so that

$$M_z=(\psi_{nlj\tau}{}^j, [g_{l\tau}l_z+g_{s\tau}s_z]\psi_{nlj\tau}{}^j)\sum_q |C_q|^2 \sum_i \frac{m(q_i)}{j},$$

and, finally,

$$M_z=(M/j)(M_z)_{nlj\tau}. \quad (32)$$

APPENDIX II

Let an arbitrary number of nucleons in the $nlj\tau$ subshell couple to a state with angular momentum J and an arbitrary number of nucleons from the $n'l'j'\tau'$ subshell couple to a state with angular momentum J', and let these two states couple together to angular momentum 2 with maximum projection:

$$\Phi_2{}^2=\sum_M a_M \varphi_J{}^M(1)\varphi_{J'}{}^{2-M}(2), \quad (33)$$

where 1 and 2 refer to the coordinates of the nucleons in the respective subshells, and the a_M are the Clebsch-Gordon coefficients. The states $\varphi_J{}^M$ and $\varphi_{J'}{}^M$ are of the form described in Appendix I, with the quantum numbers describing the subshell suppressed. Since only diagonal terms of the expectation value of the moment operator survive,

$$M_z=\sum_M |a_M|^2[(\varphi_J{}^M(1), \mu_{z1}\varphi_J{}^M(1)) + (\varphi_{J'}{}^{2-M}(2), \mu_{z2}\varphi_{J'}{}^{2-M}(2))]. \quad (34)$$

Using Eq. (10) and realizing that

$$\sum_M |a_M|^2 M=\langle J_{z1}\rangle, \sum_M |a_M|^2(2-M)=\langle J_{z2}\rangle,$$

(34) yields, using the results of the previous Appendix:

$$M_z=\frac{\langle J_{z1}\rangle}{j}(M_z)_{nlj\tau}+\frac{\langle J_{z2}\rangle}{j'}(M_z)_{n'l'j'\tau'}. \quad (35)$$

If $J=J'$, then $\langle J_{z1}\rangle=\langle J_{z2}\rangle=1$, giving the result (16).

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Elastic Photoproduction of π^0 Mesons in Helium and (γ,n) Reaction on Helium at High Energies*

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The "elastic" photoproduction of π^0 mesons in helium has been measured as a function of center-of-mass angle for gamma-ray energies from 170 Mev to 340 Mev. The total cross section shows a maximum around 270-Mev excitation energy and the angular distribution at 300-Mev peaks around 65° in the center-of-mass system. An attempt has been made to interpret the results in terms of the differential cross section for photoproduction of π^0 mesons in hydrogen, and to obtain (from the amount of interference of the waves emitted by the four nucleons) a value for the "mean radius" of the alpha particle and the relative phase of π^0 emission from proton and neutron.

The photodisintegration reaction $\gamma+He^4\rightarrow He^3+n$ has also been investigated. The angular distribution of the He^3 recoil nuclei is found to be proportional to $\sin^2\theta$ for excitation energies between 40 Mev and 120 Mev.

I. INTRODUCTION

BY "elastic" photoproduction of π^0 mesons in helium, we mean the process in which the helium nucleus is not disintegrated, i.e., the process $\gamma+He^4\rightarrow He^4+\pi^0$.

The photoproduction of π^0 mesons on hydrogen has been investigated by many researchers.[1–4] Other authors have also observed the elastic photoproduction of π^0 mesons in deuterium[5,6] and helium.[7,8] The group at the University of Illinois has compared the elastic and inelastic processes at different energies and found that the elastic process was still relatively important at an excitation energy of 190 Mev. They also find a ratio of production of π^0 mesons per nucleon in hydrogen and helium of about one. The purpose of this experiment was to measure the angular distribution, excitation curve, and total cross section for elastic photoproduction of π^0 mesons in helium. These are strongly affected by interference effects of the meson waves emitted by the four nucleons. The shapes of the angular distribution and the excitation curve depend on the mean distance between the nucleon and the data on those curves can be analyzed so as to obtain a "mean radius" of the alpha particle. The relative efficiency for elastic photoproduction of mesons, of the helium nucleus, and of the proton depends further on the relative phase of

* This work has been supported in part by the joint program of the U. S. Atomic Energy Commission and the Office of Naval Research.

