PHYSICAL REVIEW VOLUME 137, NUMBER 5B 8 MARCH 1965

High-Energy Photodisintegration of He^4†

J. G. Asbury* and F. J. Loeffler
Department of Physics, Purdue University, Lafayette, Indiana

(Received 15 October 1964)

The two-body photodisintegration of He^4 into two deuterons has been observed for average photon energies of 221 MeV and 265 MeV. The forward deuteron was detected at a laboratory angle of 45°. Absolute differential cross sections for the process were determined and total cross sections, assuming a $\sin^2\theta \cos^2\theta$ angular distribution, were calculated and compared with upper limits on the cross section for the inverse process, $d+d \rightarrow He^4+\gamma$. The results were also compared with theoretical estimates for the cross sections using two different wave functions to describe the He^4 ground state. Data were also obtained for photoproton emission from He^4 and are compared with previous measurements. These latter results are also discussed in the light of the quasideuteron model of Levinger.

I. INTRODUCTION

The photodisintegration of He^4 by photons with energies of a few hundred MeV may proceed via several channels. Heretofore most observations of this process have been limited to the detection of a single particle (usually a proton) from the photodisintegration.[1] Barton and Smith,[2] however, observed correlated proton-neutron pairs and concluded that the photodisintegration by this channel proceeds primarily through electric dipole absorption by a "quasideuteron" subunit of the He^4 nucleus as is the case for the other light elements. Gorbunov and Spiridonov[3] studied several processes with a cloud chamber and photons with energies up to 170 MeV. In particular they demonstrated that the electric dipole transition $\gamma+He^4 \rightarrow p+H^3$ was at least 50 times more likely than the process $\gamma+He^4 \rightarrow d+d$.

This is to be expected as has been pointed out by Flowers and Mandl,[4] since in the simplest model for the latter system, the transition can occur only via an electric quadrupole absorption, and hence is expected to be about two orders of magnitude less probable than the electric dipole processes which typically have cross section values of a few μb/sr. For this reason the photodisintegration into two deuterons is a difficult reaction to measure with available bremsstrahlung intensities, and has previously been unobserved.

The present attempt to measure the cross section for the $\gamma+He^4 \rightarrow d+d$ reaction was made for two reasons.

(1) Observations of the isotopic-spin-violating reaction $d+d \rightarrow He^4+\pi^0$ made by Poirier and Pripstein[5] seem to be in disagreement with a similar measurement made by Akimov *et al.*[6] Both groups were also able to observe the process $d+d \rightarrow He^4+\gamma$, and again there seemed to be a discrepancy between the two cross-section values for this reaction. Since the cross sections for the deuteron- and photon-induced reactions can be related by the principle of detailed balancing, it appeared that a direct measurement of the $\gamma+He^4 \rightarrow d+d$ cross section would shed some light on these discrepancies.

(2) A study of the two-deuteron final state permits a unique opportunity for a direct measurement of an electric quadrupole cross section. Quadrupole contributions to various photodisintegration channels can normally only be inferred from the relative magnitudes of interference terms in predominantly electric dipole transitions.

In addition, experimental data on the high-energy quadrupole photodisintegration of He^4 provide an independent test of the several wave functions which have been used to describe the He^4 ground state.[4,7,8,9]

We chose to measure at photon energies of approximately 225 and 270 MeV. These correspond roughly to the equivalent center-of-mass photon energies in the experiments of Akimov *et al.*, and Poirier and Pripstein, respectively.

Since the instrumentation for this experiment could be readily modified to permit an investigation of the photoproton spectrum of helium, a portion of the running time was given over to such a measurement.

II. EXPERIMENTAL PROCEDURE

A. Experimental Arrangement

This experiment required the detection in coincidence of two deuterons. This was accomplished with two counter telescopes of fairly conventional design. The

---

† This work was supported in part by the U. S. Atomic Energy Commission.

* This work constituted part of a thesis submitted by J. G. Asbury to the Purdue Graduate School in partial fulfillment of the requirements for the Ph.D. degree. Present address: DESY, Hamburg, Germany.

[1] T. S. Benedict and W. M. Woodward, Phys. Rev. **83**, 1269 (1951).

[2] M. Q. Barton and J. H. Smith, Phys. Rev. **110**, 1143 (1958).

[3] A. N. Gorbunov and V. M. Spiridunov, Zh. Eksperim. i Teor. Fiz. **33**, 21 (1957) [English transl.: Soviet Phys.—JETP **6**, 16 (1957)]; A. N. Gorbunov and V. M. Spiridunov Zh. Eksperim. i Teor. Fiz. **34**, 862–865 (1958) [English transl.: Soviet Phys.—JETP **7**, 596 (1957)].

[4] B. H. Flowers and F. Mandl, Proc. Roy. Soc. (London) **A206**, 131 (1950).

