Photoproton Cross Section for ^{18}O as a Measure of the Effect of the Valence Neutrons on the ^{16}O Core*

B. L. Berman, D. D. Faul, R. A. Alvarez, and P. Meyer
Lawrence Livermore Laboratory, University of California, Livermore, California 94550
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The ^{18}O$(\gamma,p)^{17}$N cross section has been measured with monoenergetic photons from threshold to 30 MeV. The results show striking similarities and differences with the ^{16}O$(\gamma,p)^{15}$N cross section.

We have measured an important photonuclear cross section on an unusual nucleus by a novel technique with surprising results. The ^{18}O nucleus, lying in the periodic table at the beginning of the *s-d* shell, is unusual in that although it consists to first order simply of a pair of valence neutrons bound to the doubly magic ^{16}O core, it is reported to have a large value for $B(E2, 0\rightarrow 2)$, equal to 0.0048 b^2.[1] If this nucleus were purely rotational, this value for $B(E2)$ would imply a large average ground-state deformation $\bar{\beta}_2$, equal to 0.37. Of course, this is not actually the case,[1] but possibly the ^{18}O nucleus is described best by the "coexistence" of spherical and *very* deformed ($\beta_2 \gtrsim 0.6$) configurations. This makes it very interesting to measure the photo*proton* cross section for this nucleus, which, since the ^{16}O(γ,p) cross section has been studied extensively, should result in a direct measure of the effect of the presence of the valence neutrons on the deformation (or polarization) of the ^{16}O core. Furthermore, the ^{18}O nucleus is *unique* among stable nuclei in that its (γ,p) threshold (15.94 MeV) lies at a *higher* energy than its $(\gamma,2n)$ threshold[2] (12.19 MeV); this means that the residual nucleus from the ^{18}O(γ,p) process, namely ^{17}N, can decay by β^- emission to neutron-unstable states in ^{17}O. Therefore, the ^{10}O(γ,p) cross section can be measured by observing the resulting delayed neutrons. In fact, nearly all (95%)[3] ^{17}N nuclei decay to such neutron-unstable states with a lifetime[4] ($\tau_{1/2} = 4.16$ sec) which is ideal for the purposes of the measurement we have done. The results we obtained are surprising because of their striking similarities and differences with the ^{16}O(γ,p) cross section, as will be demonstrated below.

The few previous photonuclear measurements on ^{18}O all have been performed with continuous bremsstrahlung radiation sources. Prompt photoneutron measurements[5] have heretofore been limited to the energy region below the giant resonance, delayed photoneutron measurements[6] were not sufficiently detailed for any conclusions to be drawn regarding structure in the giant resonance, and prompt photoproton measurements,[7] done only at 90°, suffer from high detection thresholds and the inability to distinguish between the ground- and excited-state cross section. Also the only electron-scattering measurement[8] was done at 180°, which selectively excites only magnetic transitions.

The source of radiation for our experiment was the monoenergetic photon beam produced by the annihilation in flight of fast positrons from the Lawrence Livermore Laboratory electron-positron linear accelerator. The photon energy resolution was approximately 1%. The technique we used to measure the ^{18}O$(\gamma,p)^{17}$N cross section was to count the delayed neutrons from ^{17}N decay between beam bursts from the linac. This was made feasible by three conditions: (1) The 4.16-sec half-life of ^{17}N is short compared with the length of a run necessary to acquire sufficient statistics at a given incident photon energy (10–20 min), so that the activity was driven into a steady-state saturation condition quickly; (2) the half-life is long compared with the time interval between beam bursts (1/720 sec), so that there was no need to correct for the ^{17}N decay lifetime in the time during which the delayed neutrons were detected; and (3) the mean decay time of the BF_3-tube–plus–paraffin 4π neutron detector[9,10] was sufficiently short[10] (~ 90 μsec) so that the number of prompt photoneutrons detected during the delayed gate (delayed with respect to the linac beam burst by 675 μsec and 700 μsec wide) was negligible. The monitoring and calibration of the photon beam, the subtraction of the neutron yield resulting from the positron bremsstrahlung, and the details of the neutron detector have been published elsewhere.[9-11] The sample used consisted of 120 g of H_2O enriched to 96.5 at.% ^{18}O. It is worth noting that neutron backgrounds were negligible, consisting entirely of machine-off (cosmic-ray) background neutrons, since no material (other than ^{18}O) in or near the photon beam could be a source of delayed neutrons. Sample-blank and annihilation-target-out runs confirmed this fact.

