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Photoneutron cross sections for ^{17}O

J. W. Jury,* B. L. Berman, D. D. Faul, P. Meyer, and J. G. Woodworth
Lawrence Livermore Laboratory, University of California, Livermore, California 94550

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Photoneutron cross sections involving the emission of one and two neutrons from ^{17}O have been measured over the energy interval 8.5 to 39.7 MeV using monoenergetic photons from positron in-flight annihilation. The 6-MeV wide giant dipole resonance is observed to be centered at 23 MeV and a pygmy resonance is seen at about 13 MeV. Such structure as is apparent in the cross sections is not as pronounced as for the cases of ^{16}O and ^{18}O. Comparison of the total photoneutron cross section with recent ground-state data indicates that much of the pygmy resonance decays to the ground or first excited state of ^{16}O, but that the giant dipole resonance decays mainly to highly excited states in the daughter. Excellent agreement is observed between the present results and a recent two-particle, one-hole shell-model calculation of the isospin-split giant dipole resonance states for this nucleus. New photoneutron cross-section results for ^{16}O up to 39.7 MeV are reported as well.

[NUCLEAR REACTIONS ^{17}O(γ,n), $E_\gamma = 8.5$–39.7 MeV and ^{16}O(γ,n), $E_\gamma = 15.9$–39.7 MeV; measured 4π neutron yield for monenergetic photons; $\sigma(E_\gamma, 1n)$, $\sigma(E_\gamma, 2n)$, integrated cross sections, isospin splitting of the giant resonance for ^{17}O.]

I. INTRODUCTION

A recent series of experiments at the Lawrence Livermore Laboratory and at the University of Toronto was undertaken in order to investigate aspects of the nuclear photoeffect in light nuclei having one or two neutrons outside of a closed shell. Ground-state photoneutron cross sections have been obtained for ^{13}C, ^{17}O, and ^{18}O (Refs. 1–3) using the neutron-time-of-flight technique at the University of Toronto and total photoneutron cross sections have been obtained for ^{13}C and ^{18}O (Refs. 4, 5) using monoenergetic photons and a 4π neutron detector at Lawrence Livermore Laboratory. This paper reports the measurement of the total photoneutron cross section for ^{17}O, thus completing the oxygen series and allowing for the first time a comparison of the photoneutron cross sections for all the stable oxygen isotopes, viz. ^{16}O, ^{17}O, and ^{18}O.

A common and interesting feature of many light nuclei with one or more extra-core nucleons is the presence of a pygmy resonance at energies below the giant dipole resonance (GDR). This pygmy-resonance effect is observed clearly in the photoreaction cross sections for ^{13}C and ^{18}O. In the latter case, this resonance is large (about one half of the magnitude of the GDR) and quite broad (nearly 7 MeV wide), and appears to consist of several sharp resonances. Attempts to describe this phenomenon theoretically have met with varying degrees of success. For example, there is good agreement between the calculations of Kissener *et al.*[6] and Maragoni, Ottaviani, and Saruis[7] and the observed pygmy resonance for ^{13}C; however, a calculation by Albert *et al.*[8] predicts only a small amount of pygmy strength for ^{13}C and nearly none at all for ^{17}O. Our recent measurement of the ^{17}O(γ, n_0)^{16}O cross section[2] indicates the presence of some strength in the ground-state channel in the energy region below 20 MeV, where a pygmy resonance might be expected. This ground-state measurement, with its high energy resolution, did delineate many individual and relatively narrow resonances in this region but did not show any evidence for the bulk of the giant dipole resonance at higher energies. This suggests that the GDR in ^{17}O decays to the excited states in the ^{16}O daughter, possibly because the isospin of the GDR states prevents significant neutron decay to the $T=0$ ground state of ^{16}O.

The ^{17}O nucleus can be excited by electromagnetic dipole radiation only to isospin $T_< = \frac{1}{2}$ and $T_> = \frac{3}{2}$ states. It is expected that an isospin splitting of the absorption strength occurs with most of the $T=\frac{1}{2}$ states being lower in energy than most of the $T=\frac{3}{2}$ states. Assuming good isospin, the (γ, n_0) reaction to the $T=0$ ground state of ^{16}O excludes transitions from the $T=\frac{3}{2}$ states and thus cannot by itself illustrate the isospin-splitting effect in this nucleus. [Such isospin splitting was seen clearly for ^{18}O (Ref. 5).]

Consequently, a measurement of the total photoneutron cross section for ^{17}O is required (a) to locate and identify any pygmy-resonance strength and to compare it with the GDR; (b) to study the GDR itself and to investigate its decay mechanisms in order to identify any isospin splitting of the photon absorption strength between $T_<$ and $T_>$ regions; (c) to compare this cross section with the theoretical result of Albert *et al.*,[8] who have employed a two-particle, one-hole (2p-1h) shell model to calculate isospin-split GDR states; and (d) to make possible a detailed comparison of the total photoneutron cross sections for ^{16}O, ^{17}O, and ^{18}O in order to see the effect on the GDR of progressively adding additional neutrons to the closed-shell ^{16}O core.

II. EXPERIMENTAL PROCEDURES

A detailed description of the experimental facilities and procedures is given in Refs. 4 and 5, and additional information can be found in Ref. 9. Only a brief summary of the procedures is presented here.

