Photoneutron Cross Sections for C^{12} and Al^{27}†

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The photoneutron cross sections for carbon and aluminum have been measured up to 37 MeV, using nearly monochromatic photons obtained from the annihilation of positrons in flight. For carbon, resonances were observed at 22.0, 23.2, 25.5, 27.1, 28.3, 30.5, and 35.2 MeV, having approximate dipole strengths of 19, 33, 14, 6, 6, 11, and 11%, respectively. The integrated cross section is 46±4 MeV mb. Peaks in the aluminum cross section were observed at 13.8, 14.5, 15.4, 15.7, 16.4, 17.0, 17.7, 18.2, 20.0, 21.5, 22.0, 23.1, and 27.2 MeV. The integral for the cross section $\sigma(\gamma,n)+\sigma(\gamma,2n)+\sigma(\gamma,np)$ is 166±12 MeV mb, while that for $\sigma(\gamma,2n)$ is 6.3 MeV mb. Measurements on the neutron energies indicate that C^{12} emits neutrons mostly in ground-state transitions, and Al^{27} mostly by direct interactions.

INTRODUCTION

THE examination of photoneutron cross sections for light elements recently has become a topic of increasing interest. This is particularly so with the advent of photon sources of higher resolution than hitherto have been available, and recent advances in methods of analysis of bremsstrahlung data. The significance of photonuclear cross-section data on such elements is that considerable light is thrown upon the structure of the giant resonance. For example, 1^- states can be identified readily and the dipole strengths of transitions determined for even-even nuclei. Accurate determination of the characteristics of the resonances is vital to the theoretical interpretation of photonuclear reactions.

The experiments described herein were undertaken for the purpose of obtaining further information on the nature of the giant resonance for the low atomic number elements. For this work, photons obtained from the annihilation in flight of positrons were used as the source of radiation. The energy resolution of the positions was 1% while that of the photons was similar. The neutrons were counted in a 4π neutron detector consisting of a 24-in. cube of paraffin moderator containing 48 BF_3 counters arranged cylindrically around a 3-in. axial hole. The BF_3 chambers were filled to a pressure of 160 cm Hg of highly enriched $B^{10}F_3$. The efficiency of the detector was approximately 0.40. Two samples were used for the carbon measurements. One was designed for quantitative measurements, and consisted of 2-in.-diam slugs weighing a total of 184 g. The second sample was much larger, weighing 1347 g, and was used for determining the structure in the giant resonance. Data from the latter were normalized to those from the former sample. The aluminum sample consisted of 2-in.-diam discs of pure metal, each approximately 0.25 in. thick, and weighed 202.6 g. The detector efficiency was checked twice daily with a PuBe source. Background corrections to the cross sections were obtained by making similar sets of cross-section measurements using the sample holder instead of the sample. The dependence of the neutron efficiency upon neutron energy was examined by the use of a number of neutron sources having different average neutron energies, i.e., Sb-Be, Pu-Be, Po-Be, Cf^{252} spontaneous fission, mock fission, Po-Li, and Pu^{238}-Li, and by use of a 14-MeV neutron generator. These measurements are described in another report.[1]

The pulses from all BF_3 chambers were combined and fed into an electronic sorting system which counted the single, double, triple, etc., events per accelerator beam burst. From these data the (γ,n) and $(\gamma,2n)$ cross sections were deduced by statistical methods. Further details of the experimental procedure can be found in previous publications.[2,3]

CARBON

Photoreactions in carbon have been the subject of much experimental study during the past few years. A comprehensive bibliography of this work is given by Toms.[4] In an effort to examine absorption in the giant dipole resonance with better resolution than the early bremsstrahlung work, some investigators have examined the reaction $B^{11}(p,\gamma)C^{12}$. Tanner *et al.*[5] measured the gamma rays from the $B^{11}(p,\gamma_0)C^{12}$ reaction, using a NaI crystal. They obtained peaks in the cross section at 22.5 and 25.5 MeV, for transitions to the ground state. Gove *et al.*[6] previously had examined this reaction for excitation energies up to 27 MeV (11.4-MeV protons) by measuring γ-ray yields. They obtained a broad resonance at 22.5±0.02 MeV and a small peak at 25.5 MeV. By detailed balance they obtained an

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[1] J. T. Caldwell, R. L. Bramblett, B. L. Berman, R. R. Harvey, and S. C. Fultz, Bull. Am. Phys. Soc. **10**, 541 (1965). Also Phys. Rev. Letters **15**, 976 (1965).
[2] S. C. Fultz, R. L. Bramblett, J. T. Caldwell, and N. A. Kerr, Phys. Rev. **127**, 1273 (1962).
[3] R. L. Bramblett, J. T. Caldwell, R. R. Harvey, and S. C. Fultz, Phys. Rev. **133**, B869 (1964).
[4] M. Elaine Toms, U. S. Naval Research Laboratory, Washington, D. C., Bibliography No. 24, 1965 (unpublished).
[5] N. W. Tanner, G. C. Thomas, and E. D. Earle, Nucl. Phys. **52**, 29 (1964).
[6] H. E. Gove, A. E. Litherland, and R. Batchelor, Nucl. Phys. **26**, 480 (1961).

