there is some degree of correspondence between the approximations L and R, at least enough so that the smallest remains smallest and the largest remains largest. The same may not be said for the exchange case. However, in both cases, the values of L are uniformly smaller than of R; that is, the nondiagonal elements calculated with pair interactions are relatively smaller than those calculated with V_i. The very small influence of the nondiagonal elements of V_i on the shape, a third of a percent as indicated in Table II, seems to come about largely by cancellations of effects of various nondiagonal elements but is still some rough measure of the magnitude of the nondiagonal elements. A similar calculation based on the pair interactions rather than of V_i would apparently involve somewhat smaller matrix elements, among which there would also be cancellations of some sort. It thus seems plausible to take the smallness of the influence calculated with V_i as an indication that the result calculated with pair interactions would likewise be quite small.

The determination of nuclear shape by minimizing the oscillator energies at constant volume is a schematic approach which probably owes most of its success to the fact that it takes kinetic energies into account to a fairly good approximation, at the same time making a rough estimate of the change in potential energy which is in reality much too complicated to have been treated adequately. Our remarks on the effect of nondiagonal elements of V_i display the effective consistency of the approximate treatment. The remarks on pairwise interactions give an inadequate hint of how this might be related to the more fundamental nuclear problem.

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Fine Structure in the Energy Spectra of Photoprotons from He^4

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The energy spectra of the photoprotons from He^4 irradiated with 31 and 32-Mev bremsstrahlung were studied by means of nuclear photoemulsions in ΔE_γ steps of 0.133 Mev. In the region of the giant resonance several peaks have been distinguished. The more evident of these have widths less than 0.5 Mev and are located at He^4 excitation energies of 24.7±0.2 and 26.1±0.1 Mev. Previous experiments on the photoproton spectra from He^4 could not give evidence of these narrow resonances because the spectra were examined in energy steps much larger than the width of these resonances.

Other types of experiments which have been performed in order to obtain information on the existence of excited states in He^4 are discussed. The fact that narrow resonances are distinguished only in the present experiment is attributable to the selective nature of the (γ,p) process, the most important contribution in the $He^4(\gamma,p)$ reaction coming only from the states of He^4 having $J=1^-$ and $T=1$.

I. INTRODUCTION

THE experiments on the $He^4(\gamma,p)$ reaction performed up to now give the energy spectra of the photoprotons from helium in large energy steps: Gaerttner and Yeater,[1] with a bremsstrahlung beam of $E_{\gamma\max}=100$ Mev, studied the $He(\gamma,p)$ reaction with a cloud chamber. The photoproton spectrum is given up to $E_\gamma=30$ Mev in ΔE_γ energy steps of several Mev. Fuller,[2] with bremsstrahlung spectra having $E_{\gamma\max}=25$, 29, 32, and 40 Mev, studied the same reaction with nuclear emulsions. The photoproton spectra are given in steps of $\Delta E_\gamma=1$ Mev. Gorbunov and Spiridonov,[3] with a bremsstrahlung beam of 170 Mev, studied the $He(\gamma,p)$ reaction with a cloud chamber located in a magnetic field. The energy spectrum of the photoprotons is given in ΔE_p steps of several Mev.

The aim of the present experiment is to study the $He(\gamma,p)$ reaction in order to obtain photoproton spectra with better energy resolution in the giant resonance region. The peak of the giant resonance is found by Fuller[2] at $E_\gamma\approx 26$ Mev. According to Reid *et al.*[4] the excitation function appeared to have a maximum in the region of 26 Mev and to decrease more rapidly with increasing energy than indicated by Fuller. According to Gorbunov *et al.*[3] the cross section reaches the maximum value at 27–28 Mev and decreases with increasing energy less rapidly than indicated by Fuller. No evidence for resonances having widths less than several Mev has been found.

II. EXPERIMENTAL PROCEDURE

A helium gas target has been irradiated with a collimated bremsstrahlung beam of $E_{\gamma\max}=32$ Mev from the betatron of Turin University. The photoprotons have been recorded by means of Ilford C2 nuclear emulsions 200 μ thick placed inside a chamber filled with helium gas. Four nuclear emulsions were placed parallel to the γ-ray beam as shown in Fig. 1.