A positron beam from the Lawrence Livermore Laboratory Electron-Positron Linear Accelerator was directed upon a 0.76-mm thick beryllium annihilation target. The resulting annihilation photons and accompanying bremsstrahlung passed through an ionization-chamber beam monitor, and were then incident upon the photonuclear sample at the center of a 4π neutron detector. This detector consists of a 61-cm cube of paraffin containing 48 BF_3 tubes arranged in four concentric rings around the beam line. Neutron moderation in the paraffin causes the ratio of counts in the outer ring to those in the inner ring (the ring ratio) to provide a measure of the average neutron energy, and hence the detector efficiency, at each bombarding photon energy used.

The energy of the positrons was varied so that the annihilation-photon energies ranged from 8.5 to 40 MeV. The measurements were repeated using electrons so that the bremsstrahlung-induced photoneutrons could be subtracted to yield only those events produced by the quasimonochromatic annihilation photons. The resolution (FWHM) of the system ranged from approximately 220 keV at $E_\gamma = 8.5$ MeV to 300 keV at $E_\gamma = 40$ MeV (see Ref. 9).

For each experimental run, the number of neutrons detected by each ring of BF_3 tubes was recorded; a multiplicity analysis of these data enabled the $(\gamma, 1n)$ and $(\gamma, 2n)$ cross sections to be extracted simultaneously and independently.

The sample characteristics are of particular interest in this experiment because of the relative scarcity of significant quantities of enriched ^{17}O. The 114-g "^{17}O" sample consisted of 59 g of ^{17}O in the form of enriched H_2O with an isotopic purity of 54.8%, and of ^{16}O and ^{18}O contaminants which constituted 34.6% and10.6%, respectively. This water sample was held in a thin-walled right-circular Lucite cylinder of diamter 38 mm and length 100 mm.

In order to facilitate subtraction of the ^{16}O and ^{18}O contaminants, measurements also were made at each energy with samples of $H_2{}^{16}O$ and $H_2{}^{18}O$, as well as with an empty Lucite container (sample blank). All of the water samples had nearly identical dimensions and masses as the enriched $H_2{}^{17}O$ sample. Furthermore, all of the Lucite containers were of identical mass, which permitted accurate subtraction of the sample-blank data.

III. DATA REDUCTION

After a small (never greater than a few percent) correction for the pileup of counts in the detector, the measured or interpolated neutron yields for runs using electrons were normalized to equal ion-chamber readings and were subtracted from the corresponding yields obtained with positrons at each energy. This was done for each of the three water samples and for the sample blank. Appropriately normalized sample-blank yields then were subtracted from the net counts of each of the water samples.

At this stage in the data processing, the ^{16}O and ^{18}O data were subtracted from the "^{17}O" data, appropriately normalized to the masses of these contaminants in the sample. It was noted, however, that the data for the ^{16}O and ^{18}O samples could be converted to photoneutron cross sections and that these would represent new and independent measurements for these nuclei. Consequently, in parallel to the continued processing of the net ^{17}O data, the net ^{16}O and ^{18}O data also were converted to photoneutron cross sections. This procedure has been described in detail previously[4,5] and involved (a) a correction for neutron multiplicity in order to ascertain the true number of single- and double-neutron events in each ring, (b) a correction for the detector efficiency for each point using the measured ring ratio (and thus the average neutron energy), (c) a correction for (atomic) attenuation of photons in the sample, and finally (d) the conversion to cross-section units using the calibrated ion-chamber response per annihilation photon and the number of sample nuclei in the beam.

The resulting ^{18}O cross section was compared at all energies to our recently-reported results (Woodworth *et al.*[5]), for which the same facility was used. The two measurements were found to yield identical results to within the small statistical errors on each data point.

The resulting ^{16}O cross section is shown in Fig. 1. In addition to the fact that this represents a new

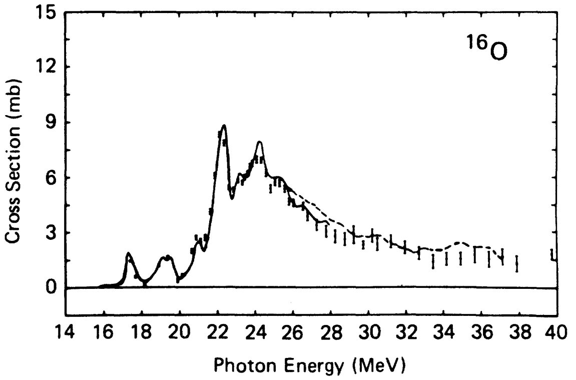

FIG. 1. The ^{16}O(γ, n_{tot}) cross section measured in the present experiment (data points), which enables the subtraction of the ^{16}O contaminant in the ^{17}O sample, is compared with previous measurements made at Livermore (solid line; Ref. 10) and at Giessen (dashed line; Ref. 11). The result of a measurement made at Saclay (not shown; Ref. 12) has the same shape as the present data but is approximately 15% higher.

measurement of the photoneutron cross section for ^{16}O, it also serves as a measure of the reproducibility of the experimental technique. The present data are compared in Fig. 1 with previous measurements of the ^{16}O(γ, n)^{15}O reaction; the good agreement of the results of previous measurements[10,11] with the present results is apparent [even though the present ^{16}O measurement was carried out to a statistical accuracy sufficient only for subtraction of the (approximately 35%) ^{16}O contaminant in the "^{17}O" sample]. [The absolute value of the ^{16}O(γ, n) cross section of Ref. 12 is somewhat larger than the other previous measurements as well as the present one, but otherwise agrees in the details.]

