at 145 MeV and a lab angle of 15°.[15] We may safely conclude that the value $\beta=-29°\pm5°$ is the correct one. All the p-carbon results are listed in Table V. The quoted error in A is a quadratic combination of the random error and the 4% systematic error mentioned in the previous section. (The p-carbon measurement followed immediately upon the p-p measurements.)

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Neutron Photoproduction Cross Section of Calcium*

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The photoneutron cross section of natural calcium has been measured from 15 to 30 MeV using the bremsstrahlung from the University of Virginia electron synchrotron. The neutron yields, measured in 0.5-MeV intervals, were used to unfold the photoneutron cross sections both in 1- and 0.5-MeV intervals. The cross section, which reaches the maximum value of 16.8 mb at 20.25 MeV, exhibits considerable structure. Below 21 MeV, it was possible to fit the data to the superposition of four discrete resonance curves of the Gaussian form, $\sigma=\sigma_0\exp\{-[(E_0-E)/\Delta]^2\}$, where σ_0 is the maximum cross section at energy E_0, and the parameter, Δ, is related to the full width at half maximum, Γ, by $\Gamma=2(\ln 2)^{1/2}\Delta=1.67\Delta$. The results are compared with the available shell-model calculations.

The importance of the residual interaction between nucleons in producing the $E1$ giant resonance has been emphasized in several papers.[1–4] Detailed shell-model calculations taking into account the residual interaction have been made extensively for the closed shell nuclei. Recent measurements of[5,6] O^{16} have shown that the calculated dipole-strength distribution is in good agreement with the energy positions of the structure observed in the photoneutron cross section. However, in the region of light nuclei where the (γ,p) cross section is often comparable to, or even larger than the (γ,n) cross section, caution is needed when one compares the partial cross-section data with the calculated absorption strengths. For the doubly magic nucleus, Ca^{40}, both the absorption strengths and the particle emission widths have been calculated,[7] which makes it possible to compare the results directly with the neutron cross-section measurements.

The neutron cross section of natural calcium (96.57% Ca^{40}) was measured using the bremsstrahlung from the University of Virginia 70-MeV electron synchrotron. A cylindrical sample of natural calcium, 3.5 cm in diameter and 14-cm long, was placed at the center of a 4π BF_3 paraffin-neutron detector. The neutrons emitted from the sample were detected by a system of eight BF_3 tubes arranged in a circle at the radial distance of 13.5 cm from the beam axis, with the total detection efficiency of 2.5%. The incident gamma-ray beam was monitored by a National Bureau of Standards type ionization chamber. The neutron yields were measured in 0.5-MeV intervals from 15 to 30 MeV of the bremsstrahlung energy. The neutron yield curve constructed from these measurements was first corrected for the background and the electronic absorption in the sample. The photoneutron cross section was unfolded from the corrected yield curve using the inverse bremsstrahlung matrix.[8]

Figure 1 shows two independent and interlacing sets

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TABLE I. Parameters of the Gaussian curves which fit the 0.5-MeV interval data. The results are compared with the monochromatic data of Ref. 9.

This experiment					Monochromatic data[a]	
E_0 (MeV)	σ_0 (mb)	Δ (MeV)	Γ (MeV)	$\int \sigma dE$ (MeV-mb)	Energy (MeV)	Photoneutron cross section (mb)
16.6	2.5	0.7	1.1	3.0	16.8	3.0
18.0	4.0	0.6	1.0	4.1		
19.0	11.4	0.5	0.9	10.6	19	14
20.25	16.8	0.85	1.4	24.5	20	15
(21.5)	8.1				21.5	11.8
(24.5)	4.5					

[a] See Ref. 9.

of cross sections which were unfolded in 1-MeV in-tervals. Figure 2 shows the cross sections obtained in 0.5-MeV intervals. In addition to the prominent peak at 19.5 MeV, Fig. 1 shows at least three structure-like bumps at 17.0, 21.5, and 24.5 MeV. In Fig. 2, which exhibits more structure below 21.0 MeV, it was possible to fit the data to the superposition of four discrete resonance curves of the Gaussian form,

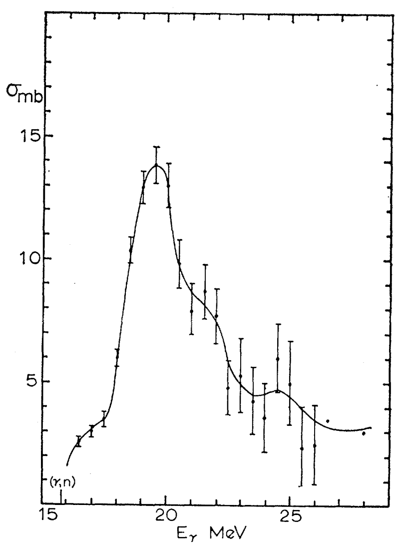

FIG. 1. Photoneutron cross section of calcium unfolded in 1.0-MeV intervals.