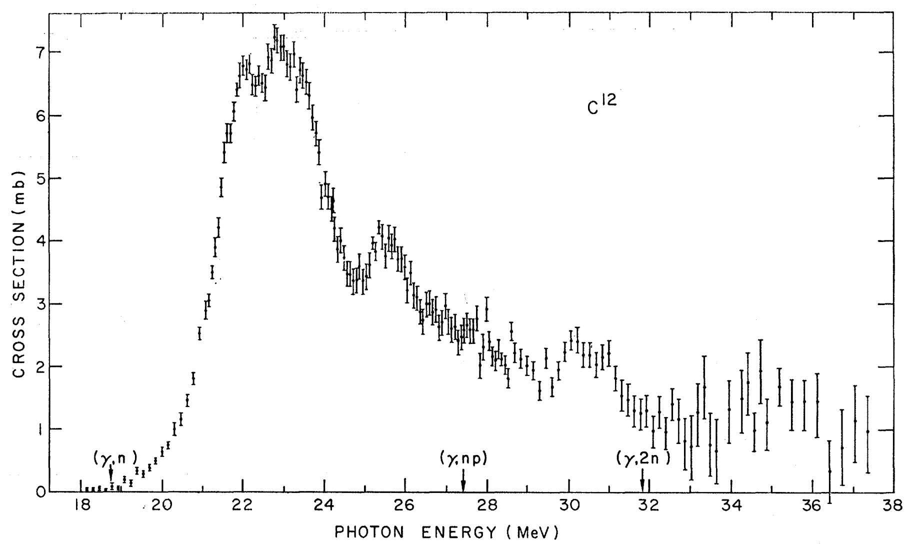

FIG. 1. Photoneutron-cross-section data for carbon $[\sigma(\gamma,n)+\sigma(\gamma,np)]$ obtained by the use of monochromatic photons, and measurements of the total neutron yield.

integrated cross section of 0.043 MeV-b for the $C^{12}(\gamma,p_0)B^{11}$ reaction. Allas *et al.*[7] examined this reaction with improved resolution using an 8-in.×12-in.-diam NaI crystal. The crystal was shielded by 2 in. of lead and 20 in. of paraffin. A pulse pile-up rejection system was used. They found a dominant resonance peak at an excitation energy of 22.6 MeV, with a second prominent peak at an excitation energy of 25.4 MeV. A number of less prominent peaks also were observed. Reay *et al.*[8] examined the $B^{11}(p,\gamma)C^{12}$ reaction up to a proton energy of 25 MeV (or nuclear excitation energy of 39 MeV), and found peaks in the cross section at excitation energies of 29.7 and 34.4 MeV. Hermann and Scheer[9] measured the energies of protons emitted from the reaction $C^{12}(\gamma,p)B^{11}$ by use of a stilbene-crystal proton spectrometer. The proton-energy distribution was calculated on the assumption that the protons are emitted during transitions to the ground state of B^{11}. Their data indicate peaks at approximately 22.1, 22.9, and 24.9 MeV.

With regard to photoneutron cross sections measured by use of γ rays, a list of numerous publications is given in Ref. 4. Among the more recent works is that of Min and Whitehead[10] who obtained resonance peaks at 22.2, 23.5, and 25.5 MeV. The activation method was used by Cook *et al.*[11] to measure the cross section of the $C^{12}(\gamma,n)C^{11}$ reaction. The positron activity of C^{11} was measured and the source of photons was bremsstrahlung radiation having endpoint energies up to 65 MeV. The "least structure" method was used for analysis and about 16 peaks were observed, with particularly strong peaks at 21.3, 22.8, 23.6, 26.0, 27.6, and 29.5 MeV. The integrated cross section up to 35 MeV was 56 MeV mb, while that up to 60 MeV was 77±6 MeV mb. The activation method also was used by Lochstet and Stephens,[12] but the source of radiation was monochromatic γ rays obtained from the $T(p,\gamma)$ reaction. Their results indicate three major peaks, at 22.2, 23.5, and 25.6 MeV. Miller *et al.*[13] measured the (γ,n) cross section of carbon by use of annihilation photons. They obtained peaks at 22.2 and 23.4 MeV. Fuchs and Haag[14] measured the photoneutron spectrum for the $C^{12}(\gamma,n)C^{11}$ reaction by use of a stilbene crystal. Assuming that the neutrons are emitted in transitions to the ground state of C^{11}, the cross section for this reaction

TABLE I. Energy levels observed in C^{12}.

