which uses monochromatic gamma rays.[9] The 25.5-MeV peak corresponds to the peak observed at the same energy in a (γ,p)[21] and total absorption[22] experiments. The integrated cross section up to 28 MeV is 39.2 MeV-mb, which corresponds to 22% of the classical dipole sum, 60 $NZ/A=180$ MeV

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-mb. It is interesting to note that this is less than the reported (γ,p) integrated cross section in the same energy range (up to 29 MeV) which is 28% of the dipole sum.[24]

Magnesium

As expected from a deformed nucleus, the absorption strengths in magnesium (Fig. 3) are distributed over a wider energy interval than in carbon; over an interval of about 9 MeV compared with the 3-MeV width in carbon. Strong levels at 19.5, 21.5, 23.5, and 25.5 MeV are clearly resolved. In addition, there is evidence of structure at 17.0 MeV near the Mg^{24} (γ,n) threshold. Below the same threshold, there is a small resonance at 14.7 MeV which must be attributed to Mg^{25} or Mg^{26}. The locations of these levels are in good agreement with those observed in other experiments[9,23] (see Table III). The integrated cross section up to 28

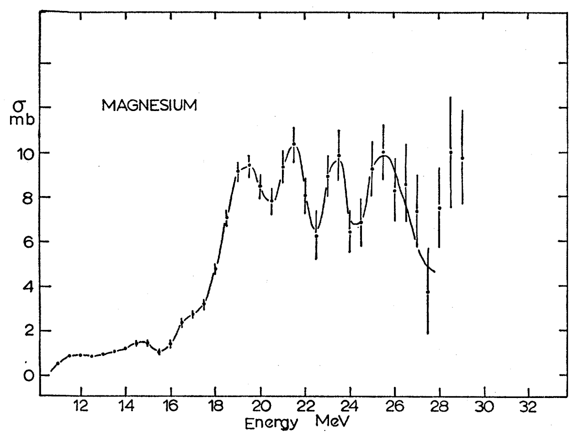

FIG. 3. Total photoneutron cross section of magnesium unfolded in 1-MeV intervals.

MeV is 90.7 MeV mb, or 25% of the dipole sum. The integrated (γ,p) cross section up to 32 MeV was reported to be 180±40 MeV mb or 50% of the dipole sum.[25]

IV. DISCUSSION

The carbon levels at 22.2 and 23.5 MeV are generally well described by the present particle-hole model. In the detailed calculations by Boeker,[15] the strongest $E1$ level is predicted at 21.9 MeV, which carries 70% of the total absorption strengths with the principal configuration $(p_{3/2})^{-1}\, d_{5/2}$. It is noteworthy, however, that the separation into two peaks as observed in this experiment and the good resolution data of Ref. 9 is not reproduced in all calculations which treat C^{12} as a spherical nucleus.[13–15] On the other hand, in the calculations by Nilsson, Sawicki, and Glendenning for deformed nuclei,[12] the dipole levels are separated into two groups corresponding to $K=0$ and $K=1$ rotational bands. For C^{12}, two levels of $K=1$ group at 22.2 and 23 MeV carry 75% of the total absorption strengths of this group. The location of these levels and the 1-MeV separation between the two agree well with the observed 22.2- and 23.5-MeV levels.

The 25.5-MeV level in carbon is not well described by either calculation. In the calculations of Ref. 13–15, an $E1$ level is predicted at 24 MeV which arises mainly from $(p_{3/2})^{-1}$ $(d_{3/2})$ configuration. The predicted strengths of less than 1% are much smaller than observed in this experiment. This discrepancy with the theory has also been noted in (p,γ) studies by Becker and Fox.[26] The $(p_{3/2})^{-1}$ $(d_{3/2})$ configuration assigned to the 24-MeV level was found to be inconsistent with the $B^{11}(p,\gamma)$ angular distribution by Allas *et al.*,[27] who observed that the angular distribution in the 25.5-MeV region allows the incident wave to contain no more than 50% $d_{3/2}$.

