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Photoneutron cross section for ^{16}O

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The photoneutron cross section for ^{16}O has been measured with monoenergetic photons from 17 to 33 MeV. This measurement was carried out by subtracting the photoneutron yield for Si from that for SiO_2, thus reducing the uncertainty in the neutron detection efficiency associated with the neutron moderation by the hydrogen in a water sample. The present cross-section results agree with the mean of several previous measurements with monoenergetic photons, and resolve a prior discrepancy at the 22.1-MeV peak. The measured average photoneutron energy is quite large in the photon energy region from 26 to 28 MeV, signifying that ground-state transitions dominate the (γ,n) cross section there.

NUCLEAR REACTIONS $^{16}O(\gamma,n)$, measured cross section and average photoneutron energy up to 33 MeV, monoenergetic photons.

INTRODUCTION

Five measurements of the photoneutron cross section for ^{16}O in the energy region of the giant dipole resonance (GDR) have been carried out with monoenergetic photons.[1–5] Each of these previous measurements used a water sample located in the center of a 4π slowing-down-type neutron detector, with a consequent uncertainty in the detector efficiency resulting from the moderation effects of the hydrogen in the water, as discussed in detail in Ref. 6. (For example, for the neutron detector at Livermore,[1,4,6] the effect of the presence of 120 g of water on the detector efficiency is about 7%.) Since there are some discrepancies among the results of these previous measurements, it is important to have another measurement of the $^{16}O(\gamma,n)$ cross section that is as independent as possible of these moderation effects. (Even though all the various discrepancies between previous measurements cannot necessarily be blamed on detector-efficiency problems, it should be noted that the analysis of the data of Refs. 2 and 3 did not take into account variations of the detector efficiency with neutron energy.) This paper reports such a measurement.

Independent measurements of the same cross section at several different laboratories also is indicative of the accuracy which state-of-the-art experimental techniques can achieve. For the case of the photodisintegration of ^{16}O, the partial photonuclear cross sections for all the major decay channels have been measured, thus allowing the total photonuclear cross section to be reconstructed from the sum of the partial cross sections. This summation has been found, in Ref. 7, to be in sharp disagreement with the total photonuclear cross section deduced from the photon transmission measurement of Ref. 8; up to 30 MeV, the integrated total cross section from Ref. 8 is $\sim 30\%$ larger than the sum of the integrated partial cross sections. Again, therefore, it is important to have an $^{16}O(\gamma,n)$ measurement that is nearly independent of moderation effects.

Finally, the determination of the average photoneutron energy $\bar{E}_n$ by the ring-ratio technique (see Ref. 9) is much improved by the reduction of these moderation effects, and the variation of $\bar{E}_n$ with photon energy E_γ is an important measure of the interplay between collective and single-particle-hole excitation of the nucleus.

EXPERIMENT

A detailed account of the experimental procedures has been given previously.[6] A beam of positrons from the Lawrence Livermore National Laboratory Electron-Positron Linear Accelerator is incident on a 0.76-mm thick beryllium annihilation target. Positrons passing through the annihilation target are swept into a well-shielded dump hole. The bremsstrahlung and annihilation photons produced in the target pass through an ionization-chamber beam monitor before striking the photonuclear sample, which is at the center of an efficient 4π neutron detector. This detector consists of a 61-cm cube of paraffin in which 48 BF_3 tubes are arranged in four concentric rings around the beam line. Because of the neutron moderation in the paraffin, this arrangement allows a measure to be made of the average neutron energy from the sample via the "ring ratio," the ratio of the counts in the outer and inner rings. A multiplicity analysis of the number of neutrons recorded in each beam burst allows the (γ,n) and $(\gamma,2n)$ yields to be extracted simultaneously and independently.[9] The measurements are repeated using electrons so that the bremsstrahlung-induced photoneutrons can be subtracted to give the event rates produced by the annihilation photons alone. For this experiment, the energy of the positrons was varied in approximately 200-keV steps from 17 to 33 MeV. The resolution of the system ranged from about 200 keV (FWHM) at $E_\gamma = 17$ MeV to around 400 keV at 33 MeV.