1 Panofsky, Steinberger, and Steller, Phys. Rev. **86**, 180 (1952).
2 A. Silverman and M. Stearns, Phys. Rev. **88**, 1225 (1952).
3 G. Cocconi and A. Silverman, Phys. Rev. **88**, 1230 (1952).
4 Goldschmidt-Clermont, Osborne, and Scott, Phys. Rev. **89**, 329 (1953); Phys. Rev. **97**, 188 (1955).
5 DeWire, Silverman, and Wolfe, Phys. Rev. **92**, 520 (1953); Phys. Rev. **94**, 756 (1954).
6 H. L. Davis and D. R. Corson, Phys. Rev. **94**, 756 (1954).
7 G. DeSaussure and L. S. Osborne, Phys. Rev. **94**, 756 (1954).
8 Goldwasser, Koester, and Mills, Phys. Rev. **95**, 1692 (1954).

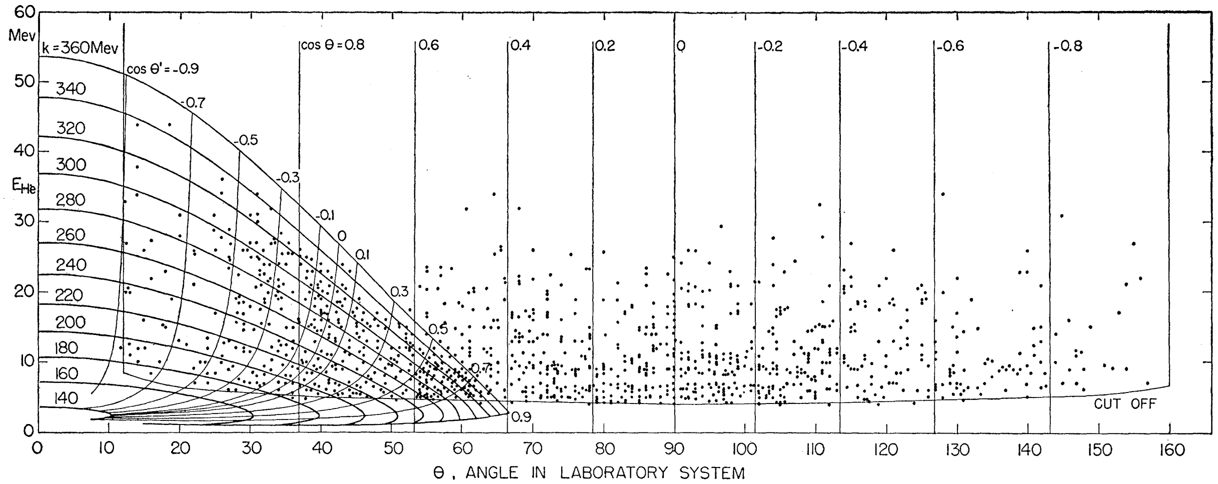

FIG. 1. Plot of events for last high-energy run. Each dot represents a recoil helium nucleus plotted with respect to its angle in the laboratory system and its energy determined from the total range. The superimposed lines give the energy of the photon responsible and the cosine of the meson center-of-mass angle. The points occurring outside this plot are mainly He^3 recoils from the photodisintegration process. The vertical lines are at equal cosθ intervals in the laboratory system. The cutoff gives a lower limit of observable tracks because of absorption in the gas or shadowing of the collimator.

meson emission by neutrons and by protons. This phase thus also can be obtained from the experimental data.

II. EXPERIMENTAL PROCEDURE

The experimental data were acquired in three runs. The experimental procedure is very similar to the one described by Goldschmidt-Clermont *et al.*[4] The gamma-ray beam from the Massachusetts Institute of Technology electron-synchrotron was passed through a helium tank and nuclear plates were placed around the beam to record the recoil nuclei from the various meson production and disintegration processes. The electron beam was accelerated to an energy of 350 Mev (calibrated by magnetic field measurement) and then made to strike a 0.06-inch tungsten wire. The resulting x-ray beam has an angular spread of about 0.3°. It was passed through a defining lead collimator so as to have a rectangular cross section of 0.5×1 inch at the position of the plate holder. The beam entered the helium tank through a 1/64 inch aluminum window and left through a 1/16 inch aluminum window. Two four-inch walls screened the plates from particles coming from the windows. The helium tank comprised four sections bolted together through large vacuum-tight flanges. A small "darkroom" was built where the two last sections join, and the plates were introduced in the tank from that point. The plates were mounted on an aluminum plate holder which was slipped into the center of the tank. The tank and collimators were optically aligned with respect to the beam, and this alignment checked with an x-ray picture. The plates were then inserted into the tank and the tank evacuated. After two helium gas flushings, the tank was filled with pure (medical) helium at a pressure of one atmosphere. Impurities in the tank were smaller than 0.5 percent by volume. The total intensity of the beam was monitored by a thick-walled ionization chamber down-stream. This chamber was later calibrated with respect to a portable ion chamber, which had been calibrated at the Cornell synchrotron[4] and the University of Illinois betatron.[4]