Another measure of the quality of the present data is an examination of the ($\gamma, 2n$) cross section for ^{17}O *below* its ($\gamma, 2n$) threshold of 19.7 MeV, as shown in Fig. 2. In this region, of course, the results should be zero. However, if the subtraction of the large ^{18}O($\gamma, 2n$) neutron yield had been carried out improperly, the resulting ^{17}O cross section would differ substantially from zero [the ($\gamma, 2n$) threshold for ^{18}O is 12.2 MeV]. As is evident in Fig. 2, the values of the ($\gamma, 2n$) cross section for ^{17}O are consistent with zero at all energies below the ($\gamma, 2n$) threshold in ^{17}O. This result allows strong confidence both in the accuracy of the subtraction of the ^{18}O contaminant in the "^{17}O" sample and in the values for the small but real ^{17}O($\gamma, 2n$) cross section above 20 MeV.

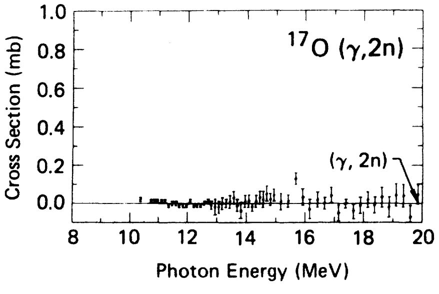

FIG. 2. The ^{17}O($\gamma, 2n$) cross section measured *below the* ($\gamma, 2n$) *threshold* and plotted on a magnified vertical scale illustrates the precision to which the approximately 11% contaminant of ^{18}O in the ^{17}O sample was subtracted to leave a cross section consistent with zero.

IV. RESULTS AND DISCUSSION

A. Cross sections

The single-photoneutron cross section for ^{16}O measured in this experiment is shown in Fig. 1. No nonzero ($\gamma, 2n$) cross section was observed, within the experimental limits, up to the highest energy measured (39.7 MeV).

The photoneutron cross sections for ^{17}O measured in this experiment are shown in Fig. 3: Part (a) shows the total photoneutron cross section $\sigma(\gamma, n_{\text{tot}}) = \sigma[(\gamma, n) + (\gamma, pn) + (\gamma, \alpha n) + (\gamma, 2n)]$, part (b) shows the single photoneutron cross section $\sigma(\gamma, 1n) = \sigma[(\gamma, n) + (\gamma, pn) + (\gamma, \alpha n)]$, and part (c) shows $\sigma(\gamma, 2n)$. The error bars indicate the statistical uncertainties only; it is estimated that the total systematic uncertainty arising from bremsstrahlung-yield subtraction, detector-efficiency correction, and ion-chamber calibration varies from about 7% below 20 MeV to somewhat less than 20% at the highest energies measured.

The existence of a pygmy resonance centered near 13 MeV, having a maximum value of 2 mb and a width of about 4 MeV, is immediately apparent in the ^{17}O(γ, n) cross section of Fig. 3(b). The GDR is centered at 23 MeV, having a maximum value of about 12.5 mb and a width of about 6 MeV. Other than these two major features, the ^{17}O(γ, n) cross section of Fig. 3(b) [or the (γ, n_{tot}) cross section of Fig. 3(a)] displays no sharp and prominent structure, very much unlike the case for ^{16}O or ^{18}O. [However, much fine structure exists in the ^{17}O(γ, n_0) cross section.[2]] This is not surprising, however; since three times as many spin states can be excited by dipole transitions from the spin-$\frac{5}{2}$ ground state of ^{17}O as from the spin-0 ground states of even-even nuclei, this large multiplicity of overlapping states smooths the total cross section. Indeed, this effect has been observed previously for the magnesium isotopes,[13] where the photoneutron cross section for ^{25}Mg (spin $\frac{5}{2}$) displays much less prominent structure than those for ^{24}Mg or ^{26}Mg. There are, how-