[1] E. R. Gaerttner and M. L. Yeater, Phys. Rev. **83**, 146 (1951).
[2] E. G. Fuller, Phys. Rev. **96**, 1306 (1954).
[3] A. N. Gorbunov and V. M. Spiridonov, J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 21 (1957) [translation: Soviet Phys.-JETP **6**, 16 (1958)]; *Comptes Rendue du Congres International de Physique Nucléaire Interactions Nucléaires aux Basses Energies et Structure des Noyaux, Paris, July, 1958*, edited by P. Guggenberger (Dunod, Paris, 1959), p. 682.
[4] J. M. Reid, P. Swinbank, and J. R. Atkinson, Physica **22**, 1142 (1956).

The mean distance between the target of the betatron and the photoplates was 110 cm. The plates were developed using the standard technique. The observations were made with binocular microscopes using 55× oil immersion objectives.

The following measurements were made on each track entering the surface of the emulsion: (1) the coordinates of the end of the track in the emulsion; (2) the angle θ projected in the plane of the emulsion between the first 50 μ of the track and the direction of the γ beam; (3) the angle β of dip of the track in the emulsion. The range of the track in the emulsion was obtained from the range of the projection of the track in the plane of the plate and the dip of the track corrected for the shrinkage of the emulsion. The energy of each photoproton was obtained from the range in the emulsion, taking into account for each

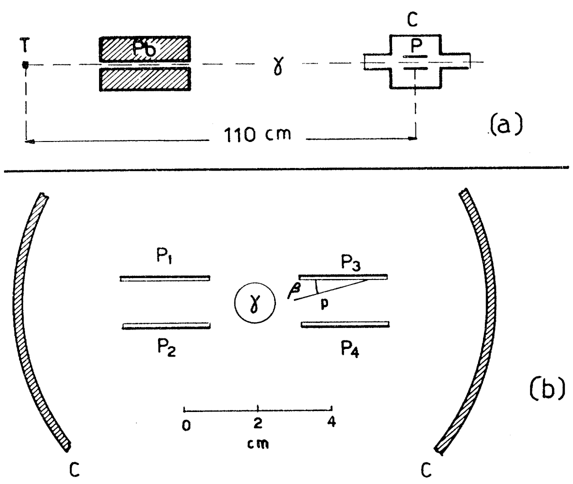

FIG. 1. (a) Experimental arrangement; (b) disposition of the photoplates. T=target of the beatron; Pb=lead collimator; C=chamber filled with He; P=nuclear photoplates 1 in. × 3 in. parallel to the γ beam; γ=collimated γ-ray beam from the betatron; p=photoproton.

track the range Δr corresponding to the length traveled in the gas of the chamber. Only tracks that entered the plates with a dip angle $\beta \leq 30°$ have been accepted. Tracks with $70° \leq \theta \leq 110°$ respect to the γ-ray beam have been selected. The mean length from the helium target to the scanned area of the plate was equivalent to a range Δr in emulsion of 16 ± 4 μ for tracks with $\theta = 90°$.

Another experiment was made at $E_{\gamma\max} \approx 31$ Mev in which the proton tracks were observed in a plate placed perpendicularly to the γ beam, as in a previous work.[5] Some data of the experiment are summarized in Table I. In Table II are summarized the reactions that may occur in He^4 irradiated with 32-Mev bremsstrahlung. As Table II shows, the contribution of the tracks arising from the reactions (c), (d), and (e) is negligible in our experiment because the corresponding cross sections are very low. The H^3 and He^3 recoil nuclei arising from the reactions (a) and (b) give a contribution of tracks having a maximum range less than 50 μ. Processes different from $He^4(\gamma,p)$ are certainly excluded if we limit our analysis to the tracks having a total range greater than 60 μ, namely, to protons having energy $E_p > 2{,}6$ Mev.

TABLE I. Characteristic data of the present He(γ,p) experiment

$E_{\gamma\max}$(Mev)	31	32		
Plates	Orthogonal to γ ray	Parallel to γ ray		
Helium gas pressure (atm)	2	3	3	3
Field view at the microscope	170 μ	Plate 1 170 μ	Plate 2 270 μ	Plate 3 270 μ
θ angle between γ-ray beam and photoproton	90°	90°±20°	90°±10°	90°±20°
Scanned area mm²	320	241	288	306
Number of accepted tracks	202	664	330	713

III. EXPERIMENTAL RESULTS AND DISCUSSION

The photoproton energy spectrum at $\theta = 90°$ obtained from the analysis of the plate exposed perpendicularly to the γ rays is reported in Fig. 2. Peaks at 3.5–4 Mev and 5.5–6 Mev may be seen. From energy and momentum conservation it may be deduced that the energy of the photon is related with sufficient accuracy to the energy of the observed photoproton by the relation:

$$E_\gamma = \frac{(4/3)E_p + E_T}{1 + (2E_p/9m_0c^2)^{\frac{1}{2}} \cos\theta}, \qquad (1)$$

where m_0c^2 is the proton rest energy and $E_T = 19.8$ Mev the threshold energy for the $He^4(\gamma,p)$ reaction.

