and concentrating the cloudiness of the crystal at the nuclear surface.[33] Some of these theoretical possibilities can be tested by means of the $\bar{\Gamma}_n^0/D$ ratio but it would be necessary to increase the number of nuclides studied as well as the statistical accuracy for individual nuclides.

[33] H. Amster and V. F. Weisskopf (private communication).

V. ACKNOWLEDGMENTS

During the course of these measurements, the assistance of R. C. Garth, H. R. Muether, and A. Stolovy in taking data was of great value, as were discussions of theoretical implications with C. E. Porter, V. F. Weisskopf, A. Bohr, and B. R. Mottelson.

PHYSICAL REVIEW VOLUME 99, NUMBER 1 JULY 1, 1955

Photoprotons from Oxygen†

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(Received January 6, 1955)

The cross section and angular distribution of the $O^{16}(\gamma,p)N^{15}$ reaction have been obtained for photon energies between 13.5 and 18.7 Mev, i.e., below the expected position of the giant resonance. The angular distribution indicated that the reaction proceeded predominantly through electric quadrupole or magnetic dipole absorption of photons, even though electric dipole transitions are allowed by isotopic spin selection rules. Suggestions are made regarding this forbiddenness of electric dipole absorption.

INTRODUCTION

STUDIES of photon absorption in oxygen have almost always used the (γ,α),[1] $(\gamma,4\alpha)$,[2] or (γ,n)[3,4] reactions. The only exception is the work of Wäffler and Younis,[1] who also obtained the (γ,p) cross section at 17.6 Mev, using γ rays from the $Li^7(p,\gamma)Be^8$ reaction.

It has been shown that if the assumption of the charge independence of nuclear forces is made, then it is expected that the (γ,α) reaction is forbidden to proceed via electric dipole absorption for energies below about 25 Mev.[5] This appears to be substantiated by experiment. The work of Penfold and the author[4] on the fine structure in the (γ,n) activation curve suggests that the (γ,n) reaction below 19 Mev proceeds by electric quadrupole and magnetic dipole absorption of photons. However, this suggestion was made on the basis of comparison of radiative widths to relatively inaccurate theoretical estimates. Therefore, it was deemed worthwhile to seek further information on the mechanism of photon absorption in oxygen below 20 Mev.

The experiment reported here was performed to obtain the cross-section and angular distribution for the $O^{16}(\gamma,p)N^{15}$ reaction between 13.5 and 18.7 Mev.

EXPERIMENTAL ARRANGEMENT

The photon source used in this experiment was a bremsstrahlung spectrum of maximum energy 18.7 Mev. The x-ray beam was collimated with lead to a pencil of angular diameter 0.012 radian, or a diameter of 1 cm at the center of the gas target, 90 cm from the source of x-rays. The scattering chamber used was similar to the one described by Fuller.[6] The line-up of the x-ray beam with respect to the scattering chamber was checked before each run by means of pictures of the beam taken on dental x-ray film. These films were positioned accurately with respect to the scattering chamber.

The scattering chamber contained oxygen gas at a pressure of one atmosphere. The gas acted as the target for the x-rays. Protons were detected in a pair of 1×3-inch 100-micron Ilford *G*-Special emulsions, which were placed parallel to, and to one side of, the x-ray beam. The emulsions were 0.87 cm apart, and their near edge was 2.40 cm from the center of the x-ray beam. Two sets of exposures were made, and in each case the dose at the scattering chamber was 5300 roentgens, as indicated by a Victoreen thimble at the center of an 8-cm cube of Lucite.

The emulsions were processed according to the dry development technique described by Beiser.[7] Observations on the tracks were made with two Leitz-Wetzlar binocular microscopes, using ×53 objective and ×8 ocular. This combination gave a field of view that was approximately 200 microns in diameter. Plates were searched by taking six-centimeter swaths along their long dimension.