E(MeV)	σ_0(mb)	Γ(MeV)	$\int_0^\infty \sigma\, dE$ MeV mb[a]	Percent dipole strength[b]
22.0	4.50	1.5	10.6	19
23.2, 24.0	5.75	2.0	18.1	33
25.5	2.50	2.0	7.9	14
27.1	1.50	1.5	3.5	6
28.3	1.50	1.5	3.5	6
30.5	1.95	2.0	6.1	11
35.2	~1.0	~3.5	~5.5	~11

[a] The integrated cross sections presented here are the areas under Lorentz lines which have been fitted to the resonances, (i.e., $(\pi/2)\sigma_0\Gamma$).
[b] The percentage of dipole strengths represented here are the fractional integrated cross sections for the resonances listed.

[7] R. G. Allas, S. S. Hanna, L. Meyer-Schützmeister, and R. E. Segel, Nucl. Phys. **58**, 122 (1964).
[8] N. W. Reay, N. M. Hintz, and L. L. Lee, Jr., Nucl. Phys. **44**, 338 (1963).
[9] K. O. Hermann and J. A. Scheer, Z. Physik **170**, 162 (1962).
[10] K. Min and W. D. Whitehead, Phys. Rev. **137**, B301 (1965).
[11] B. C. Cook, J. E. E. Baglin, J. N. Bradford, and J. E. Griffin, Phys. Rev. **143**, 724 (1966).
[12] W. A. Lochstet, Doctoral dissertation, University of Pennsylvania, 1965 (unpublished); also Bull. Am. Phys. Soc. **10**, 94 (1965). Also Phys. Rev. **141**, 1002 (1966).
[13] J. Miller, C. Schuhl, G. Tamas, and C. Tzara, Phys. Letters **2**, 76 (1962).
[14] H. Fuchs and D. Haag, Z. Physik **171**, 403 (1963). Also H. Fuchs, D. Haag, K. H. Lindenberger, and U. Meyer-Berkhout, Z. Naturforsch. **17**, 439 (1962).

TABLE II. Energy levels observed in C^{12} (MeV).

Livermore (γ,n) Peak	Livermore (γ,n) Lorentz fit	Miller *et al.* (γ,n)	Lochstet and Stephens (γ,n)	Min and Whitehead (γ,n)	Firk *et al.* (γ,n)	Fuchs and Haag (γ,n)	Dodge and Barber (γ,p)	Allas *et al.* (p,γ)	Reay *et al.* (p,γ)
				18.8					
		19.5							
					21.7		21.2	21.5	
22.1	22.0	22.2	22.2	22.2	22.0	22.0	22.5	22.6	
23.0	23.2	23.4	23.0	23.5	22.8	23.5	23.5	23.6	
					23.5				
24.0			23.7		24.8		24.8		
25.5	25.5		25.6	25.5	25.4	26.0	25.5	25.5	25.3
					25.8				
	27.1				27.5		26.6		
							27.2		
	28.3						28.0	28.0	
30.2	30.5								29.7
35.2	35.2								34.4

was deduced. The (γ,n) cross section curve shows evidence for peaks at approximately 22, 23.5, and 26 MeV. Firk *et al.*[15] and Verbinsky *et al.*[16] used the time-of-flight method to measure the energies of photoneutrons emitted from carbon. In both cases, bremsstrahlung radiation was used as the source of γ rays.

Dodge and Barber[17] measured the cross section for the (e,pe') reaction on carbon, and related this to the (γ,p) cross section by the virtual-photon concept. They observed a main resonance peak at approximately 22 MeV and considerable structure in the cross section curve. Goldemberg and Barber[18] examined carbon by measuring inelastically scattered electrons at 180°. Peaks were observed at 15.1, 18.7, 24, and 35 MeV. However, the 15.1-MeV level is known to arise from a level having J^π of 1^+. Other levels observed also could arise from magnetic dipole transitions.