The main problem of this experiment was to differentiate those recoil nuclei associated with the elastic photoproduction process from those arising from different photodisintegration processes. For this purpose, it was necessary to be able to discriminate between singly and doubly charged particles. Ilford GO nuclear plates were found to be best suited for this discrimination. The plates were under-developed by the method described by the Bruxelles group[9] (hot stage of $\frac{1}{2}$ hr at 15°C).

Various tests were made to check this discrimination: Some plates were exposed to the neutron flux near the Massachusetts Institute of Technology cyclotron. When under-developed, proton tracks were barely visible, while those alpha tracks connected with Thorium stars were still clear. About a hundred tracks were grain counted near the end of their range. Those tracks could be divided into two groups: some tracks, barely visible, had between 20 and 50 grains in the last 70 microns, others had between 70 and 130 grains for the same remaining range. Finally, by counting the number of grains *versus* the remaining range for one alpha track, one can predict the number of grains for the last 70 microns of other tracks,[10] this number turns out to be 20 for protons and 40 for tritium. It was not found

[9] Dilworth, Occhialini, Vermaesen, and Bonetti, Bull. centre phys. nucléaire univ. libre Bruxelles, Nos. 13a and 13b (1950).

[10] Lattes, Occhialini, and Powell, Proc. Phys. Soc. (London) **61**, 173 (1948).

possible to discriminate between single He^4 and He^3 tracks.

Plates of 100μ and 400μ were disposed in the collimator with one edge parallel to the direction of the beam and in such a way that the particles would come from the beam into the plates at a grazing angle (maximum dip of 40°). About 2000 tracks were scanned, and for each track the dip, the angle with the beam, and the total range were measured. The range measured was corrected to take into account the gas traversed by the particle before reaching the plate, and from this corrected range, the energy was deduced.

III. DATA

A surface of about 20 cm^2 of emulsion was scanned. All helium tracks stopping in the emulsion were recorded on a plot similar to Fig. 1. In this plot each track is represented by a dot, its abscissa corresponding to the angle it makes with the beam (in the laboratory system), its ordinate corresponding to its energy (as calculated from its range). These helium recoil tracks may arise from the Compton photoeffect on the helium nucleus, from photodisintegration, or from elastic or inelastic π-meson production, i.e., they may arise from one of the following reactions[11]:

(a) $\gamma+He^4\rightarrow He^4+\gamma$,

(b) $\gamma+He^4\rightarrow He^3+n$,

(c) $\gamma+He^4\rightarrow\pi+He^3+$nucleon,

(d) $\gamma+He^4\rightarrow\pi^0+He^4$.

We have grounds to assume that the nuclear Compton effect has a relatively small cross section: this cross section should be of the order or smaller than the Thompson cross section (2×10^{-31} cm^2). Experimental evidence seems to indicate even a much smaller value.[12] (The cross sections for photodisintegration or for photoproduction of π mesons are of the order of 10^{-28} cm^2.) In the inelastic photoproduction of π mesons, the He^3 nucleus will acquire very little recoil. It is not possible to predict exactly the dynamical variables involved in this three-body process. If one assumes either that the He^3 "sits by" the reaction, or that the three outgoing particles share the energy in such a way as to have the largest phase space available, the He^3 nucleus will acquire at most a recoil energy of 5 to 10 Mev, and will usually be stopped in the gas between the beam and the plates. The problem remains to separate the photodisintegration from the elastic photoproduction processes. These are two-body processes in which an exact relation can be calculated between the angle of emission and the recoil energy (for a specified gamma-ray energy). The diagram in Fig. 1 represents the cosine of the angle in the center-of-mass system of the emitted π meson and the energy of the gamma rays relative to the angle and energy in the laboratory system of the recoil helium nucleus, for the elastic photoproduction reaction. The tracks represented by points outside the diagram are associated with the photodisintegration process. Those inside the diagram may be associated with the photodisintegration or the elastic photoproduction processes. The kinematics of the photodisintegration process shows that all those recoil He^3 nuclei with energies less than 40 Mev must be associated with gamma rays of energies less than 150 Mev. Thus, a special low-energy run was made to study the angular distribution of the He^3 recoil nuclei from the photodisintegration of helium at gamma-ray energies below 150 Mev. This run was performed in exactly the same arrangement as the high-energy run, but with a maximum gamma-ray energy of the synchrotron beam of 160 Mev. The tracks of this run have been represented on a graph similar to the one of Fig. 1.