The proton energy spectrum $N_p(E_\gamma)$, has been obtained taking into account for each proton the relation (1). The energy spectrum $N_p(E_\gamma)$ obtained from the analysis of the tracks of the protons observed in the interval $70° < \theta < 110°$ is reported in Fig. 3 in steps of $\Delta E_\gamma = 0.133$ Mev; the correspondence between E_p and E_γ for $\theta = 90°$ is also reported. This spectrum has been obtained from the analysis of accepted tracks of protons, observed in three plates exposed parallel to the γ ray. The three partial results agree within the

TABLE II. Possible reactions in He^4 with 32-Mev bremsstrahlung.

Reaction	Threshold energy (Mev)	$E(\sigma_{\max})$ (Mev)	$\sigma_{\max}$ (mb)	References
(a) $He^4(\gamma,p)H^3$	19.8	26	1.8	(a)
$He^4(\gamma,p)H^3$	19.8	27–28	1.8	(b)
(b) $He^4(\gamma,n)He^3$	20.6	27–28	1.6	(c)
(c) $He^4(\gamma,d)D$	23.7	low yield		(b)
(d) $He^4(\gamma,pn)D$	25.9	50	0.2	(d)
(e) $He^4(\gamma,2p2n)$	28.1	very low yield		(b)

[a] See reference 2. [b] See reference 3.
[c] A. N. Gorbunov and V. M. Spiridonov, J. Exptl. Theoret. Phys. (U.S.S.R.) 34, 862 (1958) [translation: Soviet Phys.-JETP 7, 596 (1958)].
[d] A. N. Gorbunov and V. M. Spiridonov, J. Exptl. Phys. (U.S.S.R.) 34, 866 (1958) [translation: Soviet Phys.-JETP 7, 600 (1958)].

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

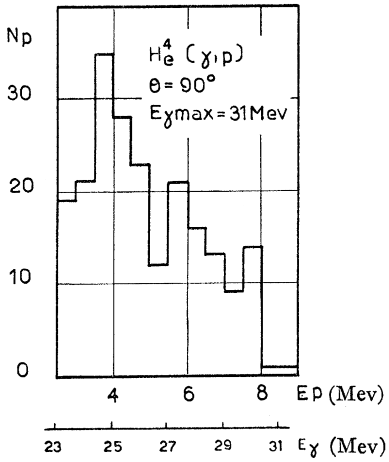

FIG. 2. Photoproton spectrum from He in ΔE_γ steps of 0.5 Mev at 90° (plat perpendicular to the γ beam).

statistical uncertainties. The contribution of proton tracks from possible impurities was negligible.

Several peaks may be seen in the spectrum shown in Fig. 3. In the same Fig. 3 is reported in steps of $\Delta E_\gamma = 1$ Mev the spectrum obtained by Fuller for $20° < \theta < 160°$ with 32-Mev bremsstrahlung. A rough agreement in the mean behavior of the two spectra may be seen.

In Fig. 4 is reported the differential cross section $\sigma(\gamma,p)$ for $70° < \theta < 110°$ obtained by dividing our proton spectrum $N_p(E_\gamma)$—reported in Fig. 3—by the bremsstrahlung spectrum $N_\gamma(E_\gamma,32)$.

It is seen from Fig. 4 that the mean behavior of the differential cross section at $90° \pm 20°$ is not in disagreement with the behavior of the cross section found previously by Fuller[2] and by Gorbunov and Spiridonov.[3] One should remember that Fuller's results refer to the θ interval from 20° to 160° and the results of Gorbunov and Spiridonov refer to all proton angles. In addition to this general behavior our data show a fine structure: peaks at 24.7 ± 0.2 and 26.1 ± 0.1 Mev may be distinguished—Figs. 3 and 4. Other peaks may be seen around 26.9 and 27.8 Mev.