EXPERIMENTAL RESULTS FOR CARBON

The present measurements were undertaken by the use of nearly monochromatic photons having a resolution of approximately 1%. The total cross section curve obtained for photoneutron production in carbon is shown in Fig. 1. No true double counts were observed; hence, the $(\gamma,2n)$ cross section is negligible up to 37 MeV. Well-pronounced peaks occur at 22.0, 23.2, 25.5, 30.5, and 35.2 MeV. Other structure (at 24.0, 27.1, and 28.3 MeV) can be deduced from the data. The integrated cross section for this experimental curve is 46.2±4 MeV mb up to 37 MeV. The data shown in Fig. 1 were analyzed by fitting Lorentz lines to the peaks and regenerating the cross-section curve. The parameters for the component resonances are given in Table I. This analysis was undertaken to obtain a more direct comparison with theoretical calculations. In Table II is given a comparison of the energies of peaks in the cross section curves observed by various experimental groups. Energies of peaks obtained in the present experiment are shown in the first column, while energies corresponding to the peaks of the Lorentz lines are given in the second column. As a result of the analysis, a slight displacement in the positions of some of the latter peaks with respect to the former may be observed.

In Fig. 2 are shown photoneutron-cross-section curves for carbon obtained at several different laboratories. The histogram represents the data of Fuchs *et al.*[14] for which the energies of the photoneutrons were measured at 90° by use of a stilbene crystal. The differential

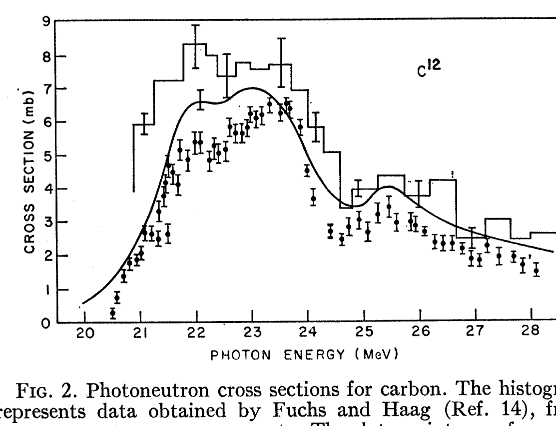

FIG. 2. Photoneutron cross sections for carbon. The histogram represents data obtained by Fuchs and Haag (Ref. 14), from neutron spectrum measurements. The data points are from the measurements of Verbinsky *et al.* (Ref. 16), also obtained from neutron-spectrum measurements. The solid line is an average of the present data shown in Fig. 1.

[15] F. W. K. Firk, K. H. Lokan, and E. M. Bowey, *Proceedings of the Padua Conference* (Gordon and Breach Science Publishers, Inc., New York, 1963). Also F. W. K. Firk and E. M. Bowey, International Conference on Nuclear Structure with Neutrons, Antwerp, EANDC 44U, 1965 (unpublished).

[16] V. V. Verbinsky, J. C. Courtney, D. F. Herring, R. B. Walton, and R. E. Sund, Bull. Am. Phys. Soc. **9**, 628 (1964); Nucl. Phys. (to be published).

[17] W. R. Dodge and W. C. Barber, Phys. Rev. **127**, 1746 (1962).

[18] J. Goldemberg and W. C. Barber, Phys. Rev. **134**, B963 (1964).

cross section was converted to total cross section using the angular distribution data of Emma *et al.*[19] and assuming ground state transitions. The data points shown in Fig. 2 were obtained by Verbinsky *et al.*[16] The solid curve represents an average of the photoneutron cross section data obtained in the present experiment.

Measurements on the ratio of the counts obtained from the outermost ring of BF_3 counters to those obtained from the innermost ring were made as a function of photon energy, when the carbon sample was irradiated with the annihilation photons. The "ring ratio" thus obtained is shown in Fig. 3. The solid curve represents the ring ratio which would be obtained from ground-state transitions only, as determined by the calibration with a number of neutron sources[1] in the presence of the carbon sample. Deviations of the data from the "ground state" curve occur at 21 MeV, and from 22.2 to 23.8 MeV, at which point the data return to the ground-state curve. Beyond 24 MeV, the ring-ratio data fall consistently below the ground-state curve. This decrease in the ring ratio below the ground-state curve signifies a drop in the average energy of the neutrons emitted by the carbon. This would be expected if the photon energy were just enough to leave the residual nucleus C^{11} in an excited state after the emission of a neutron from C^{12}. The first excited state of C^{11} occurs at 2.00 MeV, and the second excited state at 4.32 MeV. To excite these levels through neutron emission from C^{12} would require excitation energies of 20.72 and 23.04 MeV. Thus, deviations from the ground-state ring-ratio curve up to 23 MeV must arise from transitions to the 2-MeV first excited state in C^{11}. It is conceivable that if the levels in C^{12} are broad, the cross section for transitions to the first excited state would continue beyond 23 MeV, even though there is enough energy to excite the second level in C^{11}. Since the deviation in the photon-energy range from 21 to 24 MeV is a smooth function, it is attributed to transitions to the