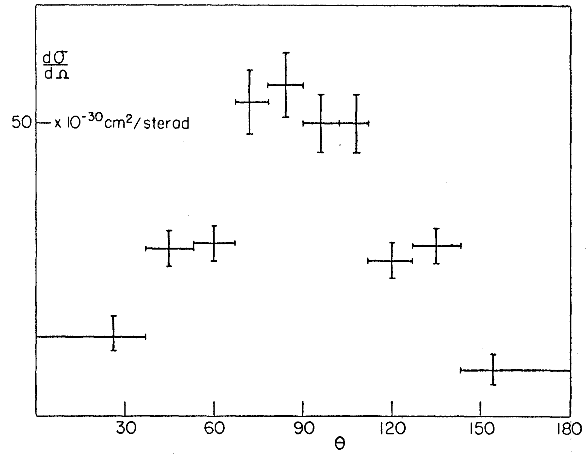

FIG. 2. Angular distribution in the laboratory system of recoil helium tracks from the reaction $\gamma+He^4\rightarrow He^3+n$. This is an average over excitation energies from 36 Mev to 84 Mev.

The angular distribution of He^3 recoil tracks of energies between 5 and 30 Mev is shown in Fig. 2 and Fig. 3. Figure 2 shows the angular distribution of He^3 from the reaction $\gamma+He^4\rightarrow He^3+n$ for excitation energies between 36 Mev and 84 Mev. Figure 3 shows the same curve for excitation energies from 84 to 132 Mev. These two curves have been made by using the data of the low-energy run and that of the high-energy run for large angles. They show that the background is nearly proportional to $\sin^2\theta$ in the laboratory system. Namely, if the background is assumed to be of the form $A\sin^2\theta+B\cos\theta+C$, then the constants that best fit the experimental points are given in the following table, in units of 10^{-30} cm^2/sterad.

E_γ	A	B	C
36 Mev–84 Mev	47.2±5	9.3 ±10	2.7±2.5
84 Mev–132 Mev	12.8±1	4.22± 6	1.5±1

[11] We have assumed that there is no bound state of the He^4 nucleus. Hornyak, Lauritsen, and Morrison, Revs. Modern Phys. **22**, 291 (1950).

[12] Pugh, Frisch, and Gomez, Phys. Rev. **95**, 590 (1954).

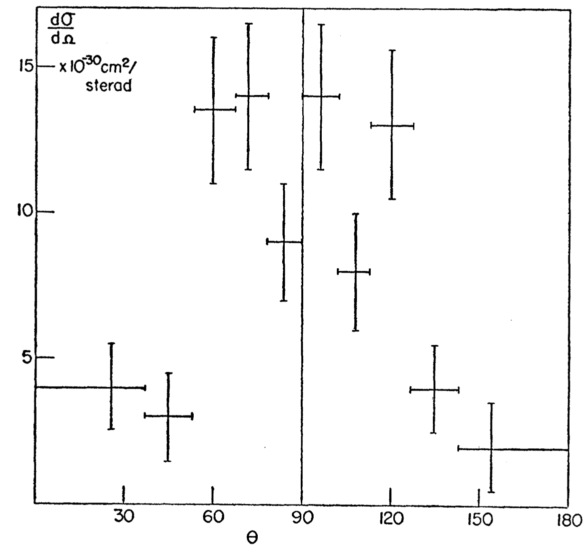

FIG. 3. Angular distribution in the laboratory system of recoil helium tracks from the reaction $\gamma+He^4\rightarrow He^3+n$. This is an average over excitation energies from 84 Mev to 132 Mev.