The $^{18}O(\gamma,p)^{17}N$-cross-section results of this experiment are shown in Fig. 1, together with the cross sections for $^{16}O(\gamma,p)^{15}N$ and for $^{16}O(\gamma,n)^{15}O$ from the literature.[12] One immediately is struck by the similarity (except for scale) of the cross sections below about 21 MeV (the appearance of the peaks at 17.3, 19.2, and 20.8 MeV) as well as by the dramatic difference between the appearance of the two broad and prominent structures at 23.4 and 27.5 MeV in the $^{18}O(\gamma,p)$ cross section and that of the four narrower and more tightly clustered peaks at 22.3, 23.1, 24.2, and 25.2 MeV in the $^{16}O(\gamma,p)$ cross section. (It should be noted that the 23.4-MeV peak has a shoulder on

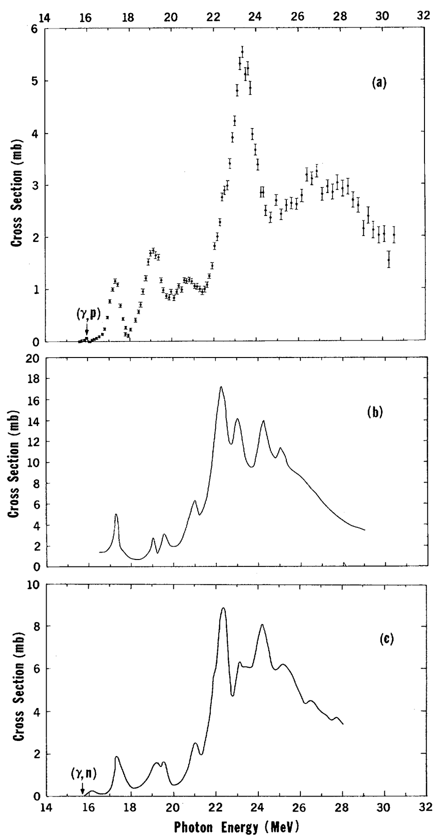

FIG. 1. (a) The $^{18}O(\gamma,p)^{17}N$ cross section measured in the present experiment compared with (b) the $^{16}O(\gamma,p)^{15}N$ and (c) the $^{16}O(\gamma,n)^{15}O$ cross sections taken from the literature (see text). Threshold energies (from Ref. 2) are indicated by the arrows. Solid lines are used to represent the ^{16}O cross sections because they have been synthesized from several experimental results; in any case, the relative precision of these results is good enough so that no important structure has been created or obscured by this procedure.

the low-energy side, at 22.4 MeV, and the 27.5-MeV structure perhaps is composed of two peaks, at about 26.6 and 28 MeV.)

The measured integrated cross section for the reaction $^{18}O(\gamma,p)$ is 29.8 MeV mb up to 30.6 MeV, compared with 81.2 MeV mb up to 29.0 MeV and 41.5 MeV mb up to 28.0 MeV for the reactions $^{16}O(\gamma,p)$ and $^{16}O(\gamma,n)$, respectively. It seems clear that the explanation of the difference in magnitude of a factor of 3 between the (γ,p) cross sections for ^{18}O and ^{16}O lies largely in the much greater number of competing reaction channels available in the ^{18}O case, chiefly the (γ,n), $(\gamma,2n)$, and (γ,pn) channels (feeding states in ^{17}O, ^{16}O, and ^{16}N), whose threshold energies are 8.05, 12.19, and 21.83 MeV, respectively.[2] This is made even more plausible by the fact that the $^{16}O(\gamma,p)$ cross section (whose threshold energy is 12.13 MeV) is so much larger than the $^{16}O(\gamma,n)$ cross section (threshold at 15.67 MeV) [Figs 1(b) and 1(c)], while the $^{16}O(\gamma,p_0)$ and $^{16}O(\gamma,n_0)$ cross sections, each consisting of a single channel, are comparable in magnitude.[13] It should be noted as well that there also is a difference in the relative sizes of the low-energy peaks; the 19.2-MeV structure is more prominent for ^{18}O than for ^{16}O.

Likewise, the expected large neutron widths for the giant-resonance states in ^{18}O will broaden them, and the presence of the valence neutrons might cause them to shift in energy to some extent. But although we cannot rule out this possibility in the absence of a detailed calculation, it seems unlikely that at the same time that the states below 21.5 MeV are not broadened very much and hardly shifted at all, the states above this energy should be broadened and shifted to a large enough extent to explain the observed difference in shape between the two (γ,p) cross sections.

One might expect naively that the 27.5-MeV hump in the $^{18}O(\gamma,p)$ cross section results from the deformation splitting of the giant resonance, but if one uses the hydrodynamic theory to compute the ground-state deformation from the 23.4- to 27.5-MeV splitting, one obtains $\overline{\beta}_2 = 0.20$, which is much less than the value $\overline{\beta}_2 = 0.37$ mentioned above, and appears to yield no deep insight into the physical process involved. In any case, one should not use the (γ,p) cross section alone for this determination, but rather the total photon-absorption cross section.