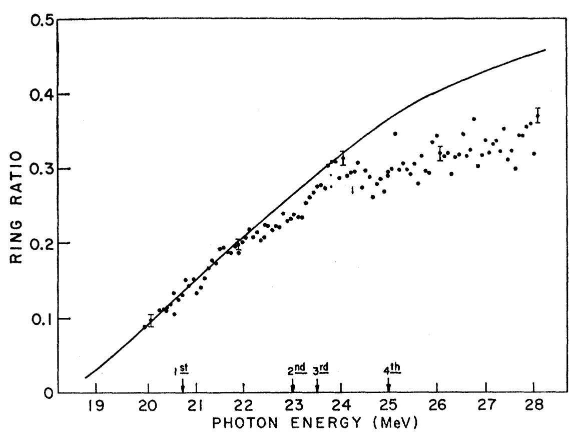

FIG. 3. The "ring ratio" for neutrons emitted from carbon. The solid curve is the ring-ratio curve for ground-state transitions.

[19] V. Emma, C. Milone, and A. Rubbino, Phys. Rev. **118**, 1297 (1960).

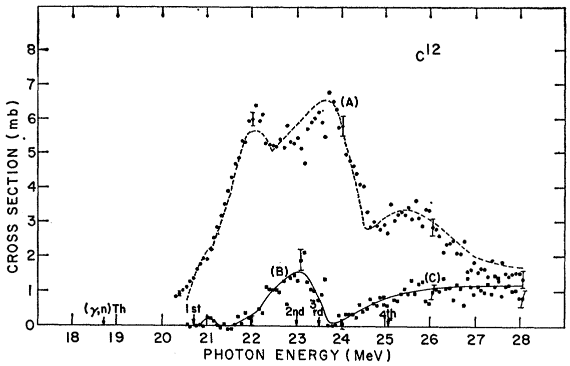

FIG. 4. Top data points (A) are cross sections for photoneutrons emitted in ground-state transitions. The dashed curve represents the data of Verbinsky *et al.* (Ref. 16). The lower data points (B) are cross sections for neutrons emitted in transitions to the first excited state of C^{11}, while data points (C) are cross sections for neutrons emitted in transitions to the third and higher excited states.

first excited state of C^{11}. We now can deduce the cross section for this excited-state transition, using the measured deviations from the ground-state curve. In a similar manner, the cross section for transitions to the third excited state and higher excitation levels can be obtained. The excited-state cross sections were deduced, along with the cross sections for transitions to the ground state, and are shown in Fig. 4. The average of the data of Verbinsky *et al.*[16] is shown by the dashed line, while the ground-state and excited state cross sections are represented by the data points. An improvement in the agreement between the two sets of data can be noted over that shown in Fig. 2. From the areas under the cross section curves of Fig. 4 it can be seen that approximately 17% of the total neutrons are emitted in transitions to the first (2.00 MeV) and higher excited states. This leaves about 83% of the neutrons being emitted in transitions to the ground state of C^{11}, (for excitation energies up to 28 MeV.)

DISCUSSION OF CARBON

The difference in the shapes of the cross section curves obtained by the neutron time-of-flight method and the monochromatic photons, as indicated in Fig. 2, was resolved by deducing the cross sections for the neutrons emitted in transitions to the excited states of C^{11}. However, the preponderance of transitions (83%) are to the ground state of C^{11}, in agreement with the conclusions of Emma *et al.*[19] who also saw evidence for transitions to the first excited state.

Among the recent theoretical treatments some success at predicting dipole transition strengths and energies has been obtained by application of the particle-hole concept to shell-model calculations. For the particular case of C^{12}, Vinh-Mau and Brown,[20] Gillet,[21]

[20] N. Vinh-Mau and G. E. Brown, Nucl. Phys. **29**, 89 (1962); also N. Vinh-Mau, Ann. Phys. (Paris) **8**, 1 (1963).

[21] V. Gillet, thesis, Universite de Paris, Saclay, 1962, Centre d'Etudes Atomique Report 2177 (unpublished).

TABLE III. Theoretical energy levels (MeV) and dipole strengths (%) for C^{12}.

Vinh-Mau and Brown[a]		Lewis and Walecka[b]		Nilsson *et al.*[c]		Boeker and Jonker	
E	f_0	E	f_0	E	f_0	E	f_0
18.7	6.5	19.6	28	22.2	38	17.7	5
22.2	75.0	23.3	55	23.0	12	21.9	67
23.9	0.5	25.0	1	23.7	5	24.2	1
34.3	18.0	35.8	15	26.3	7	33.8	27
				29.5	14		
				31.9	22		

a Ground-state correlations neglected, zero-range nuclear force used.
b Zero-range nuclear force, Tamm-Dancoff shell-model calculation.
c Ground-state correlations neglected, diagonal hole-pair interaction matrix elements included.