[5] J. A. Poirier and M. Pripstein, Phys. Rev. **130**, 1171 (1963).

[6] Yu. K. Akimov, O. V. Savchenko, and L. M. Soroko, Zh. Eksperim. i Teor. Fiz. **41**, 708–724 (1961) [English transl.: Soviet Phys.—JETP **14**, 512 (1962)].

[7] B. H. Bransden and A. C. Douglas, Phil. Mag. **2**, 1201 (1957).

[8] J. C. Gunn and J. Irving, Phil. Mag. **42**, 1353 (1951).

[9] J. S. Levinger and M. L. Rustgi, Phys. Rev. **106**, 530 (1957).

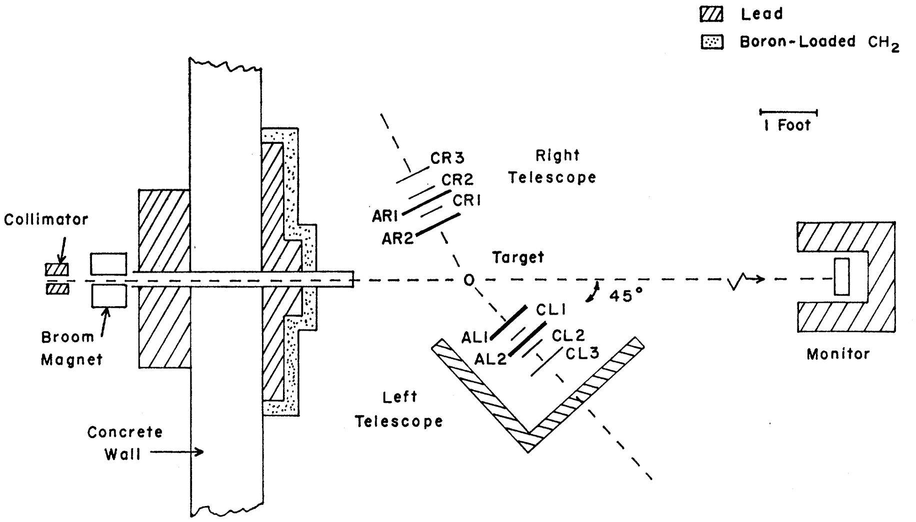

FIG. 1. Plan view of the experiment. The left counter telescope was fixed at 45° throughout the experiment. The right telescope could be moved through angles from 107° to 142°.

over-all arrangement is depicted in Fig. 1. Bremsstrahlung of the internal beam of the Purdue synchrotron in a 0.040-in. platinum wire was directed on a liquid-helium target cell which was a vertical Mylar cylinder of 2-in. diam. The beam size at the target was $1\frac{3}{4}$ in. by $1\frac{1}{2}$ in. The beam monitor was a Cornell type thick-walled ionization chamber and the calibration made at this laboratory[10] was used.

One counter telescope (left) remained at 45° to the beam throughout the experiment while the other counter telescope (right) could move continuously from 107° to 142°. Peak bremsstrahlung energies used during the experiment were 250 and 300 MeV.

B. The Counter Telescopes

The counter telescopes were required to detect deuterons, and measure their energies in the presence of a relatively large number of protons, pions, and electrons. Since we were attempting to measure an extremely small cross section it was desirable to subtend as large a solid angle as possible. All these requirements are somewhat incompatible, and a few unusual techniques were employed to help satisfy them. Since the deuterons of interest had energies between 75 and 150 MeV, and since at least two transmission counters were required per telescope for particle identification purposes, they had to be relatively thin. We used three plastic scintillators (NE102) $\frac{1}{4}$ in. thick for each telescope. The front counter in each had lateral dimensions 4 in. by $14\frac{1}{2}$ in. and the following counters were larger so that efficient light collection was difficult. In order to improve this situation a photomultiplier was attached at each end of each scintillator. If one assumes a simple exponential attenuation of light as it travels down the scintillator, and if the numbers of light quanta received at the two photomultiplier tubes A and B are P_A and P_B, respectively, then it is easy to show that the total number of quanta, P_0, produced at the site of the particle traversal is simply related to P_A and P_B, i.e.,

$$P_0 \propto [P_A P_B]^{1/2},$$

where the constant of proportionality is related to fixed properties of the plastic light-collection system. Therefore, in principle, by using a photomultiplier tube at each end of a scintillator one can exactly compensate for pulse-height dispersion due to particles traversing the scintillator at various locations. The ultimate pulse-height resolution that one can obtain is still of course limited by the statistical fluctuations introduced by the number of light quanta produced and by the number of photoelectrons produced at the photocathodes of the photomultiplier tubes.