The energy positions of the major structure observed in magnesium agree well with the levels observed in the absorption experiment of Ref. 23. (See Table III.) It is to be noted that the absorption strengths of the 17.0-MeV level are much greater than apparent in Fig. 3. The absorption cross section of Ref. 23 shows a

TABLE II. Energy levels observed in carbon (MeV).

Present work (γ,n)	Other experiments (γ,n)[a]	(γ,p)[b]	(absorption)[c]
			16.5
18.8			17.6
	19.5		19.1
22.2	22.2	22.5	
23.5	23.4	23.5	23.0
25.5		25.6	25.6
$\int_{Th.}^{28}\sigma dE=39.2$ MeV-mb			

[a] Reference 9.
[b] Reference 21.
[c] Reference 22.

TABLE III. Energy levels observed in magnesium (MeV).

Present work (γ,n)	Other experiments (γ,n)[a]	Absorption[b]
17.0	17.5	17.0
19.5	18.8	19.0
21.5	20.0	20.0
23.5	23.0	23.0
25.5	25.0	25.0
$\int_{Th.}^{28}\sigma dE=90.7$ MeV-mb		

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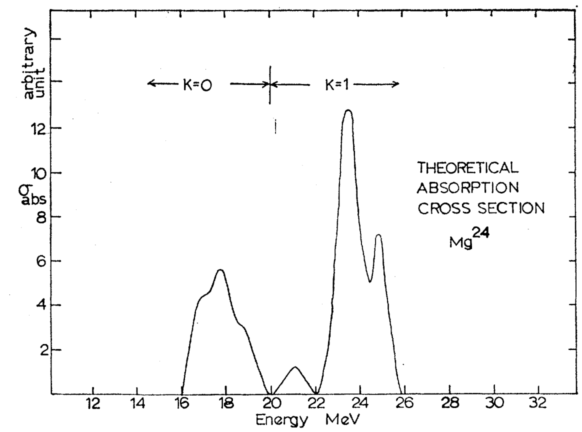

FIG. 4. Total photon absorption cross section of magnesium calculated from Ref. 12. Triangular line shapes with constant widths of 1 MeV were assumed.

strong level at 17 MeV with a peak cross section of about 20 mb. Comparison with the present (γ,n) data indicates that this level decays predominantly by proton emission. This is probably due to the fact that the 16.6-MeV $Mg^{24}(\gamma,n)$ threshold is very close to the 17.0-MeV level, which would effectively suppress the neutron emission in favor of the proton emission.

In an attempt to identify the observed levels with those predicted by theory, the absorption cross-section curve was constructed in Fig. 4, using the calculated oscillator strengths of Ref. 12, and assuming triangular line shapes of uniform widths of 1 MeV. More elaborate schemes to assign the widths would not change much the predicted peaks and the relative strengths distribution. Even though the predicted positions of the $K=1$ group levels at 21, 23.5, and 25 MeV seem to agree to the observed levels at 21.5, 23.5 and 25.5 MeV, it is difficult to identify them in view of the large discrepancy in the relative distribution of the absorption strengths among the levels. The most prominent feature of Fig. 4, the large splitting between the two groups, is not supported by the present (γ,n) data.

The small peak at 14.7 MeV is due to Mg^{25} or Mg^{26} since it lies below the $Mg^{24}(\gamma,n)$ threshold. A similar structure has been observed by Spicer *et al.*[28] at 13.5 MeV, and was interpreted as a "pygmy resonance" analogous to the structure observed in C^{13}.[29]

In summary, the main features of the observed photoneutron cross section of C^{12} are well described by the particle-hole model. The fine structure about the main resonance is better described in the calculations in which C^{12} is treated as a deformed nucleus. The photoneutron cross section of magnesium shows considerable structures which are not well understood by the photonuclear theory at present. The large splitting predicted both by the hydrodynamical model and more detailed calculations, has not been observed in the present magnesium data.

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