Energy and Angular Distribution of Photoneutrons from Oxygen-18†

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The energy and angular distribution of photoneutrons from $O^{18}(\gamma,n)O^{17}$ are investigated. An O^{18} target enriched to 90% is irradiated with bremsstrahlung of 20-MeV maximum energy from the University of Pennsylvania betatron. The photoneutrons are detected by recoil protons in nuclear emulsions at angles between 30 and 150° with the beam. Distinct peaks in the neutron spectrum at 1.3, 3.1, 7.4, and possibly at 1.7, 5.5, 9.2, and 10.5 MeV are observed. The peaks at 1.3 and 3.1 MeV can be accounted for in terms of single-particle excitation modes ($2S_{1/2}\rightarrow 2P_{3/2,1/2}$) of a valence neutron without disturbing the O^{16} core. These correspond to 1^- levels in O^{18} at 10.3 and 12.2 MeV with transitions leaving O^{17} in the $\frac{1}{2}^+$ excited state at 0.871 MeV. The angular distribution of the neutrons is predominantly $\sin^2\Theta$ at low energies. At high energies, there is an indication of interference effects between electric dipole and quadrupole absorption.

INTRODUCTION

THE yield curves for the (γ,n) reactions in Be^9, C^{13}, N^{14}, and F^{19} have revealed fine structure[1–4] interpreted as the excitation of states in the parent nuclei. Guth and Mullin[5] and Fujii[6] have interpreted some of this detail with the independent particle model in terms of valence neutron excitation. Elliott and Flowers[7] and Redlich[8,9] have shown that the low-lying levels of O^{18} are amenable to theoretical calculation using the valence neutron picture. Consequently, we have studied experimentally the energy and angular distribution of photoneutrons emitted from O^{18} by irradiation with bremsstrahlung of maximum energy just below the giant resonance in order to compare the results with those to be expected on the model of two neutrons around an O^{16} core.

Fuchs[10] has, meanwhile, reported results of $O^{18}(\gamma,n)$ at 30.5-MeV bremsstrahlung energy using recoil protons in a stilbene scintillator as neutron detector. No details of energy structure or of angular distribution were observed.

EXPERIMENT

Bremsstrahlung of maximum energy of 20 MeV from the former University of Pennsylvania O.N.R. betatron was used to irradiate a 3-g sample of water enriched to 90% in O^{18}. The neutrons were detected by observing recoil protons in 200-μ Ilford K2 emulsions placed at angles between 30 and 150° with the beam direction. The technique is described in more detail in previous work.[11] For the present experiment, however, the beam was better collimated, the selected recoil tracks were within an angle of $\pm 20°$ with the neutron direction, and the background was determined with empty sample holder and unenriched water. This background was subtracted but had negligible effect on the distribution. Also, the range energy curve of Rotblat[12] was used, and the neutron energy distribution was examined in greater detail.

The observed neutron energy spectrum based on 2189 tracks is shown in Fig. 1. This curve has been transformed into a cross-section curve using the neutron-proton scattering cross section, the bremsstrahlung spectrum of Schiff[13] and the assumption of transitions to the first excited state of O^{17}. The resulting histogram is shown in Fig. 2 where the vertical bars show statistical errors only. The integrated cross

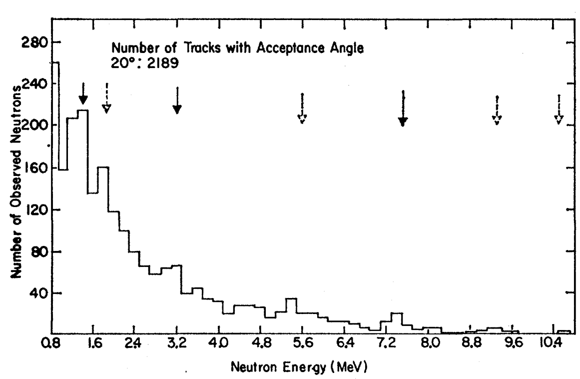

FIG. 1. Number of neutrons deduced from proton recoils plotted as a function of neutron energy in MeV. Solid arrows indicate neutron group while dashed arrows indicate further possible structure.