Similar results have been found for the reaction[13] $He^4(\gamma,p)H^3$, and there are theoretical reasons to assume a $\sin^2\theta$ distribution: It is reasonable that the main contribution to the $He^4(\gamma,n)He^3$ reaction is due to an electric dipole interaction.[14] To conserve parity and angular momentum, the neutron must be emitted in a P-wave. This, when averaged over polarization of the gamma ray, leads to a $\sin^2\theta$ distribution in the center-of-mass system. The retardation factor for the He^3 and the motion of the center-of-mass are small corrections which should favor the forward angles. These two effects are small due to the large mass of the He^3 nucleus. This may explain why they are not observed in the experimental results. Calculations by Flowers and Mandl[14] and by Gum and Irving[14] give a value for the cross section of the reaction $\gamma+He^4\rightarrow He^3+n$ around 40 Mev which correspond approximately to the value 0.5×10^{-27} cm² found in this experiment. Fuller[13] finds experimentally a somewhat lower value (0.1×10^{-27} cm²).

IV. THE RESULTS

The angular distribution of He^3 recoils from the $He^4(\gamma,n)He^3$ process is shown in Fig. 2 for low excitation energy and in Fig. 3 for high excitation energy. The excitation function of this process is shown in Fig. 4.

The differential cross section for elastic photoproduction of neutral π mesons, averaged over an energy interval from 280 Mev to 340 Mev, in the center-of-mass system, is shown in Fig. 5. The large statistical errors quoted come from the fact that a large background must be subtracted from the observed distribution.

Figure 6 shows the differential cross section for elastic photoproduction at 90° in the center-of-mass system.

V. DISCUSSION

It is interesting to compare the cross section for elastic photoproduction of mesons on helium with the cross section for photoproduction of neutral mesons in hydrogen. There have been many calculations of the elastic photoproduction of π mesons in deuterium. Those were done under the impulse approximation.[15] The validity of the approximation for the helium case is very questionable for the following reasons: (1) The distance between nucleons can hardly be considered as large compared to the radius of interaction; (2) the multiple scattering should not be completely neglected; and (3) the strong nuclear forces binding the nucleus may modify the characters of the nucleons. However, the impulse approximation may allow at least a qualitative interpretation of the results.[16] Under the impulse approximation, the cross section for elastic photoproduction of mesons on helium can be written:

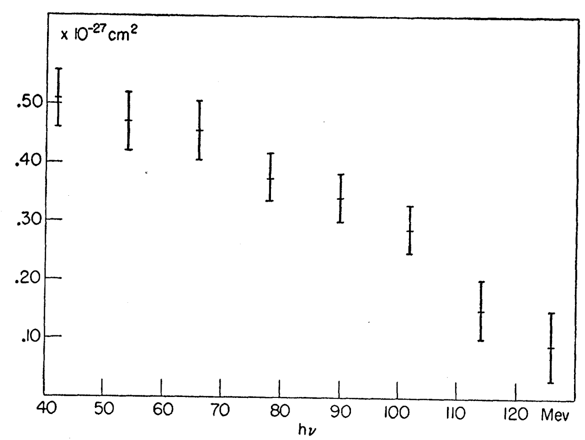

FIG. 4. The total cross section for the reaction $\gamma+He^4\rightarrow He^3+n$. The total cross section has been calculated from the experimental cross section between 60° and 160° by assuming an angular distribution proportional to $\sin^2\theta$ throughout the energy spectrum (see text).

$$(d\sigma/d\Omega')_{\mathrm{He}}=\tfrac{1}{2}\left|\int \psi_\alpha^*[T_p(1)+T_p(2)+T_n(3)+T_n(4)]\psi_\alpha d\tau\right|^2[\gamma\kappa/(2\pi)^2], \quad (1)$$

where

$$(d\sigma/d\Omega')_{\mathrm{proton}}=\tfrac{1}{2}|T|^2[\gamma\kappa/(2\pi)^2],$$

[13] T. S. Benedict and W. M. Woodward, Phys. Rev. **83**, 1269 (1951); E. R. Gaerttner and M. L. Yeater, Phys. Rev. **83**, 146 (1951); E. G. Fuller and M. Weiner, Phys. Rev. **83**, 202 (1951); E. G. Fuller, Phys. Rev. **96**, 1306 (1954).