Measurements made on the proton tracks were the

† Supported in part by the joint program of the Office of Naval Research and the U. S. Atomic Energy Commission.
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[1] H. Wäffler and S. Younis, Helv. Phys. Acta **22**, 614 (1949); Nabholz, Stoll, and Waffler, Phys. Rev. **86**, 1043 (1952).
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[3] Katz, Haslam, Horsley, Cameron, and Montalbetti, Phys. Rev. **95**, 464 (1954).
[4] A. S. Penfold and B. M. Spicer (to be published).
[5] M. Gell-Mann and V. L. Telegdi, Phys. Rev. **91**, 169 (1953).
[6] E. G. Fuller, Phys. Rev. **79**, 303 (1950).
[7] A. Beiser, Revs. Modern Phys. **24**, 273 (1952).

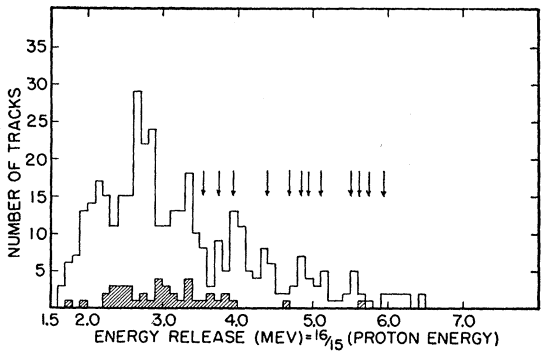

FIG. 1. Energy distribution of photoprotons (100-kev bins). Arrows indicate the energies of breaks found in the (γ,n) reaction (reference 4). The background which was subtracted is indicated by the shaded histogram.

projection of the range on to the plane of the emulsion, the angle, θ, of this projection to the beam direction, and the final depth in the emulsion reached by the track. To be accepted, the track was required to start at the surface of the emulsion, and to have a direction compatible with an origin in the irradiated part of the gas target. This latter condition required that the maximum allowable angle of dip, φ, was 23° at the front of the plate, decreasing to 11.5° at the back of the plate. The acceptable angular range in θ was 20° to 160°.

The background which arises from (n,p) reactions in the oxygen gas is negligible since the threshold for this reaction is 10.2 Mev (energy in the laboratory system). Therefore, the only source of background is due to neutrons produced in the collimator giving rise to recoil protons in the emulsion. Estimation of this background was made as follows. The emulsions were actually scanned over the angular regions $20°\leqslant\theta\leqslant 160°$ and $200°\leqslant\theta\leqslant 340°$. For both these regions the same selection rules were applied. The tracks were required to start at the surface of the emulsion, and the angle of dip was to satisfy the conditions described previously. Those tracks which were in the angular region $200°\leqslant\theta\leqslant 340°$ were taken as the background These protons could not have come from the target since their direction of motion was towards it. This method of estimating the background assumes that these recoil protons are produced symmetrically in θ about the direction of the x-ray beam. The background was approximately 11 percent of the acceptable photoproton tracks.

TREATMENT OF DATA

The energy of the proton at the surface of the emulsion was obtained from the range-energy data for Ilford emulsions given by Wilkins.[8] The energy lost by the proton in the gas between target and emulsion was calculated by using the energy loss tables of Aron, Hoffman, and Williams.[9] The energy loss formula was approximated by

$$-dE/dx=(0.1361/E)\{\ln E+2.2239\}\ \text{Mev/cm},$$

and this formula agrees with Aron's tables to within $\frac{1}{2}$ percent for the range of proton energies considered. The procedure for obtaining the initial energy from the energy at the emulsion surface and the distance traveled in the gas has been described previously.[10] All protons were assumed to start at the center of the x-ray beam. The distance travelled in the gas was obtained from the angle of the track to the beam direction and the known position of the track in the plate.