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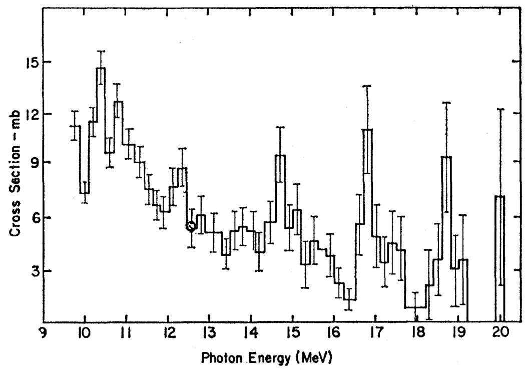

FIG. 2. Cross section versus photon energy for the photoneutrons from oxygen-18 calculated from Fig. 1 using the neutron-proton scattering cross section, the Schiff bremsstrahlung spectrum, experimental details and the assumption of transitions to the first excited state of oxygen-17. The vertical bars show statistical errors only.

section up to 20 MeV is about 60 MeV-mb. The absolute total cross section has been established by detailed geometry and monitor calculations using the observed angular distribution. Distinct peaks are apparent in Fig. 1 at 1.3-, 3.1-, 7.4-MeV neutron energy and possible structure appears at 1.7, 5.5, 9.2, and 10.5 MeV.

The angular distributions of several neutron groups are shown in Figs. 3, 4, and 5. The 1.3- and 3.1-MeV groups show a strong $\sin^2\Theta$ distribution. Analytical expression of the plotted curve in Fig. 5 is $a+b\sin^2\Theta \times(1+0.5\cos\Theta)^2$, where $a/b=0.03\pm0.01$.

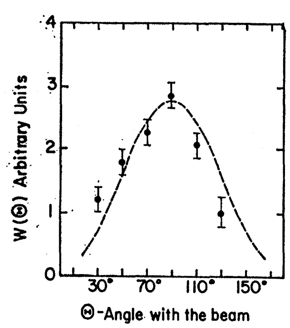

FIG. 3. Angular distribution of the neutron group at 1.3-MeV neutron energy.

DISCUSSION

Since O^{18} has a ground state of 0^+, the normally expected electric or magnetic dipole absorption of a photon would excite a 1^- or 1^+ state, respectively. There would then be expected a favoring of transitions to the $\frac{1}{2}^+$ first excited state of O^{17} with emission of a neutron of small angular momentum compared to transitions to the $\frac{5}{2}^+$ ground state of O^{17} plus a neutron of higher angular momentum. This expectation is made more quantitative by a comparison of the $\sin^2\Theta$ observed angular distributions with the calculated angular distributions given in Table I. These theoretical angular distributions have been calculated on the basis of the resonance theory of the compound nucleus by the formulas of Blatt and Biedenharn[14] and Sharp *et al.*[15] This comparison substantiates the assumption that we have, primarily, the starred transition, an electric dipole absorption to a 1^- state in O^{18} and a transition to the $\frac{1}{2}^+$ first excited state (0.871 MeV) in O^{17} with the emission of a neutron of angular momentum 1 and a channel spin 0. This conclusion would also be consistent with the direct excitation independent particle model of Courant[16] and Wilkinson[17] which gives for the angular distribution for $E1$ absorption, $W(\Theta)=l+(l/2+1)\sin^2\Theta$ (where l is the original angular momentum of the absorbing nucleon), if one of the valence

TABLE I. Theoretical angular distributions of photoneutrons from O^{18}.