If one wishes to obtain pulse heights corrected in this way from two independent counters then it is necessary to measure four pulse heights. In a counter telescope however the counters are not independent. For example, to a first approximation a particle traversing the first counter at a distance x from the center also traverses the second counter at a distance x from the center. Making use of this fact one can show that:

$$P_{02} \propto (P_{A2}+P_{B2})[P_{A1}P_{B1}]^{1/2}/(P_{A1}+P_{B1}),$$

where the first subscripts retain the previously defined meanings, and the second subscripts (the numbers 1 and 2) refer to the number of the counter being considered. From this one sees that for a counter telescope with two counters it is only necessary to measure three pulse heights, i.e., P_{A1}, P_{B1}, and $(P_{A2}+P_{B2})$. These three pulses from the right telescope along with the equivalent three pulses from the left telescope were displayed on a 517 oscilloscope and photographed. The electronic logic was triggered by sum pulses (P_A+P_B) from each of the counters. The oscillograph sweep was triggered whenever coincident pulses occured in the

---

[10] F. J. Loeffler, T. R. Palfrey, and G. W. Tautfest, Nucl. Instr. Methods 5, 50 (1959).

first two counters of each telescope, and no pulses appeared in the third counters of the two telescopes. The third counters served to define the upper end of the particle energy bins. Discriminator levels in the counter channels were generally set low enough to observe all of the deuterons in the prescribed energy range as well as all of the protons and some pions.

C. Test Procedures

The chance coincident rate in the forward telescope (left) was generally less than 5% and the chance rate contributing to the final results was completely negligible since here a coincidence between both telescopes was required and further chance discrimination was possible through a time-range requirement imposed on the photographed pulses.

Background runs were taken with an empty target. This accounted for from 1 to 3% of the total counting rate when the left-right coincidence requirement was in effect. No attempt was made to subtract from these rates that portion which was due to photon interactions with the enclosed air. Roughly one-third of the beam exposure of the entire experiment was spent observing these background rates. The yields for both measurements without helium for the two-deuteron final state were zero. The runs measuring only one proton in the final state suffered from an empty target background of 15 to 20%.

A somewhat lengthy but important check of the gain of the system was performed daily. This was done with a Th C'' radioactive source which was placed in standard positions and counted. Since the particle separation procedures depended on stable and accurate pulse height measurements, it was important to monitor the over-all gains carefully. It was found in practice that the gain shifts during 24-h periods were generally unimportant, and that a daily readjustment was usually sufficient.

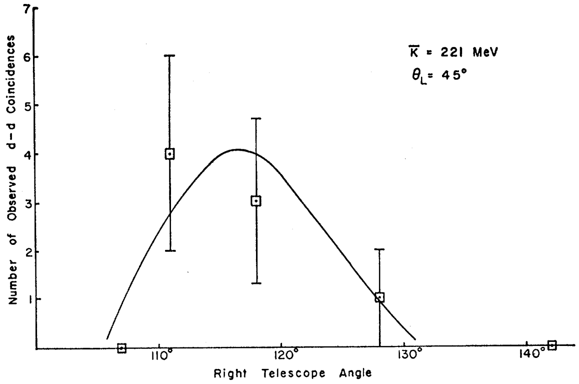

FIG. 2. Comparison of the number of *d-d* coincidences with the counter acceptance for the $\gamma+\mathrm{He}^4 \rightarrow d+d$ reaction. The number of *d-d* coincidences at each of the five angular settings of the right telescope are indicated by the points with statistical error bars. The solid curve gives the product of the counter acceptance and the number of beam monitor responses at each of the five angles.

The two-deuteron final state involves a two-body reaction, and since two of the kinematic parameters were fixed by the left telescope (deuteron kinetic energy, T_L, and deuteron angle, θ_L), the energy and angle (T_R and θ_R) of the deuteron in the right telescope are determined. To verify this we measured at several angles for the right telescope, and the results for $\bar{k}=221$ MeV are shown in Fig. 2. The points with statistical error bars represent the number of $d-d$ coincidences observed, and the solid curve is the calculated acceptance function for the apparatus multiplied by the number of beam monitor responses at each angle. The normalization was done "by eye." Some indication of the low counting rate for the two-deuteron process is already evident but the observed behavior of counting rate with angle is clearly consistent with a two-body reaction.

Absorbers AR1, AR2, AL1, and AL2 were of copper and were changed as necessary throughout the measurement to obtain the desired particle energy bins.