Lewis and Walecka,[22] Nilsson *et al.*,[23] and Boeker and Jonker[24] have made calculations on the energies and dipole strengths for $E1$, $\Delta T=1$ transitions. Various approximations and assumptions were introduced into these calculations. For example, in Ref. 20 calculations were made for the cases of (a) neglecting correlations between nucleons in the ground state, and (b) taking account of correlations between these nucleons. In Ref. 22 calculations were based upon (a) an ordinary zero-range nuclear force, and (b) a Serber force with Yukawa well. A comparison between measured and calculated energy levels and dipole strengths can be made with Tables I and III. In Table III are listed results of calculations by four groups of authors. The case presented for the calculations of Nilsson *et al.*[23] is that where the diagonal hole-pair interaction matrix elements are included.

The calculations of Vinh-Mau and Brown[20] predict that 75% of the dipole strength is contained in the particle-hole configuration $1p_{3/2}^{-1}1d_{5/2}$, at 22.2 MeV. The configuration $1s_{1/2}^{-1}1p_{1/2}$ gives 18% dipole strength at 34 MeV. Other configurations give only minor dipole strengths. This distribution of the dipole strength is not in good agreement with the results of the present experiment. The present data show evidence of a peak at 35.2 MeV, which accounts for only 11% of the dipole strength. However, the sum of the dipole strengths at 30.3 and 35.2 MeV is about 22%, in fair agreement with the particle-hole calculations of Vinh-Mau and Brown,[20] and of Boeker and Jonker.[24] The calculations of Nilsson *et al.*[23] give a distribution of dipole strengths in somewhat better agreement with experimental results, although their results inadequately describe the structure observed. For this work the carbon nucleus is regarded as deformed and the excited states include single particle excitations and collective motion of nucleus. The random-phase approximation was used to treat the residual interactions.

[22] F. H. Lewis, Jr., and J. D. Walecka, Phys. Rev. **133**, B849 (1964).
[23] S. G. Nilsson, J. Sawicki, and N. K. Glendenning, Nucl. Phys. **33**, 239 (1961).
[24] E. Boeker and C. C. Jonker, Phys. Letters **6**, 80 (1963).

The cross section for the $C^{12}(\gamma,p)B^{11}$ reaction has been measured by Shin and Stephens.[25] They observed structure with a dominant peak at 22.4 MeV. The net integrated cross section of four resonances was found to be 16.2 ± 2.5 MeV mb. This is approximately twice the integrated (γ,n) cross section obtained from the present experiment, i.e., 8.7 MeV mb, up to the same energy. The results of Hermann and Scheer[9] when compared with Fig. 1 indicate that the (γ,p) and (γ,n) total cross sections have approximately the same shape. If this be assumed true, the net integrated cross section for $C^{12}[(\sigma(\gamma,n)+\sigma(\gamma,np)+\sigma(\gamma,p)]$ would be approximately 132 MeV mb up to 37 MeV. This is 73% of the Thomas-Reiche-Kuhn sum rule value, and is in good agreement with the recent measurements of Jamnik,[26] who measured the total absorption cross section of carbon by use of a Compton spectrometer. The Jamnik data yield an integrated cross section of 134 MeV mb, up to 31 MeV.

ALUMINUM

A number of determinations of the cross section for the reaction $Al^{27}(\gamma,n)Al^{26}$ have been made by the use of bremsstrahlung radiation. Structure in the giant resonance has been observed in the more recent of these. Bolen and Whitehead[27] using a Halpern-type neutron detector observed prominent peaks at 18.1, 19.8, and 21.4 MeV, with maximum cross sections of 10.8, 12.9, and 12.5 mb, respectively. The integrated cross section up to 25 MeV was 86 MeV mb. Dular *et al.*[28] used a Compton spectrometer to measure the total absorption cross section of Al, and obtained peaks at 15.5, 18.5, 20.5, and 21.8 MeV. Thompson *et al.*[29] measured the cross section for the $Al^{27}(\gamma,n)Al^{26}$ reaction by examining the short (6.5-sec) half-life positron activity of the first excited state of Al^{26}. About 13 resonances were obtained from a "least structure" analysis. They obtained an integrated cross section of 31 ± 5 MeV mb up to 25 MeV. Since only 30%[29] of the (γ,n) transitions go to the first excited state of Al^{26}, the net integrated cross section is 103.0 ± 16 MeV mb. Shoda *et al.*[30] measured the cross section for the $Al^{27}(\gamma,p)Mg^{26}$ reaction by the use of ZnS(Ag) powder scintillators. They obtained an integrated cross section of 110 MeV mb. Measurement of protons with photographic emulsions[31] and solid state detectors[32] revealed much structure in the (γ,p)