Final state in O^{17}	Excited state in O^{18}	Photon abs.	Neutron angular momentum	Channel spin	Angular distribution
$\frac{5}{2}^+$ ground state	1^-	$E1$	3	3	$1+\cos^2\Theta$
			1	2	$6+\sin^2\Theta$
			3	2	$1+\sin^2\Theta$
	1^+	$M1$	2	3	$4+\sin^2\Theta$
			4	3	$6+5\sin^2\Theta$
			2	2	$1+\cos^2\Theta$
$\frac{1}{2}^+$ exc. state	1^-	$E1$	1	0	$\sin^2\Theta$*
				1	$1+\cos^2\Theta$
	1^+	$M1$	2	1	$2+3\sin^2\Theta$
			0	1	1

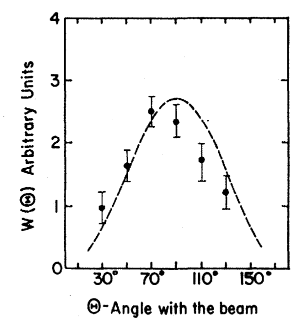

FIG. 4. Angular distribution of the neutron group at 3.1 MeV.

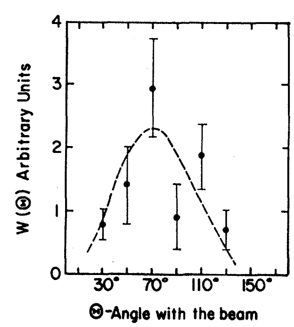

FIG. 5. Angular distribution of the 7.4-MeV neutron group.

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neutrons in O^{18} were to be excited from an $l=0$ shell model $2S$ state to a $2P$ state. Several calculations[7–9] agree in describing the O^{18} nucleus (using jj-coupling) by a wave function consisting of about 80% $D_{5/2}$, 15% $S_{1/2}$, and 5% $D_{3/2}$ configuration. The D part would yield neutrons of higher angular momentum whose emission would be inhibited by the angular momentum barrier. The same enhancement of interaction with S nucleons seems to occur in A^{40}.[18]

Consequently, it is suggested that the neutron groups of 1.3- and 3.1-MeV energy are the result of a direct interaction between the electric dipole photon and a valence neutron in a $2\,S_{1/2}$ configuration going to $2\,P_{3/2}$ or $2\,P_{1/2}$ configuration from which the neutron is ejected leaving the oxygen-16 core plus the other neutron in a $2\,S_{1/2}$ configuration. The 0.871-MeV $\frac{1}{2}^+$ level in O^{17} has been assigned a $2\,S_{1/2}$ configuration from neutron scattering.[19,20] These conclusions are summarized in Table II. Rough estimates of the magnitude of the spin-orbit splitting, relative transition probabilities,[21] position of the levels[22,23] and integrated cross section[6] support this interpretation.

The neutron group at 7.4 MeV has an angular distribution which seems to be peaked around 70°. Such an asymmetry could be explained in terms of electric dipole-quadrupole interference effects under direct interaction.[24] Five percent or more of quadrupole absorption would be needed to explain the data in Fig. 5.

TABLE II. Summary of results.

Neutron energy	O^{18} Excitation energy	Spin and parity	Excited-state configuration	Integrated cross section
1.3	10.3 MeV	1^-	$2\,S_{1/2}$, $2\,P_{3/2}$	7±2 MeV-mb
3.1	12.2 MeV	1^-	$2\,S_{1/2}$, $2\,P_{1/2}$	4.6±2 MeV-mb

The lowest energy neutrons can be regarded as the products of the reactions

$$O^{18}(\gamma,p)N^{17},\ {}_7N^{17} \xrightarrow{4\text{ sec}} {}_8O^{17*} + {}_{-}\beta,\ O^{17*} \rightarrow O^{16} + n.$$

These neutrons would be expected to show a peak at 0.92 MeV with a width of about 0.5 MeV.[25,26] Their angular distribution should be isotropic and their cross section[27] of the order of 10 mb. This is perhaps not inconsistent with the neutrons shown in Fig. 1 at about 0.8 MeV.

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