Photoproton cross section of ^{26}Mg

D. W. Anderson
Department of Radiological Sciences, University of Oklahoma Health Sciences Center, Oklahoma City, Oklahoma 73104

and

R. F. Petry and H. J. Fischbeck
Department of Physics and Astronomy, University of Oklahoma, Norman, Oklahoma 73069
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The cross section for the reaction $^{26}Mg(\gamma,p)^{25}Na$ has been measured from 15 to 60 MeV using bremsstrahlung activation methods to obtain the yield curve. The peak cross section of 15.7 mb occurs at 22.6 MeV. Prominent secondary maxima occur at 29.6, 49.0, and 57.9 MeV. The cross section integrated to 28 MeV is 80 ± 9 MeV mb. The cross section integrated to 60 MeV is 161 ± 18 MeV mb. A discussion of our results and comparison with photoneutron data for ^{26}Mg from other sources is given.

[NUCLEAR REACTIONS $^{26}Mg(\gamma,p)$, $E=15-60$ MeV; measured bremsstrahlung yield; deduced $\sigma(E)$.]

1. INTRODUCTION

Many photoreaction cross-section measurements have been reported in the past on ^{24}Mg or naturally occurring magnesium targets. References to such work can be obtained from standard bibliographies.[1] In recent years some data on separated ^{26}Mg at giant-resonance energies have been reported. The interest in photoreactions in ^{26}Mg has largely been motivated by predictions of an isospin splitting in the giant resonance for this nucleus.[2,3] In this regard useful experimental information was obtained from (e, e') work[4] and photoneutron measurements.[5-7] Previous photoproton data[8,9] are not recent and were taken at low resolution. Because of this, the present photoproton experiment was undertaken to help complete the picture of the giant resonance for this very interesting target nucleus.

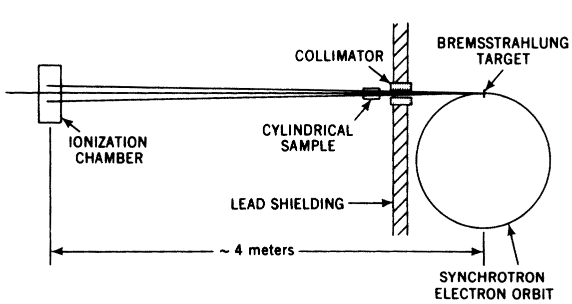

FIG. 1. The experimental arrangement for the sample and fluence monitor is shown.

In addition to giant-resonance data, some information on cross sections at higher energies for (γ, p) reactions was desired. Over the last few years photoneutron cross sections for several $1s$-$2d$-shell neighbors of ^{26}Mg have been reported to a maximum energy of about 60 MeV.[10-14] The systematics of the gross structure found above the giant resonance has been discussed previously for these nuclides.[15] High-energy structures were expected for (γ, p) reaction cross sections, in particular for the ^{26}Mg target. Similarities between the photoneutron results and the present (γ, p) data are discussed in Sec. 3.

2. EXPERIMENTAL METHOD

A sample of 29.44 g of magnesium oxide enriched to 99.42% in the isotope ^{26}Mg was used as a target. The material was packed in a thin-walled cylindrical container of aluminum, 3.2 cm in diameter. The ends of this tube were approximately 0.4 mm thick and served as entrance and exit windows. The sample was irradiated in the bremsstrahlung beam of the Oklahoma University electron synchrotron. The experimental setup is illustrated in Fig. 1 and has been described previously.[14] The bremsstrahlung end-point energy was calibrated using the 17.29-MeV break in the $^{16}O(\gamma, n)^{15}O$ reaction yield curve.[16] The ionization chamber utilized to monitor the bremsstrahlung energy fluence was a facsimile of one designed and calibrated at the National Bureau of Standards.[17]

The sample was irradiated for a period of 180 sec and the activity produced was counted for

180 sec with a 7.5-cm×7.5-cm NaI(Tl) detector system. The irradiation and counting periods were separated by 30 sec during which the sample was transferred from the synchrotron to the detector.