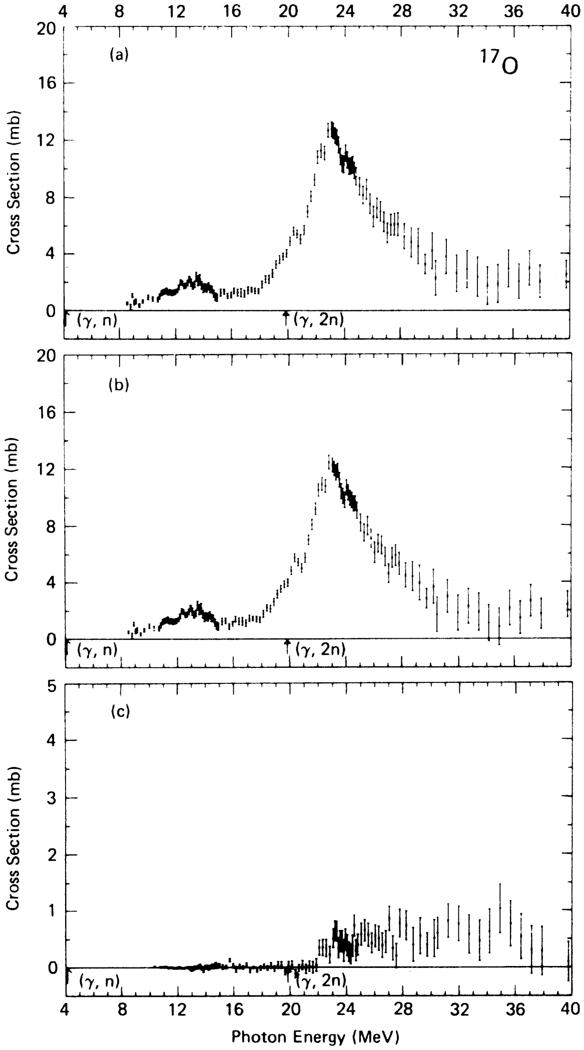

FIG. 3. Photoneutron cross sections for ^{17}O: Part (a) shows the total photoneutron cross section $\sigma(\gamma, n_{\text{tot}}) = \sigma[(\gamma, n) + (\gamma, pn) + (\gamma, \alpha n) + (\gamma, 2n)]$; part (b) shows the single photoneutron cross section $\sigma(\gamma, 1n) = \sigma[(\gamma, n) + (\gamma, pn) + (\gamma, \alpha n)]$; part (c) shows $\sigma(\gamma, 2n)$. The plotted error bars indicate the statistical uncertainties. The threshold energies are indicated by arrows in this and other plots.

ever, weak but definite peaks superimposed on the GDR for ^{17}O at 20.4, 22.2, and 24.1 MeV.

The ^{17}O(γ, 2n) cross section [Fig. 3(c)] has an average value of about 0.6 mb (above 22 MeV) and thus is very small with respect to the nearly 3.5-mb average for the ^{18}O(γ, 2n) cross section at similar energies.[5]

At higher energies (above 30 MeV) there is not apparent here the broad resonance seen near 35 MeV in ^{12}C, ^{13}C, ^{16}O, and (to a certain extent) in ^{18}O which has been described as representing an $s_{1/2}^{-1}$ excitation from the nuclear core. However, the statistical uncertainties in the present data at this energy easily could mask evidence for such a resonance in ^{17}O.

Norum, Bergstrom, and Caplan[14] have measured the elastic and inelastic scattering of electrons from ^{17}O at incident energies between 65 and 164 MeV. Their results indicate a broad resonance between 20 and 28 MeV which is no doubt the giant dipole resonance. Several weaker resonances superimposed on the GDR at energies near 21.7, 22.1, and 23.0 MeV also are in evidence. The last two agree well with some of the structure seen in the present experiment. However, the direct comparison of electron-scattering results with photoneutron cross sections can be misleading in that the former contain strength from several multipolarities, whereas the photoneutron reaction is almost entirely electric dipole in nature.

B. Average neutron energies

The ring ratios measured in the present experiment allow the extraction of information on the average energy of the emitted photoneutrons for each photon energy. This is shown in Fig. 4, where a dashed line has been drawn as a "best-eye fit" to the measured data. The diagonal solid line represents the average energy expected if all photoneutrons were emitted in (γ, n_0) decays (to the ground state of ^{16}O). It is seen that the measured data follow this line (as they must because no other channels are open) until about 10 MeV, where the (γ, n_1) and (γ, n_2) channels open. Apparently, transitions to the first two excited states of ^{16}O (6.05 MeV, $J^\pi = 0^+$ and 6.13 MeV, $J^\pi = 3^-$) are beginning to compete with the ground-

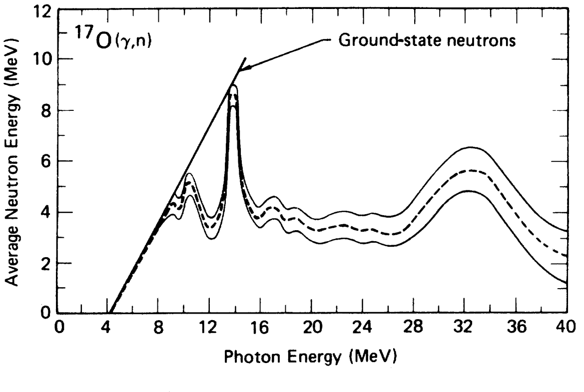

FIG. 4. The plot shows a representation of the average neutron energy vs photon energy for ^{17}O, which was obtained directly for each data point by the ring-ratio technique (see text). The light solid lines represent the estimated statistical uncertainty associated with the measurement. In addition to the nuclear information contained in this plot, the efficiency of the neutron detector is determined therewith for each data point.

state channel near about 11 MeV to lower the average neutron energy to about 4 MeV. (If all the strength suddenly switched from the ground to the first excited state at a photon energy of 11 MeV, the average neutron energy would drop from 6.5 MeV to 0.7 MeV, which is clearly not the case.)

However, near 13.5 MeV the average neutron energy returns to nearly its allowed ground-state value of about 8.5 MeV. This region corresponds to the highest peak observed in the pygmy resonance and indicates that in this narrow energy region the pygmy resonance decays primarily to the ground state of ^{16}O, even though channels to several excited states are open.