The oxygen sample for this measurement consisted of 97.3 g of SiO_2 in a thin-walled Lucite container. Measurements also were performed with 51.3 g of metallic silicon in a nearly identical container as well as with an empty container, so that the appropriate subtractions could be made (see below). At intervals throughout the run the measurements were repeated without the annihilation target in place in order to determine the contributions from neutron backgrounds, cosmic rays, and BF_3 detector noise.

After correcting for (small) pileup effects and backgrounds, the oxygen yield was determined by subtracting the yield of the silicon metal sample from that of the silicon dioxide sample after sample mass correction. In addition, the silicon dioxide sample was found to contain 18% by mass of water (21.4 g). However, this was determined accurately by weighing the sample both before and after drying it in an oven after the completion of the experiment. The number of silicon atoms in each sample, and thus the normalization factor, was obtained with less than 1% uncertainty. Since the two samples had slightly different densities and were of different thicknesses, a correction also was made for the self-absorption of the photon beam in the samples. This amounted to an 8.2% correction to the normalization factor. The energy dependence of this correction was less than 5% over the energy range considered and therefore was ignored. The normalization factor was thus determined to better than 2%. It should be noted as well that since the effect of the water contained in the SiO_2 sample on the detector efficiency scales as the mass of hydrogen,[6] the moderation effect was reduced to $\sim 1\%$ for the measurements reported here.

The normalized photoneutron yields for SiO_2 and Si are shown in Figs. 1(a) and (b). Subtraction of the latter from the former gives the yield resulting from the oxygen alone, as shown in Fig. 1(c). This procedure was not necessary for the double-neutron yields, because the $(\gamma,2n)$ cross section for ^{16}O is very small in this energy range (see Refs. 2 and 5) and the resulting double-neutron yield from oxygen was insignificant.

From the net yield rate, the photoneutron cross section for oxygen was obtained. This procedure involves (a) a correction for the detector efficiency for each energy point using the measured ring ratio (see Refs. 1 and 9), (b) a correction for the (atomic) attenuation of photons in the sample, and finally (c) the conversion into cross-section units using the calibrated ion-chamber response per annihilation photon and the number of sample nuclei in the beam.

RESULTS

The present results for the $(\gamma,1n)$ cross section and the average photoneutron energy $\bar{E}_n$ for ^{16}O are shown in Fig. 2. As noted above, these results, which were obtained by subtracting the photoneutron yields for Si from those for SiO_2, constitute an independent check on the $^{16}O(\gamma,1n)$ cross section, since, unlike all of the other $\sigma(\gamma,n)$ values obtained with monoenergetic photons, these were obtained with a sample containing little hydrogen and hence they require almost no correction for photoneutron-moderation effects on the neutron detector efficiency. Again, no statistically significant $(\gamma,2n)$ events were observed [the $^{16}O(\gamma,2n)$ threshold is 28.9 MeV].

