process in which the incident alpha-particle collides as a whole with a surface nucleon knocking it out and itself being scattered is a likely contributing mechanism. On the basis of a statistical model the $(\alpha,\alpha p)$ reaction becomes possible when the alpha particle is emitted with a low enough energy to leave proton emission energetically possible.

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Energy Spectra and Angular Distribution of Photoneutrons from Carbon

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Energy spectra and angular distribution of photoneutrons from carbon are studied by irradiation with a 30-Mev bremsstrahlung beam. The spectra exhibit a fine structure from which the following levels in C^{12} may be distinguished: 21.4, 22.2, 22.9, 23.6, (24.3), 24.8, and 25.6 Mev. Many of these coincide with levels found in the $C^{12}(\gamma,p)$ and $C^{12}(\gamma,3\alpha)$ reactions.

Photoneutron emission occurs predominantly by transition to the ground state of C^{11}.

The angular distribution is of the form $1+1.5\sin^2\theta$ for all neutrons having energy $E_n>3$ Mev. This distribution agrees with that expected according to Wilkinson's independent-particle model for ejection from the $l=1$ orbit.

1. INTRODUCTION

In previous work[1,2] it has been shown that while the photoneutron emission from heavy nuclei occurs mainly by evaporation, in a nucleus as light as oxygen the direct process prevails in photoneutron emission.

The aim of present work is to study in some detail the energy spectrum and the angular distribution of photoneutrons from carbon. These data are needed in order to study the prediction of direct interaction theories and the levels in C^{12}. This work has been suggested to us also by the analysis of the known data on the photodisintegration of C^{12}.[3–26]

As shown in Table I it may be observed that for the photoneutrons from C^{12}: (i) the energy spectra have not yet been studied; (ii) the angular distributions are given only for angles θ between 60° and 160°[16] and for $E_{\gamma\,\max}=23$ Mev.

2. EXPERIMENTAL PROCEDURE

A cylindrical target of C of ~40 g was irradiated with a 31-Mev collimated γ-ray beam of the B.B. betatron of Turin. The photoneutrons were detected by means of the proton recoil tracks in Ilford L4 plates 400 μ thick, placed, respectively, at angles $\theta=30°$, 60°, 90°, 120°, and 150° with the γ-ray beam. The experimental arrangement was the same as that used in a previous work.[27] The methods used for scanning the plates with the ⟨slow⟩ and the ⟨fast⟩ method and for analyzing the proton recoil tracks are described in previous work.[2,28] The measured background[27] was quite negligible.

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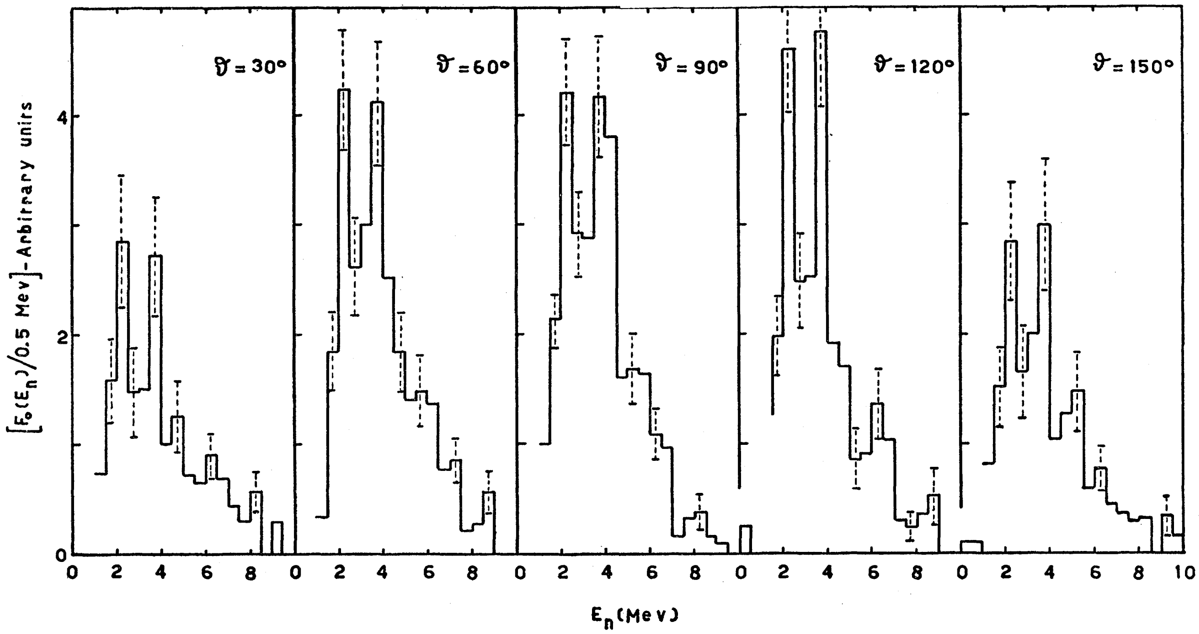

FIG. 1. Energy spectra of photoneutrons from carbon at various angles θ between the γ beam and the ejected neutrons.