[25] Y. M. Shin and W. E. Stephens, Phys. Rev. **136**, B662 (1964).
[26] D. Jamnik (private communication).
[27] L. N. Bolen and W. D. Whitehead, Phys. Rev. Letters **9**, 458 (1962).
[28] J. Dular, G. Kernel, M. Kregar, M. V. Mihailovic, G. Pregl, M. Rosina, and C. Zupancic, Nucl. Phys. **14**, 131 (1959).
[29] M. N. Thompson, J. M. Taylor, B. M. Spicer, and J. E. E. Baglin, Nucl. Phys. **64**, 486 (1965).
[30] K. Shoda, K. Abe, T. Ishizuka, N. Kawamura, and M. Kimura, J. Phys. Soc. Japan **17**, 735 (1962).
[31] K. Shoda, T. Ishizuka, K. Shimizu, and M. Akashi, J. Phys. Soc. Japan **17**, 1535 (1962).
[32] M. Masuda, M. Kondo, S. Takeda, M. Okumura, and J. Oakuma, J. Phys. Soc. Japan **19**, 2339 (1964).

TABLE IV. Energy levels observed in Al^{27} (MeV).

Present work $(\gamma,n)+(\gamma,np)$	Thompson *et al.* (γ,n)	Bolen and Whitehead $(\gamma,n)+(\gamma,np)$	Masuda *et al.* (γ,p)	Theory[a]
13.8			13.6	
	14.2		14.0, 14.2	
14.5	14.5	14.6	14.5, 14.7	14.3
15.4	15.2		15.0, 15.2	15.5
15.7	15.6		15.7	15.7
	16.1		16.0	
16.4	16.4	16.4	16.3, 16.8	16.4, 16.6
17.0	17.0		17.0, 17.3	17.0, 17.2
17.7	17.6		17.8	
18.2	18.1	18.1	18.4	18.1, 18.3, 18.4
	19.6			19.4, 19.6, 19.7
20.0	20.5	19.8		20.0, 20.1, 20.2
21.5	21.2	21.4		21.0
22.0	22.4			
23.1				
27.2				

[a] All theoretical values are given in Ref. 29.

cross section. Earlier measurements by Halpern and Mann[33] yielded a (γ,p) integrated cross section of 120 MeV mb up to 23.5 MeV.

EXPERIMENTAL RESULTS FOR ALUMINUM

The yield cross section, $[\sigma(\gamma,n)+\sigma(\gamma,np)+2\sigma(\gamma,2n)]$, and the $(\gamma,2n)$ cross section obtained from the present measurements, are shown in Fig. 5. Considerable structure is apparent and only a small contribution from the $Al^{27}(\gamma,2n)Al^{25}$ reaction is present.

The integrated cross section up to 25 MeV for $[\sigma(\gamma,n)+\sigma(\gamma,np)]$ is 102 ± 10 MeV mb, and to 37 MeV it is 166 ± 12 MeV mb. The cross section reaches a maximum of 15 mb at 21.5 MeV. The integrated cross section for $\sigma(\gamma,2n)$ is 6.3 MeV mb. A summary of the observed levels for Al^{27} is given in Table IV. Also given are results of other investigators.

As noted in Fig. 5, the contribution of the $(\gamma,2n)$ cross section is very small. From the $(\gamma,2n)$ cross section the

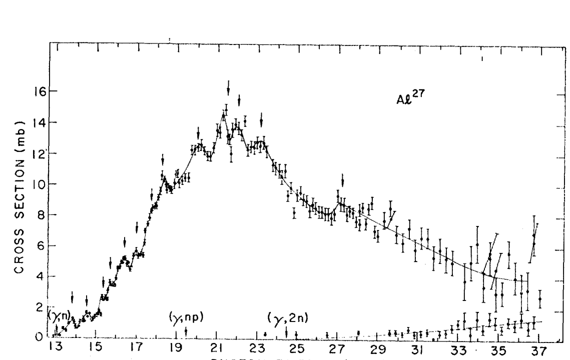

FIG. 5. Photoneutron-cross-section data for aluminum. The upper data and curve represent the photoneutron yield cross section $[\sigma(\gamma,n)+\sigma(\gamma,np)+2\sigma(\gamma,2n)]$ for Al^{27}. The lower data and curve represent the cross section for the reaction $Al^{27}(\gamma,2n)Al^{25}$.

[33] J. Halpern and A. K. Mann, Phys. Rev. **83**, 370 (1953).