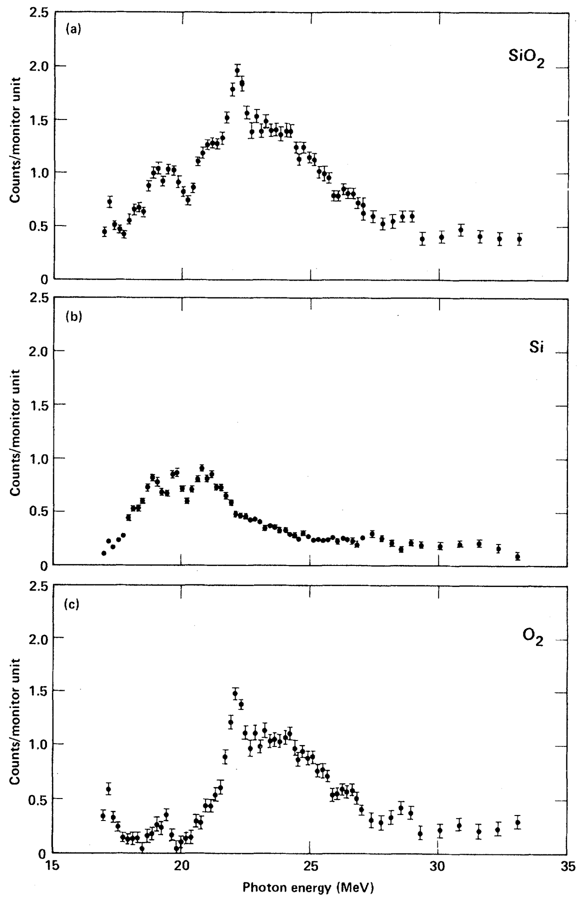

FIG. 1. Net single-photoneutron yield rates for the samples of (a) SiO_2, (b) Si metal, and (c) O_2. The yield rates for SiO_2 and Si have been corrected for all backgrounds, including those resulting from the positron bremsstrahlung and from the Lucite sample holders (see text). The yield rate from O_2 was obtained by subtraction of the yield rate for Si, properly normalized, from that for SiO_2.

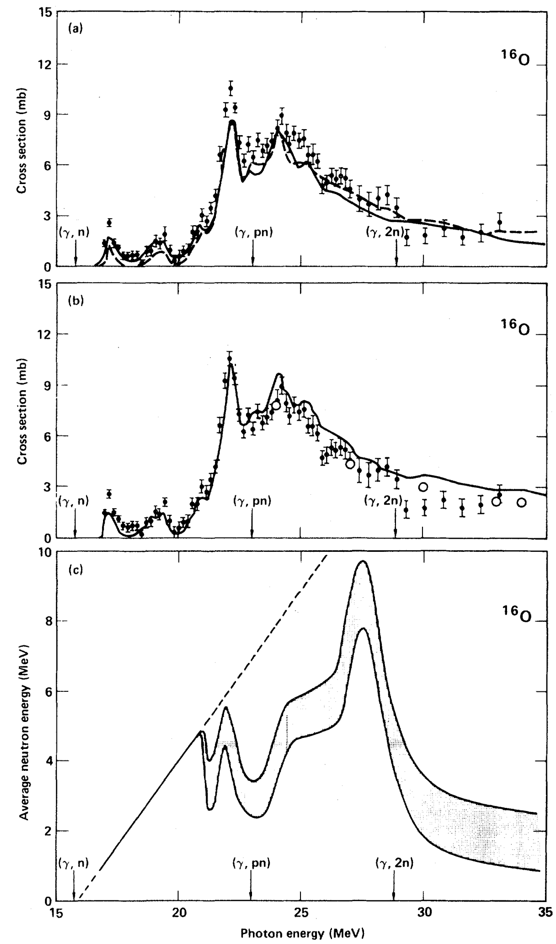

FIG. 2. Present results for ^{16}O compared with previous results: (a) $\sigma(\gamma,1n)$ from Livermore [combined results from Refs. 1 and 4 (see text), solid line], from Giessen (Ref. 3, dashed line), and present results (data points); (b) $\sigma(\gamma,1n)$ from Saclay [Ref. 2, solid line, and Ref. 5, open data points (whose uncertainties, which include systematic uncertainties as well, are smaller than the symbols)] and present results (solid data points); (c) present results for the average photoneutron energy $\bar{E}_n$ (shaded error band).