Uncertainty in the measurement of proton energy is made up of three factors. They are (i) the uncertainty in locating the beginning of the track, (ii) the uncertainty in energy due to range straggling in the emulsion, and (iii) the finite thickness of the gas target. Consideration of these three factors gave a figure of ±90 kev uncertainty in energy for 3-Mev protons, and larger uncertainties for protons of lower energy.

To plot the angular distribution, the data were grouped into 20° angular intervals, according to the angle the tracks made with the x-ray beam in the laboratory system. The mean differential cross section was calculated from the number of tracks per 20° interval, by making a correction for the solid angle subtended by each interval at the position of the track. This solid angle correction factor is very closely $\langle\sin\theta\rangle_{Av}$,[6,10] where $\langle\sin\theta\rangle_{Av}$ is the mean value of $\sin\theta$ over the 20° interval.

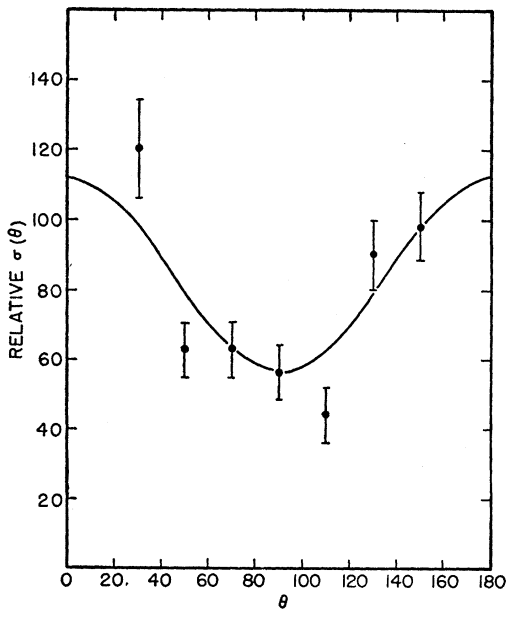

FIG. 2. The angular distribution of photoprotons. The line is 56 $(1+\cos^2\theta)$.

[8] J. J. Wilkins, Atomic Energy Research Establishment, Harwell Report G/R 664, 1951 (unpublished).

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[10] B. M. Spicer, Australian J. Phys. 6, 391 (1953).

RESULTS AND DISCUSSIONS

The observed energy distribution and angular distribution of photoprotons are shown in Figs. 1 and 2.

The irradiation energy of 18.7 Mev was chosen so that only the ground state in the residual nucleus, N^{15}, was available. Protons leaving N^{15} in the 5.28- or 5.31-Mev states were not detected, since the minimum proton energy detected was 1.5 Mev. This is illustrated by the energy level diagram in Fig. 3. The magnitude of the uncertainty in proton energy forbade the definite resolution of proton groups corresponding to the excitation of discrete levels in the compound nucleus O^{16}.

Knowing that only one state of N^{15} was available in this reaction, it was possible to determine the energy of the photon causing a particular event, from the proton energy. The threshold energy for the reaction is known to be 12.11 ± 0.01 Mev from mass data.[11] We then obtain a relative cross section curve from the energy distribution shown by dividing out the relative number of photons per unit energy interval. The cross section obtained is shown in Fig. 4.

The yield of protons at 18.5 Mev was calculated from the formula

$$Y=\frac{4\pi N}{d\Omega\cdot R}\cdot\frac{1}{MV},$$

where Y is the yield of protons per mole per roentgen, R is the dose given in roentgens, V is the effective volume of the gas target (cm^3), N is the number of tracks per unit area of the emulsion, M is the number of moles/cm^3 at the gas pressure used, and $d\Omega$ is the mean solid angle at the target subtended by unit area on the emulsion.