The activity of interest is the 59-sec β^- decay of ^{25}Na, which branches to several excited states and to the ground state of ^{25}Mg. The energies and intensities of the γ rays following the decay of ^{25}Na are listed in Table I.[18] Since our sample was MgO, ^{15}O was produced from the ^{16}O(γ, n) reaction, and the 122-sec β^+ decay of this isotope contributed a strong annihilation peak to the γ spectrum. The spectrum is shown in Fig. 2. Other photoreaction products were ^{24}Na (15h), ^{14}O (71 sec), ^{24}Ne (3.4 min), and ^{23}Ne (38 sec), all produced at higher bremsstrahlung energies.

The annihilation radiation was eliminated from the data by accepting only events in the energy range 0.9 to 1.84 MeV. This interval encompasses several γ peaks in the ^{25}Na spectrum (see Fig. 2). Contributions from γ rays from the decay of ^{24}Na are included, but because of the long half-life of ^{24}Na this contribution was subtracted with the sample background measurements. It was found to be less than 10% of the total in all cases. Contributions from the other isotopes are small since they involve multiparticle reactions. Products of their decay are not identified in the spectra but cannot be specifically excluded from the data.

About 600 yield points were obtained in 0.5-MeV increments from 15.0 (photoproton threshold is 14.1 MeV) to 60 MeV. To calculate the yield the accumulated total of events recorded was corrected for ^{24}Na activity, ^{15}O β-ray bremsstrahlung, detector dead time, and pileup effects from the ^{15}O activity. This was divided by the bremsstrahlung energy fluence incident on the sample. Yield data were analyzed for cross section by the least-structure method[19] using the Schiff bremsstrahlung spectrum.[20] Absolute cross sections were determined by comparing the ^{26}Mg(γ, n)^{25}Na yield with the ^{16}O(γ, n)^{15}O yield, identified by the β^+ decay, in the MgO sample. The integrated cross-section measurement for the oxygen reaction given by Cook *et al.*[21] was used as the comparison standard.

TABLE I. ^{25}Mg γ-ray energies and intensities following ^{25}Na β^- decay (Ref. 18).

E (MeV)	Intensity (%)
0.390	12.9
0.585	12.6
0.836	~0.1
0.975	14.5
0.990	~0.2
1.380	~0.3
1.612	9.5
1.763	<0.1
1.965	~0.2
2.216	~0.1
2.801	~0.1

3. RESULTS AND DISCUSSION

The cross-section solution obtained from the yield data is shown in Fig. 3. The vertical error bars indicate cross-section error estimates, while the horizontal bars indicate the minimum full width at half-maximum allowed in the analysis, even for a very sharp cross-section resonance. The peak in the giant resonance occurs at 22.6 MeV with a value of 15.7 mb. The secondary maxima clearly resolved in Fig. 3, occur at 29.6, 49.0, and 57.9 MeV. Other intermediate energy cross-section maxima are indicated but are not so clearly resolved.

A. Giant-resonance region

The (γ, p) cross-section curve below 32 MeV can be closely fitted by the sum of four gross reso-