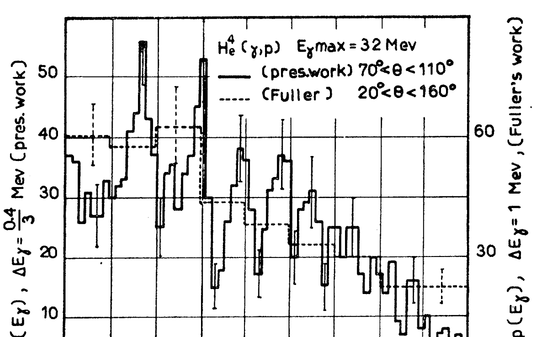

FIG. 3. Photoproton spectrum from He in ΔE_γ steps of 0.133 Mev; $70° < \theta < 110°$ (plates parallel to the γ beam). The correspondence between E_p and E_γ for $\theta = 90°$ is reported. The statistical root mean square errors are indicated. The legend on the left-hand side of the figure should read 0.133, rather than 0.4/3.

The preceding experiments[1–3] on the photoproton spectra from He cannot give evidence of the narrow resonances found here because the spectra were examined in steps much larger than the width of the resonances found in the present work.

Other types of experiments have been performed in order to obtain information on the existence of excited states in He^4:

(a) $T(p,\gamma)$

Rochlin[6] has studied the energy spectrum of γ rays with a proton beam of 0.96 Mev. No evidence has been found for transitions other than that to the ground state of He^4. Experiments on the yield of the $T(p,\gamma)$ have been performed with protons up to 2.6 Mev by Argo *et al.*,[7] up to 5 Mev by Willard *et al.*,[8]

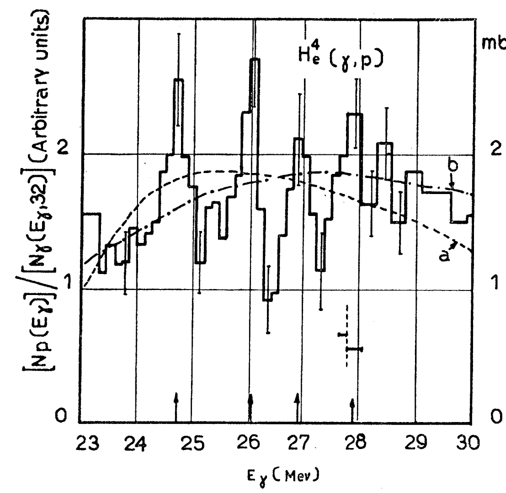

FIG. 4. Histogram: $He(\gamma,p)$ differential cross section derived from the $90° \pm 20°$ spectrum of Fig. 3 (present work) in arbitrary units. Curve (a): $He(\gamma,p)$ cross section in millibarns according to Fuller.[2] Curve (b): $He(\gamma,p)$ cross section in millibarns according to Gorbunov and Spiridonov.[3]

and up to 6.2 Mev by Perry *et al.*[9] in ΔE_p steps of about 0.1 Mev. A broad maximum around $E_p = 4$ Mev has been found. No evidence for narrow levels in He^4 has been found. The quoted experiments on the $T(p,\gamma)$ yield refer to excitation energies in He^4 from about 20 to about 24.4 Mev.

(b) $T(p,n)$

This reaction shows a maximum with $\Gamma > 1$ Mev around $E_p = 3$ Mev.[8,10,11] According to Baz *et al.*[12] these

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[7] H. V. Argo, H. T. Gittins, A. Hemmendinger, G. A. Jarvis, and R. F. Taschek, Phys. Rev. **78**, 691 (1950).

[8] H. B. Willard, J. H. Bair, and J. D. Kington, Phys. Rev. **90**, 865 (1953).

[9] J. E. Perry and S. J. Bame, Phys. Rev. **99**, 1368 (1955).

[10] N. A. Vlasov, S. P. Kalinin, A. A. Ogloblin, L. M. Samoilov, V. A. Siridov, and V. I. Chuev, J. Exptl. Theoret. Phys. (U.S.S.R.) **28**, 639 (1955) [translation, Soviet Phys.-JETP **1**, 590 (1955)].