430 tracks were found and measured on a scanned area

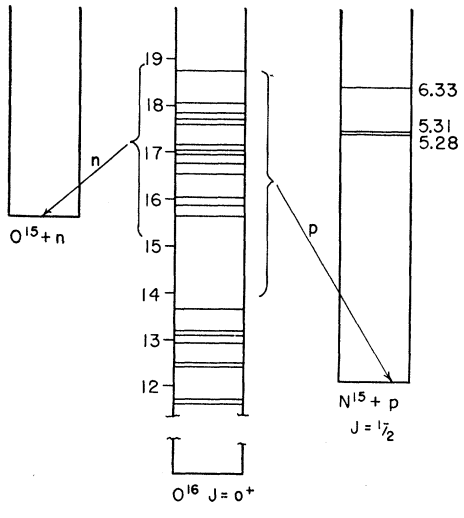

FIG. 3. Energy level diagram. The levels shown are known from other reactions. Maximum photon energy is 18.7 Mev. (γ,p) threshold is at 12.1 Mev.

[11] F. Ajzenberg and T. Lauritsen (to be published).

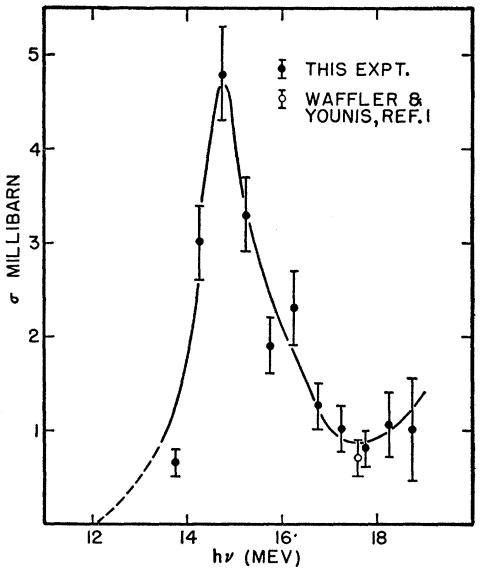

FIG. 4. Cross section for $O^{16}(\gamma,p)N^{15}$.

of 8.84 cm^2. Using this in the aforementioned formula, one finds the yield of protons at 18.7 Mev to be 4×10^4 protons per mole per roentgen. This may be compared with (γ,n) yields at 18 Mev of 5×10^3 neutrons per mole per r,[12] and 10^4 neutrons per mole per r.[13] The (γ,p) yield is expected to be higher than the (γ,n) because of its lower threshold energy.

Now

$$Y=k\int_0^{E_0}P(E,E_0)\sigma(E)dE,$$

where $P(E,E_0)dE$ is the number of photons per cm^2 per r between energies E and $E+dE$, in a spectrum of maximum energy E_0, and $\sigma(E)$ is the cross section at energy E. The k is a constant. By putting in the value of k such that the cross section is given in millibarns, and the yield in protons per mole per r, a value of 11 Mev-millibarns is obtained for $\int_{12.1}^{18.5}\sigma dE$ if the $P(E,E_0)$ is removed from the integral as $\langle P(E,E_0)\rangle_{Av}$. Having this, absolute values may be put on the cross-section curve in Fig. 4. Also shown in that figure is the cross-section value obtained by using the lithium γ rays.[1]

It should be noted that this measurement excludes the energy region where the giant resonance is expected to occur. Therefore, the cross section is expected to have a second peak at about 22 Mev, as indicated by the (γ,n) cross-section measurements of Montalbetti and Katz.[12]

The angular distribution has the form $a+b\cos^2\theta$, with a approximately equal to b. This form was also obtained when angular distributions were plotted separately for protons of energy less than 3 Mev, and for those with energy greater than 3 Mev. The angular distribution may be compared with the forms calculated[14] by using

[12] R. Montalbetti and L. Katz, Can. J. Phys. **31**, 798 (1953).
[13] G. A. Price and D. W. Kerst, Phys. Rev. **77**, 806 (1950).
[14] J. H. Smith (private communication).

TABLE I. Theoretical angular distributions.