If one is tempted, on the other hand, to ascribe this splitting of the giant resonance to isopin effects, one obtains equally unsatisfactory results.

First, one expects that nearly all the $^{18}O(\gamma,p)$ cross section represents $T_>$ ($T=2$) strength because it lies in the same energy region as the ^{16}O cross sections (which must be $T_>$ because of the $\Delta T=+1$ selection rule for dipole transitions in self-conjugate nuclei). Second, one expects that nearly all the $T_<$ ($T=1$) strength is manifested in the photoneutron [(γ,n) and $(\gamma,2n)$] channels. Finally, the energy splitting should be given by something close to the empirical relation[14]

$$\Delta E = E(T_>) - E(T_<) = 55(T_0+1)/A$$

which yields a value greater than 6 MeV for ^{18}O.

One can speculate that the $^{18}O(\gamma,p)$ cross section should look like some sort of superposition of the (γ,p) cross sections for ^{16}O and ^{20}Ne, since the latter nucleus bears some resemblance to the deformed part of the ^{18}O ground state in the coexistence picture.[15] One gets no support for this point of view from existing measurements of the (γ,p)[16] and (γ,n)[17] cross sections for ^{20}Ne, however, which show no prominent structure in the 23- to 30-MeV energy region; but then again one expects that the large concentration of dipole strength characteristic of deformation splitting should lie above 30 MeV for ^{20}Ne, in an energy region where no measurements as yet have been carried out.

We are left with a substantial difference between the shapes of the (γ,p) cross sections for ^{18}O and ^{16}O which does not appear to result from any of the above considerations. Clearly, this difference must be a measure of the effect of the valence neutrons on the ^{16}O core. One even can speculate that a large core-polarization effect in ^{18}O might result from an unexpectedly large tensor component of the nuclear force.[18] This, if true, would have important ramifications for many aspects of nuclear physics, and, in particular, would make necessary a fundamental reexamination of may microscopic nuclear calculations.

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[1]A. M. Kleinfeld, K. P. Lieb, D. Werdecker, and U. Smilansky, Phys. Rev. Lett. 35, 1329 (1975), and references therein.

[2]A. H. Wapstra and N. B. Gove, Nucl. Data Tables 9, 303 (1971).

[3]M. G. Silbert and J. C. Hopkins, Phys. Rev. 134, B16 (1964); J. Gilat, G. D. O'Kelley, and E. Eichler, Oak Ridge National Laboratory Report No. ORNL-3488, 1963 (unpublished), p. 4.

[4]I. Dostrovsky, R. Davis, Jr., A. M. Poskanzer, and P. L. Reeder, Phys. Rev. 139, B1513 (1965).

[5]H. Fuchs, Z. Phys. 171, 416 (1963); S. F. Mughabghab and W. E. Stephens, Phys. Rev. 133, B660 (1964); J. D. Allan, J. W. Jury, R. G. Johnson, K. G. McNeill, J. G. Woodworth, and Y. S. Horowitz, Can. J. Phys. 53, 786 (1975).

[6]W. E. Stephens, J. Halpern, and R. Sher, Phys. Rev. 82, 511 (1951); R. Montalbetti and L. Katz, Can. J. Phys. 31, 798 (1953).

[7]R. Kosiek, K. Schlüpmann, H. W. Siebert, and R. Wendling, Z. Phys. 179, 9 (1964); W. Hofmann, R. Kosiek, G. Kraft, and R. Mundhenke, Z. Phys. 225, 303 (1969).

[8]G. J. Vanpraet, Phys. Lett. 17, 120 (1965).

[9]S. C. Fultz, R. A. Alvarez, B. L. Berman, and P. Meyer, Phys. Rev. C 10, 608 (1974).

[10]B. L. Berman, J. T. Caldwell, R. R. Harvey, M. A. Kelly, R. L. Bramblett, and S. C. Fultz, Phys. Rev. 162, 1098 (1967).

[11]B. L. Berman and S. C. Fultz, Rev. Mod. Phys. 47, 713 (1975).

[12]Values for the $^{16}O(\gamma,p_0)$ cross section have been taken from R. C. Morrison, thesis, Yale University, 1965 (unpublished); and from J. E. E. Baglin and M. N. Thompson, Nucl. Phys. A138, 73 (1969), normalized to the mean of several other results in the literature; for $^{16}O(\gamma,p_{i>0})$, from J. T. Caldwell, thesis, Lawrence Livermore Laboratory Report No. UCRL-50287, 1967 (unpublished); and for $^{16}O(\gamma,n)$, from R. L. Bramblett, J. T. Caldwell, R. R. Harvey, and S. C. Fultz, Phys. Rev. 133, B 869 (1964), and J. T. Caldwell, R. L. Bramblett, B. L. Berman, R. R. Harvey, and S. C, Fultz, Phys. Rev. Lett. 15, 976 (1965).