Above the pygmy-resonance region, the average neutron energy drops back to a value of about 4 MeV, and remains there with notable constancy across the GDR region.

Between 28 and 36 MeV a broad peak is observed, where the average neutron energy rises from 4 to 6 MeV. In order to account for this rise at these high excitation energies, where very many low-energy neutron-producing reactions are allowed, a significant number of transitions must be proceeding to relatively low-energy excited states in the ^{16}O daughter. Because the lowest-energy $T=1$ state in ^{16}O is at 12.8 MeV, it is reasonable to conclude that much of the strength near 32 MeV decays to $T=0$ states in ^{16}O. This in turn indicates the presence of $T=\frac{1}{2}$ strength near 32 MeV in ^{17}O, which might account for an appreciable fraction of the absorption strength at this energy. This possible $T_<$ strength near 32 MeV was predicted by the calculation of Harakeh, Paul, and Gorodetzkey,[15] but not by the theory (using a δ-function potential with a Soper exchange mixture) of Albert *et al.*[8] Appreciable strength also was observed in the ground-state channel by Johnson *et al.*[2] at this energy.

C. Comparison with the ^{17}O(γ,n_0)^{16}O differential cross section

Figure 5 shows a comparison of the present (γ, 1n) cross section with the ground-state differential cross section (at 98°) of Johnson *et al.*[2] in the energy interval from 8 to 20 MeV. It should be noted that the resolution of the latter measurement is somewhat better (about 200 keV at 12 MeV) than that of the present experiment (about 240 keV in this energy region); moreover, the ground-state measurement was carried out with a much finer spacing of data points.

Under the somewhat crude assumption of isotropic angular distributions of the emitted ground-state photoneutrons, there is very good agreement between the two results up to about 11 MeV. Near 12 MeV, angular distribution effects might be playing an important role in the ground-state cross section, and it is likely that the narrow resonance at 11.39 MeV reported by Johnson *et al.*[2] has an angular distribution which is peaked near 90°. No other evidence of this resonance has been reported. It appears as a broader resonance in the present data, which includes, however, transitions to excited states, as discussed above.

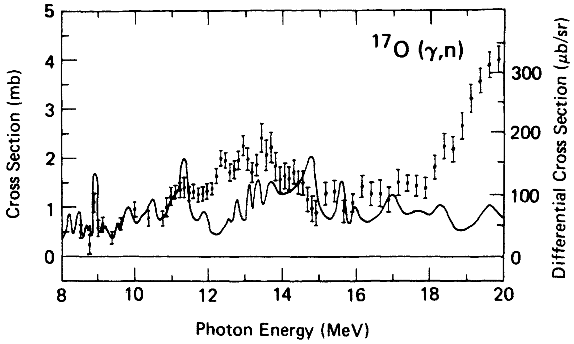

FIG. 5. The present results for the ^{17}O(γ,n) cross section at low energies (data points) are compared with the ground-state differential cross section of Ref. 2 (solid line). The vertical scale has been chosen to reflect a factor of 4π between the two cross-section scales. Below 10.2 MeV (the threshold for photoneutron emission to the first excited state of ^{16}O), the two results should be identical except for (a) angular-distribution effects in the differential measurement and (b) resolution differences.

The fact that the pygmy resonance is centered near 13.5 MeV is not obvious in the 98° ground-state results. Instead, there are three narrow resonances near this energy, at 13.06, 13.30, and 13.68 MeV,[2] which, even together, do not account for the total strength seen in the present results. This not only reflects some strength feeding excited-state transitions, but also the possibility exists that enough $E2$ or $M1$ absorption strength is present near 13.5 MeV to cause the angular distribution of the ground-state photoneutrons to be strongly forward or backward peaked. Also, the strong ground-state resonance at 14.65 MeV[2] is not apparent in the present data. Here, the average neutron energy (Fig. 4) indicates the presence of considerable non-ground-state transition strength, which easily could mask the existence of a narrow ground-state resonance (especially if the angular distribution were sharply peaked near 90°). In order to resolve these questions unambiguously, a measurement of the photoneutron angular distributions should be made.

Finally, above 18 MeV, the present data begin to exhibit the giant resonance, which is not manifested in the ground-state results. In fact, a comparison of the two experiments at higher energies shows that there is little evidence for the GDR in the ground-state cross section.

Assuming photoneutron isotropy, the integrated ground-state cross section from 20 to 26 MeV is about 8 ± 1 MeV mb, whereas the present (γ, n_{tot}) measurement yields a value of 51 ± 5 MeV mb for this (GDR) region. Also, the present experiment shows that the average photoneutron energy in the region of the GDR (23 MeV) is at a nearly constant value of ~4 MeV, which suggests that when the giant-resonance states in ^{17}O decay by neutron emission, highly excited states in ^{16}O (with an average energy of about 15 MeV) are populated preferentially. Many of these ^{16}O states will be $T=1$ in nature and probably will be fed from the $T=\frac{3}{2}$ part of the GDR in ^{17}O. However, in order to determine the isospin strength distribution of the total photonuclear reaction cross section for ^{17}O, the (γ, p) cross section must be known, as is the case for ^{18}O (Refs. 5, 16); such a measurement clearly is needed for ^{17}O as well.