J_A	l_γ	J_B	l_p	J_C	$\sigma(\theta)$
0^+	1	1^-	0	1	constant
0^+	1	1^-	2	1	$2+3\sin^2\theta$
0^+	1	1^+	1	0	$\sin^2\theta$
0^+	1	1^+	1	1	$1+\cos^2\theta$
0^+	2	2^+	1	1	$1+\cos^2\theta$
0^+	2	2^+	3	1	$1+6\cos^2\theta-5\cos^4\theta$

assumed values for the spin and parity of the intermediate state (see Table I). J_A is the spin of the initial state, J_B is the spin of the intermediate state, l_γ is the angular momentum carried in by the photon, l_p is the emitted proton's orbital angular momentum, and J_C is the final channel spin, which is obtained by adding vectorially the spin of the final state of the residual nucleus and the intrinsic spin of the outgoing proton. The spin of N^{15} ground state is $\frac{1}{2}^-$.

The only cases which give a distribution of the same form as the observed distribution are those for electric quadrupole absorption leading to emission of p-wave protons, and for magnetic dipole absorption, p-wave proton emission, and a final channel spin $J_C=1$. In practice, it is not possible to separate out the contributions of different final channel spins, and so the angular distribution for magnetic dipole absorption must be written $a\sin^2\theta+b(1+\cos^2\theta)$. The a and b here are both positive. The conclusion that the reaction proceeds predominantly by electric quadrupole and magnetic dipole absorption confirms the tentative conclusion drawn in the activation work of Penfold and Spicer.[4]

Using the assumption of charge independence of nuclear forces, Gell-Mann and Telegdi[5] showed that the expected threshold for the allowed, electric dipole-induced (γ,α) reaction in O^{16} is about 25 Mev. This is apparently confirmed by experiment, as Livesey and Smith[2] report a change in mechanism in this reaction at about 25 Mev. However, the isotopic spin selection rules, while forbidding the (γ,α) reaction below 19 Mev, do not forbid the (γ,p) or (γ,n) reactions in this region. In fact, the (γ,p) and (γ,n) reactions are allowed to proceed via electric dipole absorption from 13 Mev up. One must therefore seek another reason for the forbiddenness of $E1$ absorption between 13 and 19 Mev. Some possible reasons for this forbiddenness are:

(i) The number of 1^- levels in O^{16} between 13 and 18 Mev is zero or very small. This explanation does not appear reasonable since the spacing of 1^- levels is known to be 600 kev at 13 Mev,[10] and at 20 Mev is about 120 kev.[4]

(ii) The alpha-particle model for photon reactions put forward tentatively by Levinger and Bethe[15] accounts for this lack of dipole transitions. In this model, no electric dipole transitions can occur until the photon has enough energy to disrupt a particular alpha particle by a dipole transition, and this energy is about 20 Mev.

(iii) There is a selection rule, as yet unknown, which forbids electric dipole transitions in the case discussed above, and other similar cases.

The success of the alpha-particle model in accounting for most energy levels in O^{16} up to 13 Mev[16] gives reason to believe that explanation (ii) may hold in the case of the oxygen nucleus. However, similar studies of other nuclei, where the α-particle model does not have such success would help to discriminate between explanations (ii) and (iii). In this regard, it is interesting to note that photoreactions in some other nuclei do have double-peaked cross section *versus* energy curves. Examples are $Li^7(\gamma,p)$,[17] $O^{16}(\gamma,n)$,[4] $N^{14}(\gamma,n)$,[18] and $F^{19}(\gamma,n)$.[19]

ACKNOWLEDGMENTS

The author is indebted to Dr. J. H. Smith for his very considerable help in the calculation of the theoretical angular distributions, and to Dr. A. O. Hanson for many helpful discussions. Thanks are also due to Mr. H. Moore for his assistance in scanning the plates, and to T. J. Keegan and the crew of the 22-Mev betatron for their assistance in making the irradiations.

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