Figure 2(a) compares the present single-photoneutron cross section $\sigma(\gamma,1n)$ [note that this cross section includes the (γ,pn) channel] for ^{16}O (data points) with previous results obtained at Livermore (solid line) and at Giessen[3] (dashed line). The solid line in Fig. 2(a) represents a new evaluation of all previous Livermore results; those of Ref. 1 (shown graphically in Ref. 10) were shifted downward in energy by 150 keV relative to those of Ref. 4 in the light of the more recent data not only from Refs. 2–4 but from the present results as well. One sees that there is reasonable agreement among the three data sets; however, the present data are somewhat larger in magnitude than the earlier Livermore data between approximately 21 and 29 MeV and the Giessen data below ~26 MeV. It is interesting to note that the present data show a (not very well defined) peak in the $^{16}O(\gamma,n)$ cross section at ~28.5 MeV, as does the early data of Bramblett *et al.*,[1] but which does not appear in any more recent data set; this could be related to the structure in the average photoneutron energy (see below).

Figure 2(b) compares the present $^{16}O(\gamma,1n)$ cross section (data points) with the results from Saclay: recent results from that laboratory (Ref. 5) are shown as the open data points, and previous results (Ref. 2) are shown as the solid line. The present data agree very well indeed with the recent Saclay results, which, moreover, were taken in such a way as to be nearly independent of systematic uncertainties in the measurement of the photon flux (see Ref. 5 for details). But in spite of the fact that the earlier Saclay cross-section values are systematically higher than those of all other data sets obtained with monoenergetic photons above ~23 MeV, the present data are in good agreement with the data of Ref. 2 below that energy, and, in particular, at the 22.1-MeV peak. The present data are also in agreement with the earlier photoneutron-time-of-flight data of Jury *et al.*[11] near 22 MeV (10.0±0.4 mb at 22.1 MeV), thus resolving a long-standing discrepancy. It is very important as well that the value of the integrated cross section up to 30 MeV measured here, 54.8±5 MeV mb, is in excellent agreement with the mean value of 55±6 MeV mb from the work of Refs. 1–4, and thus confirms the discrepancy with the total photon-absorption results of Ref. 8. (We again refer the reader to Ref. 7 for an up-to-date discussion of both the values and the importance of the integrated cross sections for ^{16}O.)

The average energy of the photoneutrons $\bar{E}_n$ from ^{16}O, as measured by the ring-ratio technique, is shown in Fig. 2(c). Perhaps the most notable new result of the present measurement on ^{16}O is the clear delineation of a sharp rise in $\bar{E}_n$ just above 26 MeV, followed by an even sharper fall in this quantity below 30 MeV. An examination of the previous ^{16}O data, the cross-section results of which were reported in Ref. 4, verifies this behavior of $\bar{E}_n$. This indicates that in this energy region, particularly from 26 to 28 MeV, a large fraction of the photoneutrons from ^{16}O are emitted to the ground state of ^{15}O, which in turn means that $\sigma(\gamma,n_0)$ for ^{16}O is a large fraction of $\sigma(\gamma,n)$ there. Indeed, a comparison of recent (γ,n_0) results from Livermore[12] with the present $(\gamma,1n)$ data indicates that the ratio

$$\sigma(\gamma,n_0)/\sigma(\gamma,n)\simeq\tfrac{2}{3}$$

at 28 MeV. Also, the A_2 angular-distribution coefficient reported by Jury *et al.*[11] is approximately zero at 26–28 MeV, which is consistent with a dominant component of ground-state photoneutrons there. Finally, the sharp decrease in $\bar{E}_n$ above 28 MeV undoubtedly results from the onset of significant strength in the (γ,pn) channel there, which introduces many low-energy photoneutrons. In fact, the data of Ref. 2 show that $\sigma(\gamma,pn)$ rises to about half of $\sigma(\gamma,1n)$ by about 32 MeV. Although this kind of behavior for $\bar{E}_n$ just above the GDR has been seen before (e.g., see Refs. 13 and 4 for ^{13}C and ^{17}O, respectively), it is notable that it is true for ^{16}O as well, and probably implies significant single-particle-hole excitation of ^{16}O near 28 MeV, just as the relatively lower values for $\bar{E}_n$ in the central part of the GDR for ^{16}O and for many other nuclei as well imply significant collectivity of the GDR proper.

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