The comparison of total vs ground-state cross sections in the pygmy- and giant-resonance regions reveals a strong similarity between the photoneutron reactions in ^{17}O and ^{13}C. For the case of ^{13}C (Ref. 4), a pygmy resonance was observed below the giant resonance and much of the giant-resonance strength was seen to decay to highly excited states in ^{12}C. This suggests a simple isospin-splitting model for ^{13}C, wherein the $T_<$ strength is concentrated mostly in the pygmy resonance (and to some small extent under the low-energy part of the GDR) and the $T_>$ absorption strength makes up most of the GDR and the cross section at higher energies. A sharp increase in the average neutron energy above the GDR (at about 30 MeV) also was observed for ^{13}C, which suggests the presence of appreciable $T_<$ strength there. This appears also to be the case for ^{17}O.

D. Integrated cross sections

The integrated cross sections and their moments for ^{17}O and ^{16}O measured in the present experiment are given in Table I, along with the values for ^{16}O from Refs. 11 and 12. Figure 6 shows running sums of the integrated cross sections for the $(\gamma, 1n)$, $(\gamma, 2n)$, and (γ, n_{tot}) reactions for ^{17}O [part 6(a)], and of their energy-weighted moments [parts 6(b) and 6(c)] as well. The integrated (γ, n_{tot}) cross section from threshold to 40 MeV is 120 ± 12 MeV mb, which is 47% of the Thomas-Reiche-Kuhn sum-rule strength. This can be compared with 26% and 72% for the total photoneutron channel for ^{16}O and ^{18}O, respectively. This rapid increase in the integrated strength in the photoneutron channel results only in part from the rapid increase in size of the pygmy resonance in proceeding from ^{16}O to ^{18}O. It also must be noted that the integrated photoproton strength is much higher for ^{16}O, where it is about twice as large as the photoneutron strength, than for ^{18}O, where it is less than one-third as large.[5,16] The strength of the photoproton channel for ^{17}O remains an open question; this provides another reason for measuring the ^{17}O(γ, p) cross section across this energy region.

E. Comparison with theory

The total photoneutron cross section measured in this experiment is compared in Fig. 7 with the photon-absorption cross section calculated by Albert *et al.*[8] This calculation employed a 2p-1h shell model with a harmonic-oscillator basis and allowed for absorption of $E1$ and $M2$ radiation. The calculation of the photon absorption cross section was carried out using two different types of residual forces: (a) a δ-function potential with a Soper exchange mixture and (b) a Tabakin potential. The present data support the theoretical results obtained using the former residual interaction much more strongly than those obtained with the latter. In fact, as is apparent from Fig. 7, the agreement between the calculated and measured location and distribution of the giant-resonance strength is very good indeed. As is the case for ^{13}C (Ref. 4), this theoretical treatment (using the Soper mixture) provides a good description of the giant resonance, its location, width, approxi-

TABLE I. Integrated cross sections and their moments.

Nucleus	reaction	E_{thresh} (MeV)[a]	$E\gamma_{max}$ (MeV)	σ_{int} (MeV mb)	σ_{-1} (mb)	σ_{-2} (mb MeV^{-1})	Reference
^{17}O	$(\gamma, 1n)$	4.14	39.7	111	4.94	0.256	This work
	$(\gamma, 2n)$	19.81	39.7	9	0.31	0.010	This work
^{16}O	$(\gamma, 1n)$	15.66	39.7	63	2.4	0.10	This work
	$(\gamma, 1n)$	15.66	37.0	63	2.4	0.09	Ref. 11
	$(\gamma, 1n)$	15.66	37.1	79	3.0	0.12	Ref. 12

[a] From A. H. Wapstra and K. Bos, At. Data Nucl. Data Tables 19, 215 (1977).

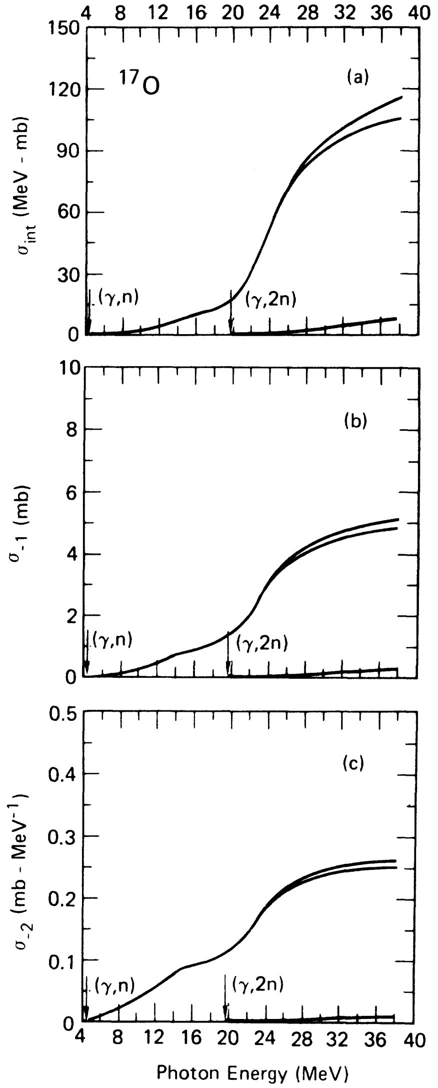

FIG. 6. Integrated photoneutron cross sections for ^{17}O are plotted as functions of the upper limit of integration. Part (a) shows the integrated cross sections $\sigma_{\rm int} = \int \sigma(E_\gamma)dE_\gamma$ for the $(\gamma, 2n)$ reaction (bottom curve), the $(\gamma, 1n)$ reaction (middle curve), and their sum, the $(\gamma, n_{\rm tot})$ reaction (top curve). Integrated cross sections over any desired limits can be obtained from these curves by subtraction. Parts (b) and (c) show the energy-weighted moments of the integrated cross sections $\sigma_{-1} = \int \sigma(E_\gamma)E_\gamma^{-1}dE_\gamma$ and $\sigma_{-2} = \int \sigma(E_\gamma)E_\gamma^{-2}dE_\gamma$, respectively.