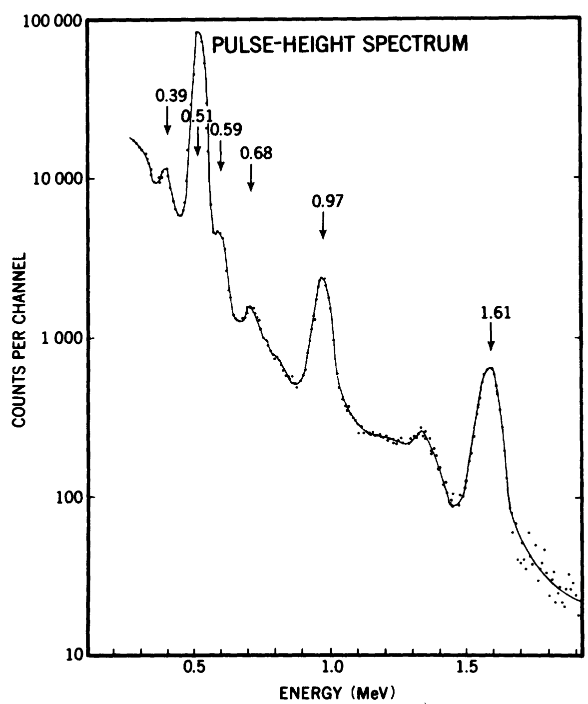

FIG. 2. A pulse-height spectrum for the activity generated in the magnesium oxide sample is shown. The energies given by arrows are due to decay of ^{25}Na at 0.39, 0.59, 0.97, and 1.61 MeV. The 0.51-MeV peak is due to annihilation of positrons from ^{15}O. The 0.68-MeV peak results from accidental summing.

nances with peak energies of 17.6, 22.6, 25.2, and 29.6 MeV and peak cross sections of 2.1, 15.7, 5.7, and 7.6 mb, respectively. In the high-resolution photoneutron works of Fultz *et al.*[6] and Ishkhanov *et al.*,[7] groups of resonances centered around 17.5, 22, and 25 MeV can be easily identified, but the experimental energy range is insufficient to draw conclusions at 30 MeV. Since the energies of the photoneutron resonance groups and our (γ, p) peaks agree quite well, we hypothesize that they have similar origins, and in the following we will compare peak cross-section values.

The 17.5-MeV group has a smoothed photoneutron peak cross section of about 20 mb, while that of the 22-MeV group is about 23 mb.[6] This would indicate that the average photon absorption cross section is comparable in the two regions. However, the ratio of the peak cross section at 17.6 MeV to that at 22.6 MeV for the (γ, p) result is only 0.13. The qualitative explanation for this small ratio was first discussed by Morinaga[2] and later by Titze, Goldmann, and Spamer.[4] It was pointed out that the high (γ, p) reaction threshold of 14.15 MeV means that Coulomb barrier suppression of proton emission is substantial for the 17.5-MeV group but not nearly so important at about 22 MeV, assuming ground-state transitions.

In an attempt to test this explanation we have calculated the barrier penetration probabilities P for protons in magnesium, after the manner of Christy and Latter,[22] using tabulated values of the Coulomb wave functions as given by Bloch *et al.*[23] We have used functions for p-wave protons, since the 1^- giant-resonance states in ^{26}Mg decay to the $\frac{5}{2}^+$ ground state in ^{25}Na via proton emission. The radius parameter used was $r_0 = 1.33$ fm, as given by Hofstader[24] for ^{24}Mg. The ratio obtained from these calculations is

$$P(17.6)/P(22.5) = 0.4\,.$$

This is inadequate to explain the experimental peak cross-section ratio of 0.13. An admixture of f-wave emission is required to explain our results on the basis of barrier penetration alone.

Morinaga[2] has suggested that Coulomb barrier effects would not be sufficient to explain differences in (γ, n) and (γ, p) cross sections in ^{25}Mg and ^{26}Mg. His hypothesis is that proton emission is favored for the higher isospin excitations while neutron emission is favored for the lower isospin excitations. If p-wave emission is dominant, our results support this idea, since the 17-MeV group is the $T = 1$ group and the 22-MeV group is the $T = 2$ group.

The relationship between the energy groups and the isospin is illustrated in Fig. 4. The isospin values for the ^{26}Mg giant-resonance groups were suggested to Titze, Goldmann, and Spamer[4] and confirmed by Wu and Firk.[5] Notice that decay of the $T = 2$ giant-resonance group to the $T = \frac{1}{2}$ ground state of ^{25}Mg by neutron emission is forbidden.

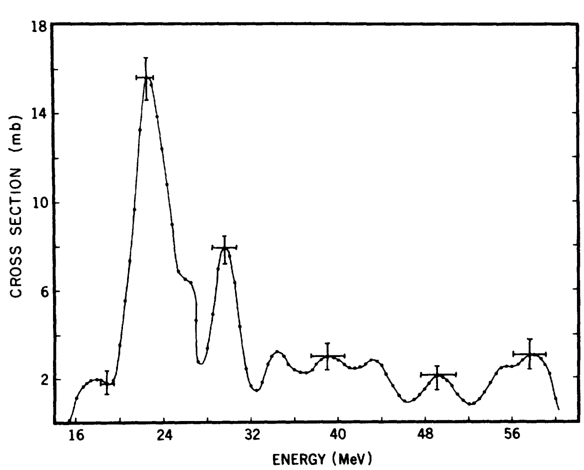

FIG. 3. The cross section for the ^{26}Mg$(\gamma, p)^{25}$Na reaction is shown.