[14] B. H. Flowers and F. Mandl, Proc. Roy. Soc. (London) **A206**, 131 (1951); J. C. Gum and J. Irving, Phil. Mag. **42**, 1353 (1951).

[15] G. F. Chew and H. W. Lewis, Phys. Rev. **84**, 779 (1951); Heckrotte, Henrich, and Lepore, Phys. Rev. **85**, 490 (1952); N. C. Francis and R. E. Marshak, Phys. Rev. **85**, 496 (1952); N. C. Francis, Phys. Rev. **89**, 766 (1953).

[16] A similar calculation by Y. Yamaguchi at the University of Illinois has just been reported to the authors. (Dr. B. T. Feld, private communication.)

T_p and T_n represent the interaction matrices for photoproduction on protons and neutrons, respectively, and ψ_α, the wave function of the helium nucleus. The neutral meson photoproduction amplitudes on neutrons and protons have been measured to be about the same magnitude[3,17]; however, they may differ by a phase factor δ. The T matrices may be expressed in terms of the spin $\boldsymbol{\sigma}$ of the nucleon:

$$T=\mathbf{K}\cdot\boldsymbol{\sigma}+L. \quad (2)$$

Since both the initial and the final states of the helium nucleus have spin zero, there can be no spin flip and

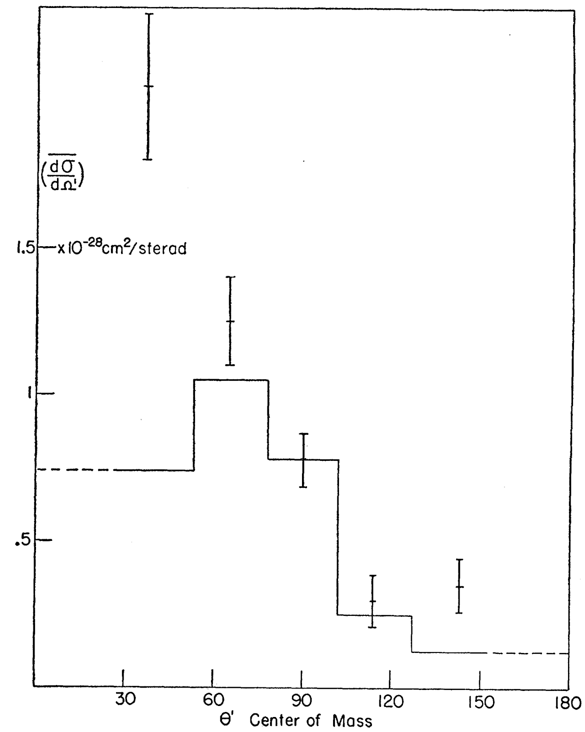

FIG. 5. Angular distribution of π^0 mesons from the reaction $\gamma+He^4\rightarrow He^4+\pi^0$, in the center-of-mass system of the reaction. Averaged from $\gamma=280$ Mev to $\gamma=340$ Mev. The points represent the cross section divided by $\sin^2\theta'$.

formula (1) may be rewritten:

$$(d\sigma/d\Omega')_{He}=16[\tfrac{1}{2}(1+\cos\delta)] \times\tfrac{1}{2}|L|^2|F(\mathbf{K})|^2[\gamma\kappa/(2\pi)^2], \quad (3)$$

$$F(\mathbf{K})=\int|\psi_\alpha|^2e^{i\mathbf{K}\cdot\mathbf{r}_i}d\tau. \quad (4)$$

Here $\mathbf{K}=\boldsymbol{\gamma}-\boldsymbol{\kappa}$, where $\boldsymbol{\gamma}$ and $\boldsymbol{\kappa}$ are the momenta of the photon and of the meson, $\mathbf{r}_i$ is the coordinate of one of the nucleons, and the integration has to be performed over all four nucleons. In order to investigate the behavior of the form factor (4), we assume for each nucleon an $\exp(-r^2/R^2)$ distribution law, where R is a sort of "mean radius" of the alpha nucleus. The expression (4) reduces then to

$$F(K)=\exp[-\tfrac{1}{4}(KR)^2] =\exp[-\tfrac{1}{4}R^2(\kappa^2+\gamma^2-2\kappa\gamma\cos\theta')], \quad (5)$$

where γ and κ are the energy of the incoming photon and the momentum of the outgoing meson (in units of $mc^2=1$). For dipole production, the term $|L|$ has an angular dependence proportional to $\boldsymbol{\kappa}\cdot[\boldsymbol{\gamma}\times\boldsymbol{\varepsilon}]$, where $\boldsymbol{\varepsilon}$ is the polarization vector. This term is proportional to $\sin\theta'$, thus we may write

$$\tfrac{1}{2}|L|^2[\gamma\kappa/(2\pi)^2]=Q_L\sin^2\theta', \quad (6)$$

where Q_L is independent of θ'.