Some data on the present experiment are summarized in Table II.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Energy Spectra and Levels in C^{12}

In Fig. 1 the energy spectra obtained at angles θ of 30°, 60°, 90°, 120°, and 150° are reported in ΔE_n steps of 0.5 Mev. The ordinates are proportional to the observed neutron flux $F_0(E_n)/0.5$ Mev. The spectra at various angles show the same fine structure, with peaks evident around $E_n=2.2$ and 3.8 Mev. Other possible peaks are also seen for $E_n>4$ Mev. We have found a similar situation in the photoneutron spectra from oxygen.[1,2]

In order to obtain more detailed information from the photoneutron spectra, we have added the experimental results obtained at all of the various angles θ for the same scanned volumes and in ΔE_n steps of 0.2 Mev. This procedure is possible because the number of peaks and the position of the peaks in the energy spectra are the same at all angles in our data. The experimental spectrum so obtained, shown in Fig. 2 in ΔE_n steps of 0.2 Mev, shows well-defined and narrow peaks.

The mean behavior of the experimental spectrum agrees with the spectrum $\sigma(\gamma,n)I(E_\gamma,30)$ calculated from the experimental $\sigma(\gamma,n)$ cross section[10] taking account of the 30-Mev bremsstrahlung spectrum $I(E_\gamma,30)$.[10,29] This gives evidence that the direct emission process is occurring according to theoretical expectations[30,31] and that the photoneutrons leave the C^{11} residual nucleus predominantly in the ground state.

TABLE I. Experimental work on the photodisintegration of C^{12}.

$C^{12}(\gamma,n)$ process			$C^{12}(\gamma,p)$ process		
Measurement	$E_{\gamma\,max}$ (Mev)	References	Measurement	$E_{\gamma\,max}$ (Mev)	References
Neutron yield curves	22	3			
	23	4, 5			
	100	6			
$\sigma(\gamma,n)$	24	7	$\sigma(\gamma,p)$	24	17
	25	8			
	27	9			
	31	10			
	38	11			
	50	12			
	60	13			
	70	14			
	98	12			
	320	15			
Angular distrib.	23	16	Angular distrib.	23	18
				31	19
				40	20
				60	21
				65	22
				195	23
				265	24
				322	25
Photoneutron energy spectra			Photoproton energy spectra	25	26
				31	19
				40	20
				195	23
				265	24
				322	25

[29] C. Milone, S. Milone Tamburino, R. Rinzivillo, A. Rubbino, and C. Tribuno, Nuovo cimento **7**, 729 (1958).

[30] A. Agodi, Nuovo cimento **8**, 516 (1958).

[31] G. E. Brown and J. S. Levinger, Proc. Phys. Soc. (London) **71**, 733 (1958).

We will now compare the structure of the photoneutron spectrum with that of the photoproton spectrum obtained by Cohen et al.[26] This comparison is made by referring to the same value of $E_\gamma^* = 18.7 + (12/11)E_n = 15.9 + (12/11)E_p$, 18.7 Mev and 15.9 Mev being the threshold energies for the $C^{12}(\gamma,n)$ and $C^{12}(\gamma,p)$ processes, respectively. Obviously this comparison is possible only if the emitted particles leave the residual mirror nuclei C^{11} and B^{11} in their ground states.

There appears to be good agreement between the positions of the peaks *a*, *b*, *c*, *d* and *a'*, *b'*, *c'*, *d'*, in Fig. 2. A comparison in the higher energy region is not possible because the photoproton spectrum[26] is obtained with 25-Mev bremsstrahlung. The peaks *b* and *d* correspond well—within the experimental errors—to the known levels at 21.3 and 22.8 Mev in C^{12} [32]; the peak *c* at 22.1-Mev confirms the suggested peak found from the $B^{11}(p,\gamma)$ and $B^{11}(p,n)$ reactions.[32] Therefore it may be concluded that the peaks *b*, *d*, and possibly *c* are due to γ resonance absorption in C^{12}.