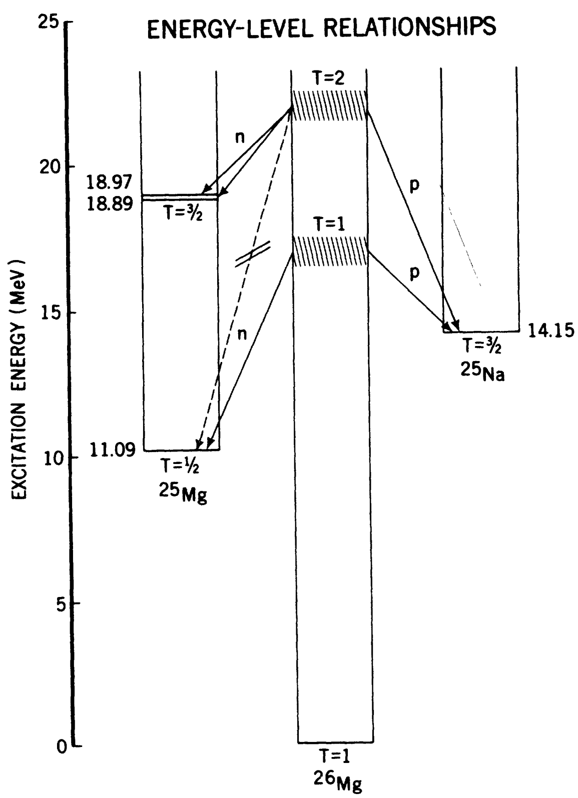

FIG. 4. Energies and isospins involved in the decay of giant-resonance states in ^{26}Mg by neutron and proton emission are shown.

Confirmation of the isospin assignments was based on this fact.

The isospin sum-rule results of Hayward, Gibson, and O'Connell[25] can be used to calculate the ratio of the integrated cross section for $T=2$ states to that for $T=1$ states. The result is about 0.8 for ^{26}Mg for the groups at 22.0 and 17.5 MeV, respectively. Fultz *et al.*[6] obtain a larger experimental ratio of about 2 for this result. To explain the discrepancy they propose a splitting in the isospin groups because of deformation of the ground state of ^{26}Mg. Thus, the cross section between 20 and 28 MeV is said to consist of two groups, the $T=2$ group at 22 MeV and another $T=1$ group at about 25 MeV. To complete the picture they predict the existence of another $T=2$ group at about 30 MeV.

The (γ, p) results of Fig. 3 have a very prominent maximum at 29.6 MeV which in part, at least, may be due to $T=2$ states. The integrated cross-section ratio for this 29.6-MeV maximum compared to the maximum at 25.2 MeV is 1.33. This is not consistent with the sum-rule results and further indicates that proton emission may be favored from the $T=2$ states. However, smaller maxima in this energy region have also been reported in ^{24}Mg$(\gamma, n)^{23}$Mg, ^{27}Al$(\gamma, n)^{26}$Al, and ^{28}Si$(\gamma, n)^{27}$Si[11,12] cross sections, possibly due to $E2$ absorption, which makes these cross-section ratios difficult to interpret.