Equations (3), (5), and (6) show that

$$\ln[(d\sigma/d\Omega')_{He}/\sin^2\theta']=\text{const}+\gamma\kappa R^2\cos\theta'. \quad (7)$$

In Fig. 7 are plotted values of $\ln[(d\sigma/d\Omega')_{He}/\sin^2\theta']$ for different values of $\cos\theta'$. The results correspond to a mean excitation energy of 300 Mev; at this energy, $\gamma\kappa=4.05$. The experimental points are consistent, within statistical errors, with a law like (7). The best fit of the experimental points give a value for the mean radius[18] $R=(0.76\pm0.10)\times10^{-13}$ cm corresponding to a rms value $R=(0.93\pm0.12)\times10^{13}$ cm. [The error is only the statistical error on the determination of (7).] Multiple scattering would give an angular distribution that was less peaked. We might expect that our measurement is a lower limit on the real radius.

There is an independent way to obtain a value for the "mean radius" R: It is known that at low energies at least, the cross section for production of π^0 mesons on protons increases as $\gamma\kappa^3$. Thus, using Eqs. (3) and (5), one finds for the differential cross section at 90°:

$$(d\sigma[90°]/d\Omega')_{He}=\text{const}\gamma\kappa^3\exp[-\tfrac{1}{2}R^2(\gamma^2+\kappa^2)]. \quad (8)$$

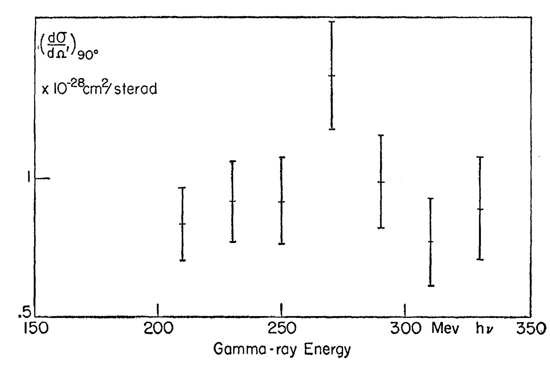

FIG. 6. Differential cross section for the reaction $\gamma+He^4\rightarrow He^4+\pi^0$ at 90° in the center-of-mass system of the reaction as a function of excitation energy.

[17] Jakobson, Schulz, and White, Phys. Rev. 91, 695 (1953).

[18] Hofstadter, McAllister, and Wiener, Phys. Rev. 96, 854 (1954), give a rms value $R=1.4(\pm0.2)\times10^{-13}$ cm. Their rms radius is taken with respect to charge. It is an experimental determination of R by electron scattering.

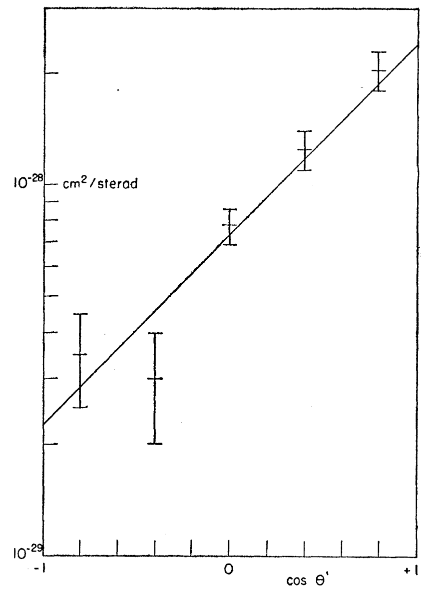

FIG. 7. Plot of the logarithm of points of Fig. 6, as a function of the cosine of the angle in the center-of-mass system. For a certain energy, the slope of the line is proportional to the spread of the radius of the alpha nucleus (see text).