[13]C.-P. Wu, F. W. K. Firk, and T. W. Phillips, Phys. Rev. Lett. 20, 1182 (1968).

[14]P. Paul, in *Proceedings of the International Conference on Photonuclear Reactions and Applications*, edited by B. L. Berman (Lawrence Livermore Laboratory, Livermore, Calif., 1973), p. 407.

[15]G. E. Brown, in *International Congress on Nuclear Physics, Paris, 1964, Proceedings*, edited by P. Gugenberger (Centre National de la Recherche Scientifique, Paris, 1964), p. 129, and private communication.

[16]W. R. Dodge and W. C. Barber, Phys. Rev. 127, 1746 (1962); R. E. Segel, Z. Vager, L. Meyer-Schützmeister, P. P. Singh, and R. G. Allas, Nucl. Phys. A93, 31 (1967); W. Hofmann *et al.*, *op. cit.* (Ref. 7).

[17]A. Veyssière, H. Beil, R. Bergère, P. Carlos, A. Leprêtre, and A. de Miniac, Nucl. Phys. A227, 513 (1974).

[18]J. P. Vary, P. U. Sauer, and C. W. Wong, Phys. Rev. C 7, 1776 (1973); J. P. Vary, private communication.

Evidence for New Minima in Photoionization Cross Section Obtained by Spin-Polarization Measurements

U. Heinzmann, H. Heuer, and J. Kessler
Physikalisches Institut der Universität Münster, 44 Münster, Germany
(Received 23 February 1976)

It has recently been predicted that Cooper-type minima of the photoionization cross section should also exist for $l \to l-1$ transitions. This theoretical conclusion is supported by measurements of the spin polarization of photoelectrons that have been ejected from thallium atoms by circularly polarized light.

Recently Msezane and Manson[1] predicted the existence of a new kind of minimum in the wavelength dependence of the photoionization cross section. Studying the example of the excited Cs 5d photoionization they found, apart from the well-known Cooper minimum,[2] a second minimum for the $l \to l+1$ photoionization channel and a minimum for the $l \to l-1$ channel. These minima arise when the matrix elements of the photoionization process vanish as a result of positive and negative contributions to their radial parts caused by details of the overlap between the discrete and continuum wave functions.

A zero of the matrix element for the $l \to l-1$ channel is a novel feature which has not been predicted before and which was thought not to exist. It is the purpose of the present Letter to report experimental evidence of such a zero which causes a zero minimum of the partial cross section for the $l \to l-1$ channel.

The measurements have been made with thallium atoms in their ground state $6s^2p(^2P_{1/2})$ which were photoionized by circularly polarized light. A measurement of the wavelength dependence of the photoionization cross section would have hardly revealed the new minimum, since the effect to be studied is masked by the influence of the $l \to l+1$ channel. Consequently, instead of measuring the photoionization cross section the polarization of the photoelectrons produced by the circularly polarized light has been observed.

The relation between the polarization P and the photoionization cross section has been discussed in an earlier paper[3] which also gives a brief account of the experimental procedure (a detailed description of the apparatus will be given elsewhere[4]). The following facts have been shown there: According to the selection rules $l \to l \pm 1$, the outer p electron of a thallium atom can make a transition into the S or the D continuum. If circularly polarized light is used for photoionization, the photoelectrons in the S continuum have a polarization $P=1$, whereas their polarization in the D continuum is $P=-0.5$. The resulting polarization of all the photoelectrons produced is therefore

$$P=(1\times Q_S-0.5\times Q_D)/(Q_S+Q_D), \quad (1)$$

where the polarizations of the two final states have been superimposed after weighting them with the cross sections Q_S and Q_D for reaching the S and D continuum, respectively.

In a conventional photoionization experiment one measures the cross section

$$Q=Q_S+Q_D, \quad (2)$$

since one cannot distinguish between transitions into different continua. A measurement of the polarization yields, however, information on the individual channels as one can immediately see from Eq. (1). If, for example, Q_S or Q_D dominates, the polarization tends to $+1$ or -0.5, respectively. If both P and Q are known, one has from Eqs. (1) and (2)

$$Q_S=Q\frac{P+0.5}{1.5}, \quad Q_D=Q\frac{1-P}{1.5}, \quad (3)$$

so that one can study the $l \to l-1$ and the $l \to l+1$ channels separately.

In the case of thallium discussed here, the situation is complicated by the fact that the continuum cannot be reached solely by the direct transitions on which our interest in focused. There are also transitions via autoionizing states