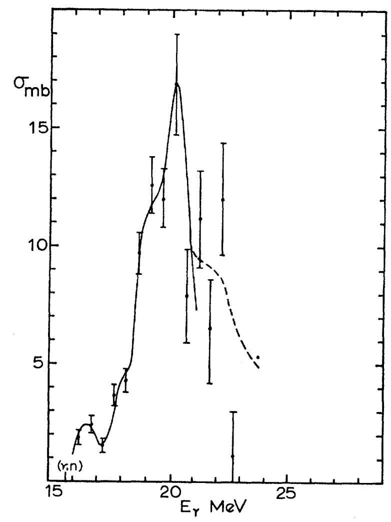

FIG. 2. Photoneutron cross section of calcium unfolded in 0.5-MeV intervals. The solid line represents the superposition of four Gaussian resonance curves listed in Table I.

$\sigma = \sigma_0 \exp\{-[(E_0 - E)/\Delta]^2\}$, where σ_0 is the maximum cross section at energy E_0, and the parameter Δ is related to the full width at half-maximum Γ by $\Gamma = 2(\ln 2)^{1/2}\Delta = 1.67\Delta$. The result is shown by the solid line in Fig. 2. Because of the increasing statistical errors, no attempt was made to fit the data above 21 MeV. It was impossible to reproduce the energy dependence of the cross section by fitting the data to the

TABLE II. Comparison with shell-model calculations.

Our data		Balashov, Schevchenko, and Yudin[a]			Brown, Castillejo, and Evans[b]	
Energy (MeV)	$\int \sigma(\gamma,n) dE$ (MeV-mb)	Energy (MeV)	$\int \sigma_{abs.} dE$ (MeV-mb)	$\int \sigma(\gamma,n) dE$ (MeV-mb)[c]	Energy	Relative dipole strengths
16.6	3.0	16.2	0.5	0.02	16.8	1%
18.0	4.0	18.4	8.8	0.21		
19.0	11.0	18.7	129.0	0.38	19.2	55%
20.25	25.0	19.6	815.0	57.2	20.6	44%
21.5 / 24.5	} ~23.0	24.4	50.0	7.8		
(25.0–28.0)	~10.0					
	$\Sigma = 76.0$		$\Sigma = 1003.3$	$\Sigma = 65.61$		$\Sigma = 100\%$

[a] See Ref. 4.
[b] See Ref. 3.
[c] The integrated neutron cross sections were obtained using the integrated absorption cross sections and the particle-emission widths given in Ref. 4.

Lorentz curves. The parameters of the Gaussian curves which were used to reproduce the data, are listed in Table I, along with the 21.5- and 24.5-MeV cross section values given by the solid line in Fig. 1. Also included for comparison is the previously reported measurements using monochromatic gamma rays.[9] The two sets of data shown in Figs. 1 and 2 are consistent with each other in that the two curves yield the same value of integrated cross section from the neutron threshold up to 21 MeV: The integrated cross section under the solid line in Fig. 1 is 43 MeV-mb in good agreement with 42 MeV-mb which is the sum of four integrated cross sections listed in Table I.

The observed structure in the photoneutron cross section is compared with the available calculations[3,4] in Table II. It is seen from Table II that except for the structure at 21.5 MeV, the energy positions of the observed structure in the photoneutron cross section are in reasonable agreement with the calculations by Balashov *et al.*[4] The integrated photoneutron cross sections also agree fairly well. However, a serious discrepancy exists between our data and the theory in the relative distribution of strengths among the observed states. Our data indicate that the strength concentration above 21 MeV is much more than predicted. The structure at 21.5 MeV, which is not given by the calculations, may correspond to the pronounced peak observed at about 21 MeV in the energy spectra of the photonuetrons[10] from Ca^{40}, and also in the $K^{39}(p,\gamma_0)Ca^{40}$ reaction.[11]

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Gamma Rays from Neutron Capture in Helium-3 and Deuteron Capture in Deuterium*

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The gamma rays from the $He^3(n,\gamma)He^4$ and the $D(d,\gamma)He^4$ reaction have been observed. The gamma detector, a 3-in.×4-in. NaI crystal, was surrounded by a plastic scintillator to eliminate the cosmic-ray background. A pileup rejection circuit was used to reduce the background from neutron induced reactions in the NaI. The cross section of the $He^3(n,\gamma)He^4$ reaction at 4 MeV is $\sigma = 5\ \mu$b/sr at 90°. The intensity ratio, $I(90°/I(45°)\approx 2$, agrees with that expected for electric dipole radiation ($\Delta M=0$). The $D(d,\gamma)He^4$ reaction at 1.35 MeV has a cross section $\sigma = 2\times 10^{-33}$ cm²/sr at 45°.

INTRODUCTION

THE calculation of electromagnetic-transition probabilities is a good method for testing the correctness of the wave functions of the pertinent nuclear states. Some attempts have been made to calculate the excitation function of the $T(p,\gamma)He^4$ reaction,[1–4] which occurs predominantly with emission of electric dipole radiation, and to get an agreement with the experimental data. Wave functions, which give the proper binding energy of the ground state of the alpha particle, do not give an excitation function in agreement with experiments.[5] The maximum cross section always occurs at too high a proton energy. To eliminate this discrepancy, an excited state of the alpha particle has been suggested.[6]

There are two other capture reactions whose final state is an alpha particle but which has not been observed:

$$He^3 + n \rightarrow He^4 + \gamma,$$
$$D + D \rightarrow He^4 + \gamma.$$

The calculation of their cross section also, of course, would allow some testing of the wave function of the alpha particle. This experiment was performed to obtain data on these two reactions.

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