mate amplitude, and isospin composition. However, the theory does not account adequately for the presence of the pygmy resonance either for ^{13}C or for ^{17}O.

F. Comparison with ^{16}O and ^{18}O

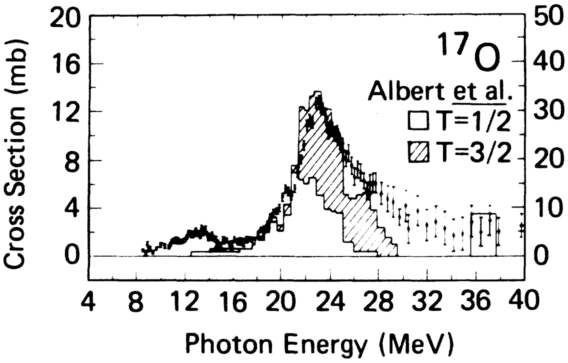

FIG. 7. The ^{17}O$(\gamma, n_{\rm tot})$ cross section is compared with the theoretical result of Albert *et al*. (Ref. 8), calculated using a δ-function potential with a Soper exchange mixture. Note that the calculated result is the total photoabsorption cross section (right-hand scale, in mb). The cross-section scales have been chosen to compare the shape and location of this theoretical result with the present measured result for the photoneutron channel.

Figure 8 presents a comparison of the $(\gamma, n_{\rm tot})$ cross sections for ^{16}O, ^{17}O, and ^{18}O over the energy range up to 40 MeV. Significant differences in these cross sections are immediately apparent. Clearly, the addition of neutrons to the ^{16}O "core" has a profound effect upon the photoneutron (as well as the photoproton[16]) cross section. To first order, the GDR remains centered at about 23.5 MeV in each case. As neutrons are added, the peak of the cross section increases from about 9 mb for ^{16}O to about 12 mb for ^{17}O and ^{18}O. (For the integrated strengths, see Sec. D above.) For the ^{18}O case, however, the $(\gamma, 2n)$ cross section[5] is very large (about 4 mb at 23 MeV, compared with about 0.6 mb for ^{17}O and zero for ^{16}O) and contributes significantly to the spreading of the GDR to higher and lower energies.

It also is apparent that the substantial sharp structure in the GDR for ^{16}O is not manifested in the ^{17}O case, probably for the reason given in Sec. A above. This structure (for ^{16}O) might come about from interference effects involving multiparticle, multihole excitations, as has been discussed in detail by O'Connell and Hanna.[17] For the case of ^{17}O, the shoulder near 22.2 MeV might correspond to the narrow resonance seen at 22.1 MeV in the ^{14}C$(\tau, \gamma_0)^{17}$O reaction, measured by Chang, Diener, and Ventura.[18] If the correspondence were significant, there would be good reason for including 3p-2h configurations in the theoretical treatment of ^{17}O. However, the structure in the GDR for ^{17}O, which might be caused by interference effects, is weak, and such interference effects are expected to be spread over many states; therefore, the failure of a theory to include such configurations is not a major flaw.

Another interesting feature of the comparison shown in Fig. 8 is the onset and strengthening of

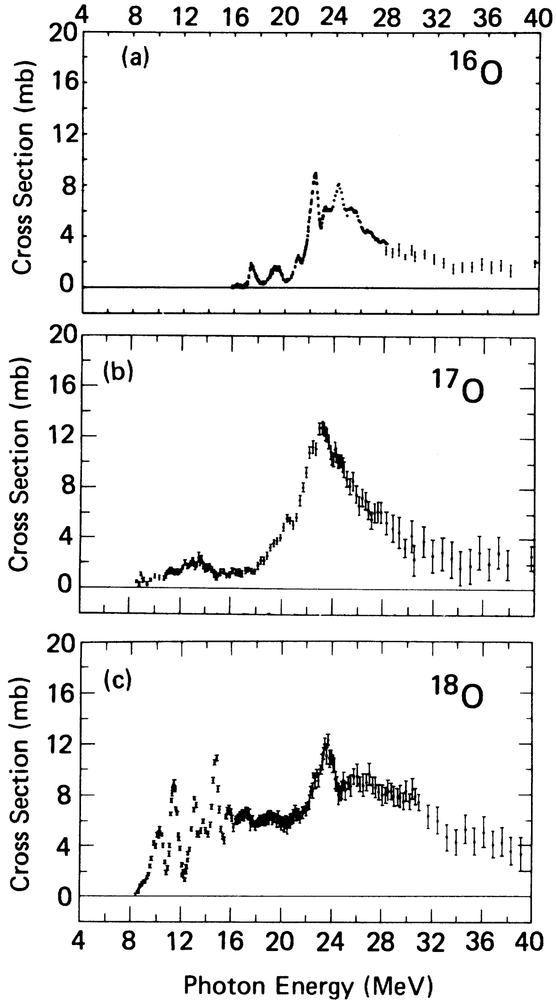

FIG. 8. Comparison is made of the total photoneutron cross sections for ^{16}O [part (a); the data below 28 MeV are from Ref. 10 and those above 28 MeV were measured in the present experiment], ^{17}O [part (b); present data], and ^{18}O [part (c); from Ref. 5]. Note that all of the cross-section scales are identical.