Now, taking into account that the first energy levels of the residual nucleus C^{11} are, respectively, 1.99 and 4.26 Mev above the ground state,[32] and observing the behavior of the $\sigma(\gamma,n)I(E_\gamma,30)$ function (Fig. 2), it appears very unlikely that the peaks *e*, *g*, *h* found in the experimental spectrum can be due to neutrons leaving C^{11} in excited states. Therefore, we also attribute these peaks to γ resonance absorption around 23.6, 24.8, and 25.6 Mev. Levels at 24.3 and 25.4 Mev have been found previously[32] and are given with some uncertainty; the first of these two levels is confirmed by the peak *f*, while the second is very near to the peak *h*.

For a detailed comparison, in Fig. 2 are also reported:

TABLE II. Data on the present $C(\gamma,n)$ experiment.

Element		C^{12}			
Weight (g)		40			
(γ,n) threshold (Mev)		18.72[a, b]			
$(\gamma,2n)$ threshold (Mev)		32.0[b]			
(γ,np) threshold (Mev)		27.4[b]			
$E_{\gamma\,max}$ (Mev)		30			
Energy of the cross-section peak (Mev)		22.5[c]	22.9[d]		
Integrated cross section to 31 Mev		42±7 Mev mb[d]			
Dose (roentgens)		~5000			
Angle θ	30°	60°	90°	120°	150°
Scanned volume (mm³)	185	185	185	191	192
Slow scanning, number of experimental accepted tracks $E_n \leq 5$ Mev	122	188	198	183	128
Slow and fast scanning, number of experimental accepted tracks $E_n \geq 5$ Mev	49	73	76	64	51

[a] See reference 32.
[b] G. R. Bishop and R. Wilson, *Handbuch der Physik*, edited by S. Flügge (Springer-Verlag, Berlin, 1957), Vol. 42, p. 309.
[c] See reference 11.
[d] See reference 10.

[32] F. A. Ajzenberg and T. Lauritsen, Nuclear Phys. **11**, 1 (1959).

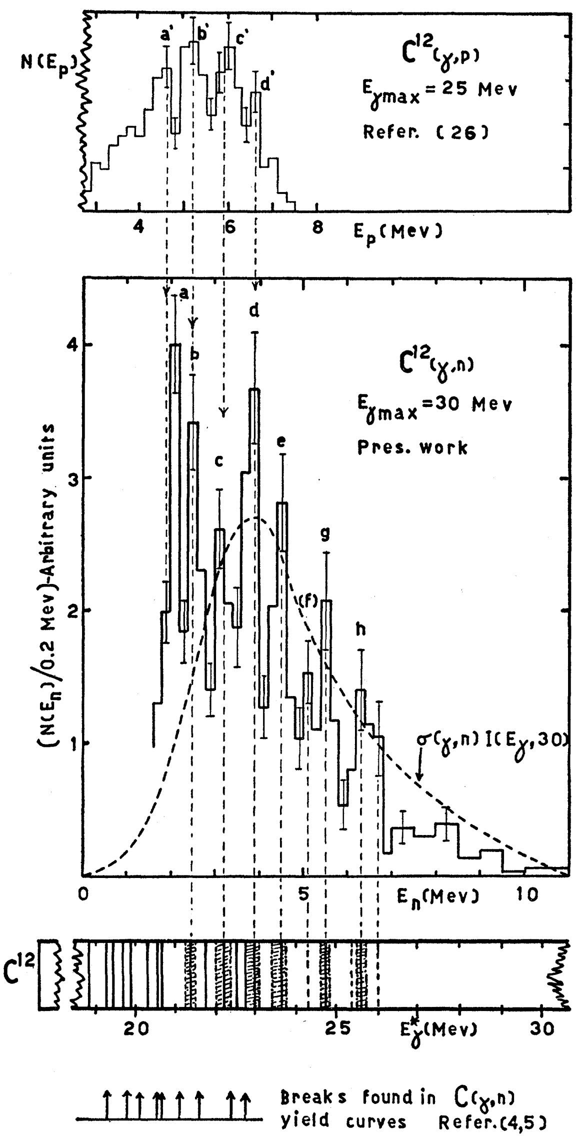

FIG. 2. Energy spectra of photoprotons and photoneutrons from carbon.