The derivative with respect to energy of expression (8) should equal zero at the excitation energy at which the experimental cross section at 90° goes through a maximum. It is seen on Fig. 6 that this maximum occurs at 270±10 Mev. This gives a new value[18] of $R=(1.15\pm0.2)\times10^{-13}$ cm, corresponding to a rms value $R=(1.41\pm0.2)\times10^{-13}$ cm. From Eq. (3) and the experimental data, it is possible to obtain a value for the phase factor δ by which the photoproduction amplitude on protons and neutrons may differ. This is done by comparing the absolute value of the cross section for elastic photoproduction of mesons in helium with the one for photoproduction of neutral mesons in hydrogen. However, the $|L|^2$ term entering in Eq. (3) does not represent the total cross section on the free proton, but only that part which is spin-dependent.[19] From Eq. (2) one obtains for the cross section on the proton:

$$(d\sigma/d\Omega')_{\text{proton}}=\tfrac{1}{2}\{|K|^2+|L|^2\}[\gamma\kappa/(2\pi)^2], \quad (9)$$

and to obtain the value of $|L|^2$ from the experimental data on hydrogen, one needs a theory giving the relative values of $|K|^2$ and $|L|^2$. Chew[20] worked out the photomeson production in the cut-off theory. He obtains the following expression for the neutral meson production cross section on protons:

$$(d\sigma/d\Omega')_{\text{proton}}=A\{|m_1-e_2|^2\cos^2\theta' +[\tfrac{1}{2}|m_1+e_2|^2+2|m_1|^2]\sin^2\theta'\}, \quad (10)$$

[19] W. Thirring, Helv. Phys. Acta **27**, 515 (1954).
[20] G. F. Chew, Phys. Rev. **95**, 1669 (1954).

where A does not depend on the angle; m_1 and e_2 are constants given in the reference. The term

$$Q_L=A\cdot2|m_1|^2 \quad (11)$$

is the spin-independent term. From (10) and (11), it is easy to obtain

$$Q_L=[4|m_1|^2/4|m_1|^2+|m_1+e_2|^2]\times(d\sigma[90°]/d\Omega')_{\text{proton}}, \quad (12)$$

where $(d\sigma[90°]/d\Omega')$ is the differential cross section at 90°. It is easy to see that in the forward direction, the form factor (5) is almost unity. If in formula (12) we take $|m_1|=0.58$ and $|e_2|=0.18$, values given by Chew,[20] we obtain

$$\lim_{\theta'\to0}\{(d\sigma/d\Omega')_{\text{He}}/\sin^2\theta'\} =11.2[(1+\cos\delta)/2](d\sigma[90°]/d\Omega')_{\text{proton}}. \quad (13)$$

If in formula (12) we neglect $|e_2|$ with respect to $|m_1|$,[21] we obtain a factor of 12.8 instead of 11.2 in (13). From (13), the angular distribution of $(d\sigma/d\Omega')_{\text{He}}$ at a certain energy and the value of $(d\sigma[90°]/d\Omega')_{\text{proton}}$ at that same energy, it is possible to obtain a value for the phase factor. At 300-Mev excitation energy, we obtain

$$\lim_{\theta'\to0}\{(d\sigma/d\Omega')_{\text{He}}/\sin^2\theta'\} =(2.39\pm0.29)\times10^{-28}\ \text{cm}^2/\text{sterad}.$$

This gives, if we neglect e_2 with respect to m_1, $\cos\delta=0.97\pm0.11$ or, if we use the values of m_1 and e_2 given by Chew[20] and favored by the experimental work,[4] $\cos\delta=1.12\pm0.13$. This is consistent with a phase difference $\delta=0$.

VI. CONCLUSIONS

There is no satisfactory theory to interpret the results obtained by this experiment: those results must be interpreted in a qualitative way. They indicate constructive interference in the contributions of protons and neutrons to the elastic photoproduction of π mesons in helium. The results also indicate a strong interference of the contributions of the four nucleons to the elastic photoproduction process, even at large emission angles of the mesons. This can be understood if the four nucleons are very closely bound.

ACKNOWLEDGMENTS

The authors are indebted to Dr. B. T. Feld and Dr. S. Drell for many helpful discussions on the interpretation of the results of this experiment.

One of them (Gerard deSaussure) is also especially indebted to Dr. Y. Goldschmidt-Clermont and Dr. D. M. Ritson who initiated him into the techniques of the nuclear emulsions.

[21] B. T. Feld (private communication).