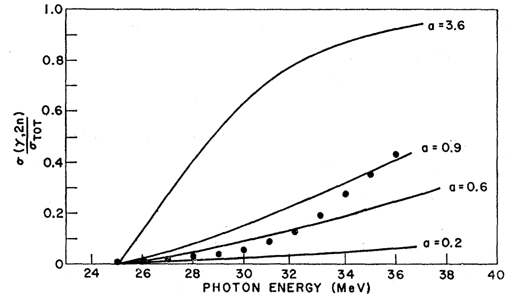

FIG. 6. Data points are values of $\sigma(\gamma,2n)/\sigma_{tot}$ for Al^{27} (where σ_{tot} denotes the total cross section for photon absorption) at various incident photon energies. The curves are calculated values for this ratio corresponding to values of the level-density parameter $a=3.6$ (top curve), 0.9, 0.6, and 0.2 MeV^{-1} (bottom curve).

ratio $\sigma(\gamma,2n)/\sigma_{tot}$ was derived as a function of photon energy and is shown in Fig. 6. Also shown are various calculated curves representing this ratio as a function of energy, for different assumed values of the level density parameter for Al^{26}. It is evident that the calculated curves agree best with the data when Al^{26} is given an "a" value below 0.9 MeV^{-1} and above 0.2 MeV^{-1}, i.e., in the region of $a=0.6$ MeV^{-1}. This is to be compared with values of 3.6, 4.0, 4.5, and 4.9 for excitation energies of 2.14, 4.14, 6.64, and 14 MeV, respectively, as reported by Erba *et al.*[34] for Al^{27}. Thus a reasonable value for Al^{26} is 3.6 MeV^{-1}, as based upon the compound nucleus model. As can be seen in Fig. 6, this value gives a curve distinctly different in magnitude and shape from those more nearly representing the data. We may therefore conclude that the compound nucleus model is not adequate to explain the greater part of the neutron emission from Al^{27}. The low value obtained for the level density parameter is consistent with this conclusion and indicates that the majority of photoneutrons are emitted by a direct interaction process between the incident photons and the nuclei.

Aluminum, having many more nucleons than carbon, is a more complicated case to treat theoretically. Lewis and Walecka[22] calculated the squared form factors for Al^{27}, based upon the Goldhaber-Teller[35] and the Steinwedel-Jensen[36] collective models, and have shown that these disagree with the electron scattering measurements. This indicates the necessity of using a shell-model type of calculation. Such calculations were undertaken by Spicer *et al.*[29,37] For these calculations the model used involved radiative transitions between single particle levels in a spheroidal potential well, and it was assumed that the intrinsic nucleon levels calculated by Nilsson[38] applied to all degrees of deformation. The

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single-particle excitation can occur alone or together with a collective rotational excitation. Pairing energy and zero-point energy terms were included. A comparison of the last column of Table IV with the results of the present work indicates general agreement on the energies predicted, although the theoretical treatment predicts many more levels than are observed. There is also fair agreement between the results obtained at the different laboratories, although it must be remembered that in the various experiments different reaction products were examined in some cases.

SUMMARY AND CONCLUSIONS

New levels were observed in carbon at 27.1, 28.3, 30.3, and 35.2 MeV through measurement of the photoneutron cross section. The relative dipole strengths of all levels observed were measured and compared with theoretical predictions. It is evident that the present theoretical treatments are inadequate to describe the energies and dipole strengths of the resonances observed. The distribution of energies and dipole strengths given by Nilsson appears to be slightly better than those obtained from particle-hole treatments. The integrated cross section of carbon for total γ-ray absorption $[\sigma(\gamma,n)+\sigma(\gamma,np)+\sigma(\gamma,2n)+\sigma(\gamma,p)]$ is approximately 132 MeV mb, or 73% of the saturated dipole sum rule value. Area measurements on curves in Fig. 4 indicate that approximately 83% of the photoneutrons are emitted from carbon during transitions to the ground state of C^{11}, while about 6 and 11% are emitted in transitions to the 2.00 and 4.81 MeV (and higher) levels, respectively. The $(\gamma,2n)$ cross section was found to be negligibly small, indicating that little or no compound nucleus formation takes place. Hence, the photoneutrons are emitted from carbon essentially by direct processes.

In the case of aluminum, a large number of peaks were observed. It has not been possible to measure their dipole strengths and consequently a detailed comparison with theory is not feasible, although general agreement with some theoretical energy values has been obtained. The integrated cross section for neutron production is in agreement with values obtained at other laboratories for similar energy ranges. The integrated cross section for total γ ray absorption as deduced from the sum of the photoneutron contribution (172 MeV mb) and the (γ,p) contribution[33] up to 23 MeV (120 MeV mb) represents 72% of the saturated dipole sum. Extension of the (γ,p) cross-section measurements to higher energies would increase this fraction. The value of the level-density parameter as deduced from the ratio of $\sigma(\gamma,2n)$ to σ_{tot} is too low, indicating an excess of high-energy neutrons. This can be explained by assuming that a large percentage of direct interactions occur during photoneutron emission.