(a) the E_γ^* energies previously introduced corresponding to the excitation energies of the C^{12} nucleus;

(b) the energy levels of C^{12} represented by full lines if well known, by dashed lines if uncertain, and by cross hatching if found or confirmed in the present experiment;

(c) the breaks found in the activation[5] curves and in the neutron yield[4] curves from the (γ,n) reaction in C^{12} up to $E_{\gamma\,max} = 23$ Mev. The separation between the peaks *d* and *a* is just ~2 Mev; then, taking also into account the behavior of the $\sigma(\gamma,n)I(E_\gamma,30)$ function, it appears possible that the peak *a* may be partly due to photon absorption in the $E_\gamma \approx 23$-Mev region with transition to the first excited state of the residual nucleus C^{11}.

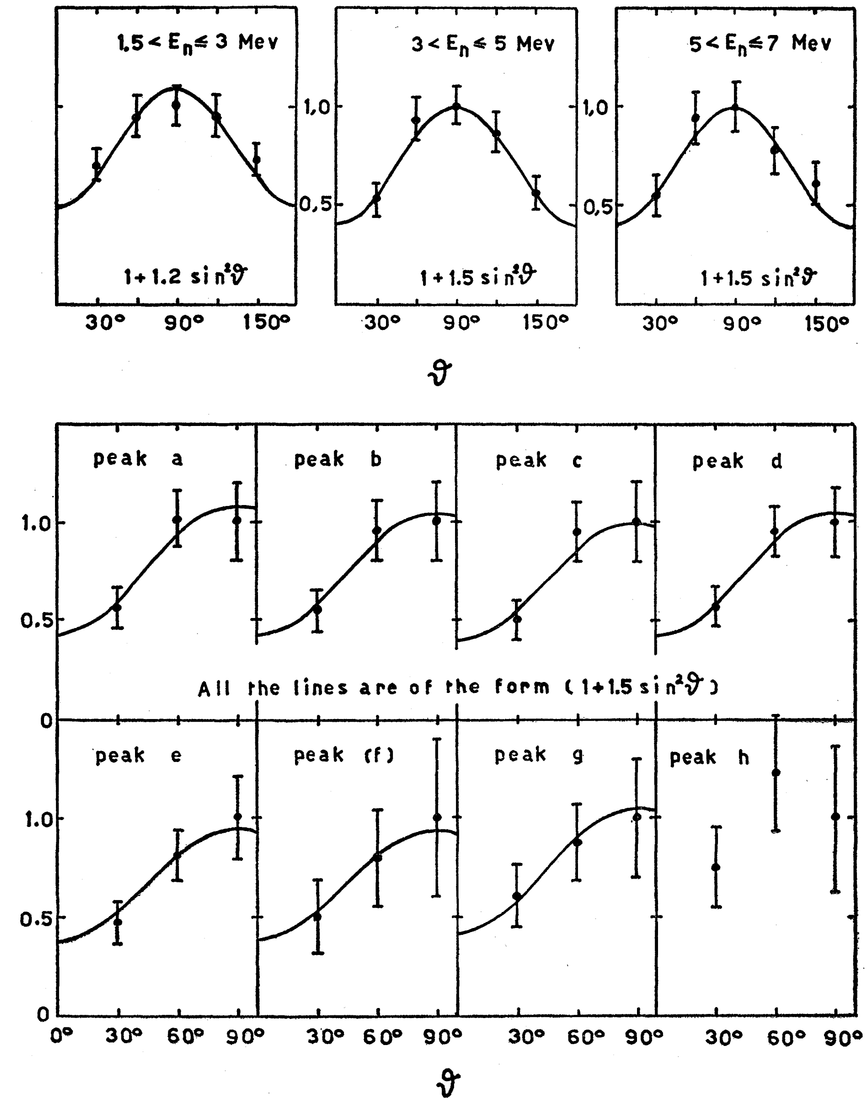

FIG. 3. Experimental angular distribution of photoneutrons from carbon.

In Table III, the levels that may be distinguished in the photoproton spectrum from the $C^{12}(\gamma,p)$ reaction,[26] in the $C^{12}(\gamma,3\alpha)$ reaction,[33] and in the photoneutron spectrum from the $C^{12}(\gamma,n)$ reaction (present work) are compared with the known levels[32] of C^{12}. It is interesting that many coincident levels are seen in the three processes.

3.2. Angular Distribution

In Fig. 3, the angular distributions are reported for the following neutron groups: $(1.5<E_n<3)$ Mev, $(3<E_n<5)$ Mev, $(5<E_n<7)$ Mev, and separately for each neutron peak found in the energy spectrum.

All the experimental angular distributions may be fitted by curves of the form $1+1.5\sin^2\theta$ with the exception of the neutron energy region between 1.5 and 3 Mev.