the pygmy resonance (from 10 to 16 MeV). For ^{16}O, this region is below the photoneutron threshold, but for ^{17}O the pygmy resonance is present and is beginning to display structure of the order of the experimental resolution (but see Ref. 2). For ^{18}O, this resonance has increased remarkably in magnitude (by a factor of 4) and is nearly completely broken up into a series of relatively narrow resonances. This trend suggests a model for the pygmy resonance as predominantly a single-particle effect in which the "valence" neutron (or neutrons) outside of the ^{16}O core plays the dominant role in photon absorption at energies below the GDR. In this model, the pygmy resonance represents a collective absorption of radiation by the nucleus leading immediately to the formation of an excited state formed by the elevation of one of the extra-core neutrons from the $d_{5/2}$ shell to a higher-energy orbital before being emitted from the nucleus. For predominantly $E1$ absorption, the single-particle excitations would be $d_{5/2} \rightarrow f_{7/2}$ and/or $d_{5/2} \rightarrow p_{3/2}$, and the emitted neutrons would have characteristic f- or p-wave angular distributions. This simple model accounts for the factor-of-4 enhancement of the pygmy-resonance strength (a factor of 2 in the dipole matrix element) for ^{18}O over that for ^{17}O noted above. This model also predicts that the pygmy resonance should decay exclusively to the ground state; this is supported to an extent by the comparison (presented in this paper) of the ^{17}O(γ, n) cross section with the ground-state measurement, and to a lesser extent by the similar comparison for ^{18}O (given in Ref. 5), which shows that the pygmy resonance for ^{18}O has a branching to the ground state of approximately 20% and to the first excited state of about 10% (also see Ref. 3).

A less naive model of the pygmy resonance could be based on the core-polarization effects of the valence neutron(s) and the corresponding "coexistence" of spherical and highly deformed configurations of ^{17}O and ^{18}O, as well as the role of similar effects built upon the deformed (or 4p-4h) configurations of ^{16}O. Recently, Hynes *et al.*[19] have investigated the magnetization distribution of ^{17}O, using elastic electron scattering. Their results indicate that core-polarization effects indeed play an important (but not the only) role in the electromagnetic structure of this nucleus. Once again, a measurement of the ^{17}O(γ, p) cross section is needed, in order to delineate the *shape* of the giant-resonance states in this channel for comparison with the strong photoproton structure in the GDR for ^{16}O and ^{18}O.

V. SUMMARY AND CONCLUSIONS

The photoneutron cross sections for ^{17}O obtained in this experiment provide a new source of information to aid in the description of light nuclei with one or more extra-core nucleons. The present results differ markedly from our recent ground-state measurement[2] in that they clearly delineate the giant dipole resonance. In addition, they elucidate the relative and absolute magnitude of the pygmy resonance near 13 MeV.

The results show that the $T=\frac{1}{2}$ pygmy resonance decays to the first few excited states in ^{16}O as well as to the ground state, which reflects the presence of multiparticle-hole configurations. Evidence, in the form of the average energy of the photoneutrons, is seen as well for some absorption strength proceeding through $T=\frac{1}{2}$ states near 32 MeV. Such information for the GDR region (near 23 MeV) suggests that much of the GDR strength decays to highly excited states in ^{16}O. This is significantly different from the case of ^{16}O, where only a few percent of the GDR strength decays to excited states in ^{15}O. This difference also suggests that 2p-1h (or higher-order) configurations play the dominant role in the photoabsorption process. The excellent agreement between the present results and the shell-model 2p-1h calculation of Albert *et al.*[8] supports this view. The low average photoneutron energy in the GDR region also suggests strongly that most of the GDR strength decays to $T=1$ states in ^{16}O, which implies a $T=\frac{3}{2}$ assignment for the main part of the GDR for ^{17}O, again in keeping with the prediction of Ref. 8.

Finally, these results permit mutual comparison of the photoneutron cross sections for ^{16}O, ^{17}O, and ^{18}O. Analysis of the similarities and differences among these cross sections provides us with information on such important nuclear phenomena as multiparticle, multihole interference effects, core polarization by "valence" nucleons, and the formation and decay of the giant and pygmy resonances. Combining the comparison of the (γ, n_{tot}) cross sections for the three stable oxygen isotopes given in Fig. 8 of this paper with the comparison of their (γ, n_0) cross sections given in Ref. 2 at last gives one a detailed view of the manifestation of these phenomena in the photoneutron reaction.

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*Permanent address: Department of Physics, Trent University, Peterborough, Ontario, Canada K9J 7B8.

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