[11] G. F. Bogdanev, N. A. Vlasov, C. P. Kalinin, B. V. Rybakov, L. N. Samoilov, and V. A. Siridov, J. Exptl Theoret. Phys. (U.S.S.R) **36**, 630 (1959) [translation, Soviet Phys.-JETP **36**(9), 440 (1959)], and references quoted here.

experiments can be interpreted as indicating the system H^3+p to have two broad levels $J=2^-$, isotopic spin $T=0$ at 22 Mev and $J=1^-$, $T=0$ about 1–2-Mev higher. These experiments have been performed with proton beams from 1 to 12 Mev, which correspond to excitation energies in He^4 from about 21 to about 29 Mev.

(c) $He^4(p,p)$

Experiments performed with 32 Mev[13] and 40 Mev[14] protons give no evidence of excited states in He^4. The experiments performed by Selove *et al.*[15] with 95-Mev protons could indicate the existence of a broad virtual level, or group of levels, with $\Gamma\sim 10$ Mev about 25 Mev above the ground state. The proton energy resolution was of the order of 1 Mev.

It is seen that most of the experiments quoted above give evidence of broad resonances with a Γ of several Mev. None give evidence of the narrow resonances found in the present work. It should be noted however that of all the quoted experiments only the $T(p,n)$ measurements reported by Bogdanov *et al.*[11] had sufficiently good proton energy resolution (about 0.1 Mev) and an appropriate He^4 excitation energy interval to have given evidence of the resonances found here. The fact that narrow resonances are distinguished only in the present experiment may be due to the relatively good energy resolution employed and to the selective nature of the (γ,p) process.

At photon energies in the neighborhood of the giant resonance, electric dipole absorption is expected to be predominant. Thus in the reaction $He(\gamma,p)$ the most important contribution should to come from $J=1^-$ He^{4*} states of $T=1$, since the selection rules do not allow $\Delta T=0$ dipole absorption by nuclei with $A=2Z$.

These states may be expected in He^4 at excitation energies as high as found in the present work (>20 Mev) because in the nuclei O^{16}, C^{12}, and Be^8 ($A=4n=2Z$) the lower excited states with $J=1$ and $T=1$ are located many Mev above the ground state and the corresponding excitation energies are higher for lighter nuclei [O^{16}: $E_x=13.09$ Mev, $J=1^-$ ($T=1$). C^{12}: $E_x=15.11$ Mev, $1^+(1)$; $E_x=17.23$ Mev, $1^-(1)$. Be^8: $E_x=17.64$ Mev, $1^+(1)$.][16,17] In the reaction $T(p,n)$, He^4 states having $T=0$ and $T=1$ may be excited (T transitions $0\rightarrow 0$ and $1\rightarrow 1$). The fact that peaks have been found only in the $He(\gamma,p)$ reaction might indicate that transitions involving the states with $J=1^-$, $T=1$ are weak in the $T(p,n)$ reaction in comparison with other transitions.

We expect that the $T=1$ levels distinguished in the photoproton spectrum would be also revealed by the $T(p,\gamma)$ reaction at proton energies higher than have been used in experiments already reported. Also experiments on the photoneutron spectra from He should give the same indication as the photoproton spectra; this experiment is in process.

It is relevant to note that a level whose width is only 100 kev has been found recently at 16.7 Mev in He^5 by means of the $He^4(n,n)$ reaction.[18]

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Interpretation of Isomeric Cross-Section Ratios for (n,γ) and (γ,n) Reactions*

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The relative probability of forming each member of a pair of nuclear isomeric states has been compared with theoretical predictions in order to learn which nuclear parameters can be determined from these data. For thermal neutron capture reactions, the observed ratios do not give much information about the dependence of the nuclear level density on spin, but they are consistent with a spin cutoff factor, $\exp[-(J+\frac{1}{2})^2/2\sigma^2]$, where $\sigma\leq 5$. The calculations are sufficiently consistent with experiment to make their predictions usable as a guide for assigning spins to the compound states formed in thermal or resonant energy neutron capture. For (γ,n) reactions, the calculations reproduce the energy dependence of the experimentally observed isomeric cross-section ratios. In order to obtain quantitative information about the spin dependence of the nuclear level density, it is necessary to consider reactions where particles are emitted which can carry off enough angular momentum to reach many spin states of the residual nucleus.

1. INTRODUCTION

THE relative probability of forming each state of an isomeric pair seems to be governed mainly by the spin differences between the states which decay to the isomers and the isomer spins themselves. In the many cases (encountered in radioactivity) in which a third low-lying state can decay to either of the isomers, the well-known preference of the photon transition of

* Based on work performed under the auspices of the U. S. Atomic Energy Commission.