The angular distributions show back and front symmetry within the limits of the statistical errors. Hence, in order to improve the statistic of the single peaks (Fig. 3), we have added the experimental figures obtained at angles symmetrical with respect to $\theta=90°$. For neutrons with energy $E_n>7$ Mev, the angular distribution is not given because the experimental data are poor.

The marked anisotropy found in the angular distribution together with the results found in the energy spectra strongly suggests a direct process in the photoneutron emission from C^{12}, because the angular distribution following compound nucleus formation should be almost isotropic in this case.

[33] E. J. Jones, *Proceedings of the 1954 Glasgow Conference on Nuclear and Meson Physics* (Pergamon Press, London, 1955), p. 147.

TABLE III. Levels in C^{12} above 21 Mev.[a]

Peaks	Cohen et al.[b]	Ajzenberg and Lauritsen[c]	Jones[d]	Present work
b, *b'*	21.3±0.2	21.34		21.4±0.1
		21.80		
c, *c'*	22.2±0.2	(22.1)		22.2±0.2
		22.55±0.1		
d, *d'*	23.0±0.1	(22.8)	22.7±0.2	22.9±0.2
e				23.6±0.2
(*f*)		(24.3)	24.3±0.2	(24.3±0.1)
g			25.0±0.2	24.8±0.2
h		(25.4)		25.6±0.2

[a] Levels in parenthesis are given with uncertainty.
[b] See reference 26.
[c] See reference 32.
[d] See reference 33.

The form $(1+1.5\sin^2\theta)$ of the experimental angular distribution agrees with the predictions of the independent-particle model of Wilkinson.[34–36] According to this model, the angular distribution of the direct photonucleons for ejection from the orbit l is given by

$$W(\theta)=1+\tfrac{1}{2}(1+2/l)\sin^2\theta.$$

The fact that the experimental angular distribution (Fig. 3) for neutrons with energy $E_n>3$ Mev is of the form $(1+1.5\sin^2\theta)$ suggests that the neutrons are ejected from the $l=1$ orbit in good agreement with the shell-model expectation that in the case of the C^{12} nucleus the predominant photon absorption is due to $p_{\frac{3}{2}}\rightarrow d_{\frac{5}{2}}$ transitions.

Our results agree within the experimental errors with the distribution $1+(1.35\pm0.88)\sin^2\theta$ found by Fabricand et al.[16] with 23-Mev bremsstrahlung for neutrons having energy $E_n<4$ Mev.

For $(1.5<E_n<3)$ Mev, the angular distribution exhibits a lower anisotropy which may be due to a contribution from levels in the compound nucleus which are not of the single-particle type. However, it is difficult to make any conclusion about the possible existence of levels other than the peaks shown by our data. Certainly high-resolution data on the $B^{11}(p,\gamma)$ reaction would be very interesting.

All the narrow peaks, found in the energy spectrum, show an angular distribution of the form $(1+1.5\sin^2\theta)$ (Fig. 3). This behavior indicates a large component of single-particle states in agreement with the physical interpretation of the giant resonance given by Wilkinson. Also the behavior of the $C^{12}(\gamma,p)B^{11}$ reaction at about 22-Mev excitation[37] suggests the same conclusion.

[34] D. H. Wilkinson, see reference 33, p. 161.
[35] D. H. Wilkinson, Phil. Mag. **1**, 127 (1956).
[36] D. H. Wilkinson, *Proceedings of the Amsterdam Conference, 1956* (Nederlande Natuurkundige Vereniging, Amsterdam, 1956); Physica **22**, 1039 (1956).

4. CONCLUSIONS

(1) The energy spectrum exhibits a fine structure from which levels in C^{12} may be distinguished at 21.4, 22.9, 23.6, (24.3), 24.8, and 25.6 Mev.

(2) Most of the photoneutron emission occurs predominantly by transition to the ground state of C^{11}, suggesting a direct emission process.

(3) The angular distribution is of the form $1+1.5\sin^2\theta$ for neutrons having energy $(3<E_n<7)$ Mev. The same distribution is valid also for each peak found in the neutron energy spectrum and agrees with the contribution expected according to Wilkinson's independent-particle model for ejection of a neutron from the $l=1$ orbit.

(4) Besides, the coincidence between the peaks obtained in the (γ,n) and (γ,p) processes for the same excitation energy of C^{12}, together with the same conclusions of an independent-particle description of the giant resonance derived from $C^{12}(\gamma,p)$[37] and $C^{12}(\gamma,n)$ processes, suggests that the charge independence of nuclear forces,[38] up to 30-Mev excitation energy in the C^{12} nucleus, is a good approximation.

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