B. Cross section at higher energies

No other results have been reported at energies above the giant resonance in the $2s$-$1d$ shell, so comparison must be made with photoneutron data for other $2s$-$1d$-shell targets. Low-resolution total neutron measurements by Cost *et al.*[26] indicate that photoneutron cross sections are substantial above the giant resonance. Secondary high-energy maxima in photoneutron cross sections for $2s$-$1d$-shell nuclei including ^{24}Mg have been reported.[10-14] In this light the present photoproton results are not surprising. The excitation energy is so substantial that nucleons in deep-lying shells are most likely involved. This has been discussed previously by Cook, Anderson, and Englert.[15] Hartree-Fock calculations by Brueckner, Lockett, and Rotenberg[27] and Pal and Stamp[28] indicate that the $1s$ nucleons are bound by 50–70 MeV for $2s$-$1d$ nuclei. Experimental evidence from $(e, e'p)$ and $(p, 2p)$ measurements[29,30] is in essential agreement with these predictions. Thus, we suggest that the 49.0- and 57.9-MeV maxima in our cross section are associated with absorption transitions from the $1s$ shell; $1p$ absorption could account for the intermediate-energy cross section.

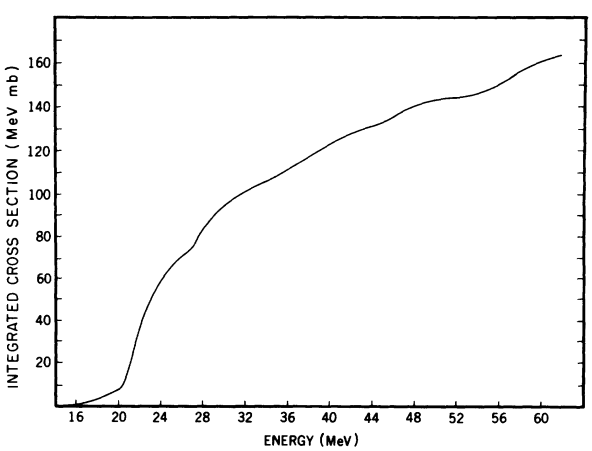

FIG. 5. The integrated cross section for the ^{26}Mg$(\gamma,p)^{25}$Na reaction is displayed as a function of energy.

C. Integrated cross section

Figure 5 contains a plot of the integrated cross section for the (γ, p) reaction in ^{26}Mg as a function of energy. Integrated cross sections for this reaction from the low-resolution data of Katz and Cameron[8] and Katz *et al.*[9] are 85 and 70 MeV mb, respectively, integrated to about 26 MeV. The cross section integrated to 26 MeV obtained from the present data is 72 ± 8 MeV mb. Thus, our results agree reasonably well with earlier data.

The photoneutron integrated cross section reported by Fultz *et al.*[6] is 226 MeV mb at 28 MeV, of which 68 MeV mb is attributed to the $(\gamma, 2n)$ reaction, leaving 158 MeV mb associated with the (γ, n) and (γ, np) reactions. This compares with 80 ± 9 MeV mb from the present (γ, p) results to 28 MeV. The total cross section for the (γ, n), $(\gamma, 2n)$, (γ, np), and (γ, p) reactions integrated to 28 MeV is

$$\int_0^{28} \sigma\, dE = 306 \text{ MeV mb}.$$

This comprises nearly all of the cross section expected at this energy since the $(\gamma, 2p)$ threshold is at 24.8 MeV and the reaction is barrier inhibited. This value is 79% of the dipole sum-rule result with no exchange contribution.[31]

The ratio of integrated cross sections is

$$\int_0^{60} \sigma\, dE \Big/ \int_0^{28} \sigma\, dE = 2.0$$

for the ^{26}Mg$(\gamma, p)^{25}$Na reaction. Similar ratios for integrated photoneutron cross sections in ^{24}Mg and ^{28}Si are 1.8 and 2.1, respectively.[11,12] Using the ratio of 2, the projected total integrated cross section to 60 MeV will be

$$\int \sigma\, dE \approx 600 \text{ MeV mb}.$$

This result is considerably in excess of the theoretical estimate of 521 MeV mb by Gell-Mann, Goldberger, and Thirring[32] for the integrated absorption cross section to 150 MeV (including absorption of all multipoles).

[1]E. G. Fuller, H. M. Gerstenberg, H. Vander Molen, and T. C. Dunn, National Bureau of Standards Publication No. 380 (1973).
[2]H. Morinaga, Phys. Rev. 97, 444 (1955).
[3]S. Fallieros, B. Goulard, and R. H. Venter, Phys. Lett. 19, 398 (1965).
[4]O. Titze, A. Goldmann, and E. Spamer, Phys. Lett. 31B, 565 (1970).
[5]C. P. Wu and F. W. K. Firk, Phys. Lett. 32B, 675 (1970).
[6]S. C. Fultz, R. A. Alvarez, B. L. Berman, M. A. Kelly, D. R. Lasher, T. W. Phillips, and J. McElhinney, Phys. Rev. C 4, 149 (1971).
[7]B. S. Ishkhanov, I. M. Kapitnov, E. V. Laxutin, I. N. Piskarev, and V. G. Shevchenko, Nucl. Phys. A186, 438 (1972).
[8]L. Katz and A. G. W. Cameron, Phys. Rev. 84, 1115 (1951).
[9]L. Katz, R. N. H. Haslam, J. Goldemburg, and J. G. V. Taylor, Can. J. Phys. 32, 580 (1954).
[10]D. W. Anderson, B. C. Cook, and T. J. Englert, Nucl. Phys. 83, 584 (1969).
[11]D. W. Anderson, B. C. Cook, and T. J. Englert, Nucl. Phys. A127, 474 (1969).
[12]D. W. Anderson, A. J. Bureau, B. C. Cook, and T. J. Englert, Phys. Rev. 183, 978 (1969).
[13]D. W. Anderson, A. J. Bureau, B. C. Cook, T. J. Englert, and R. E. Schramm, Nucl. Phys. A156, 74 (1970).
[14]D. W. Anderson, R. F. Petry, and H. J. Fischbeck, Radiat. Res. 50, 33 (1972).
[15]B. C. Cook, D. W. Anderson, and T. J. Englert, Phys. Lett. 26B, 341 (1968).
[16]D. W. Anderson and S. C. Swift, Phys. Med. Biol. 15, 349 (1970).
[17]J. S. Pruitt and S. R. Domen, National Bureau of Standards Nomograph No. 48 (1962).
[18]D. E. Alburger and D. H. Wilkinson, Phys. Rev. C 3, 1957 (1971).
[19]B. C. Cook, Nucl. Instrum. Methods 24, 308 (1963).
[20]L. I. Schiff, Phys. Rev. 83, 252 (1951).
[21]B. C. Cook, J. E. E. Baglin, J. N. Bradford, and J. E. Griffin, Phys. Rev. 143, 712 (1966).
[22]R. F. Christy and R. Latter, Rev. Mod. Phys. 20, 185 (1948).
[23]I. Bloch, M. D. Gull, Jr., A. A. Broyles, W. G. Bouricious, B. E. Freeman, and G. Breit, Rev. Mod. Phys. 23, 147 (1951).
[24]R. Hofstader, Rev. Mod. Phys. 28, 214 (1956).
[25]E. Hayward, B. F. Gibson, and J. S. O'Connell, Phys. Rev. C 5, 846 (1972).
[26]S. Costa, F. Ferrero, S. Ferroni, B. Minetti, C. Molino, and R. Malvano, Phys. Lett. 6, 226 (1966).
[27]K. A. Brueckner, A. M. Lockett, and M. Rotenberg, Phys. Rev. 121, 255 (1961).
[28]M. K. Pal and A. P. Stamp, Phys. Rev. 158, 924 (1966).
[29]V. Amaldi, Jr., G. Campos Venuti, G. Costellessa, E. DeSanctis, S. Fullani, R. Lombard, and P. Salvadori, *Proceedings of the International Conference on Nuclear Physics, Gatlinburg, Tennessee, 12–17, September 1966*, edited by R. L. Becker and A. Zucker (Academic, New York, 1967).
[30]G. Jacob and T. A. J. Maris, Rev. Mod. Phys. 38, 121 (1966).
[31]J. S. Levinger and H. A. Bethe, Phys. Rev. 78, 115 (1950).
[32]M. Gell-Mann, M. L. Goldberger, and W. E. Thirring, Phys. Rev. 95, 1612 (1954).