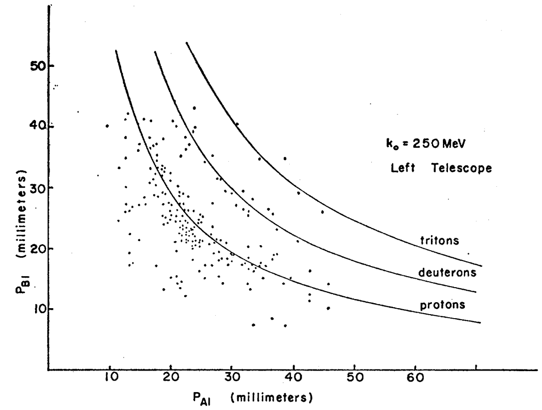

FIG. 3. Distribution of pulse heights from the two photomultiplier tubes viewing the first scintillator in the left telescope. The product $(P_{A1})(P_{B1})$ is seen to be approximately constant for a given type of particle because the energy range observed is small.

III. ANALYSIS OF THE DATA

Particle identification was achieved through a technique similar to the $E\,dE/dx$ method. Owing to the need for a relatively thick absorber in front of the left telescope to keep the counting rate due to low-energy electrons low, it was impossible to obtain direct measurements of E and dE/dx. Indeed the first counter pulse, P_{01}, was proportional to $(dE/dx+A)$ where A is a quantity generally about 50% as large as dE/dx. The sum of the counter 1 and counter 2 pulses, $(P_{01}+P_{02})$ was proportional to $(E-C)$ where C is a sizeable percentage of E. Ideally one would like to display the quantity $E\,dE/dx$ which can be shown[11] to be propor-

---

[11] B. Wolfe, A. Silverman, and J. W. DeWire, Rev. Sci. Instr. **26**, 504 (1955).

tional to $M^{0.8}Z^2E^{0.2}$. As an approximation of this quantity $P_{01}(P_{01}+P_{02})$ was used.

Figures 3 and 4 show the results of plotting P_{A1} versus P_{B1} and $P_{01}(P_{01}+P_{02})$ versus $(P_{01}+P_{02})$. The data pertain to the left telescope during the $K_0=250$ MeV run. Ideally, points in the first plot should aggregate into a family of hyperbolas with major axes increasing with particle mass. The proton and deuteron hyperbolas are clearly discernable, while most of the pions have been biased out with the counter discriminators. In Fig. 4 the mass discrimination is unambiguous for the events plotted. The coordinates of the centers of mass of the respective clusters are in good agreement with a model based on the assumption that $P_{01}\propto(dE/dx+A)$ and $(P_{01}+P_{02})\propto(E-C)$. Values for A and C were calculated from range energy data and absorber thicknesses.

The various counting rates were corrected for multiple scattering and nuclear attenuation in the counter telescopes and in the target. Proton attenuation was estimated from the semiempirical relationship of Keck and Tollestrup.[12] The resultant correction in single telescope proton counting rates was 10% for 100 MeV protons. In view of the dearth of experimental information regarding the total inelastic or attenuation cross sections for deuterons, we decided to use a theoretical formula. We chose the elementary relationship of Serber[13] with a correction term added by Glauber[14]: $\sigma=\pi R^2+\pi r_dR/2+\pi r_dR(2\ln 2-\frac{1}{2})/3$, where R is the nuclear radius and r_d the radius of the deuteron. The correction for double telescope deuteron counting rates was 14% for the $k_0=250$ MeV run and 21% for the $k_0=300$ MeV run.

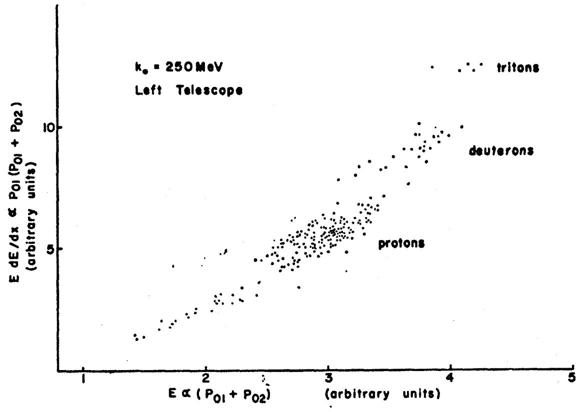

FIG. 4. EdE/dx versus E distribution as determined from pulse height analysis.

The counting rates corrected for background and particle attenuation are given in Table I. The indicated errors for the single telescope data are those associated with ambiguities in the particle identification. These errors were estimated by fitting smooth curves to the particle-mass distribution, observing the overlap between adjacent particle distributions, and selecting conservative values for the overlap uncertainties. These errors were invariably small compared with the uncertainty in the energy-bin widths of the telescopes.

TABLE I. The data collected during the single and double telescope measurements. The $\gamma+\text{He}^4\rightarrow d+d$ data at $\bar{k}=221$ MeV were obtained with peak bremsstrahlung energy $k_0=250$ MeV; the data at $\bar{k}=265$ MeV with $k_0=300$ MeV. In addition to the $\gamma+\text{He}^4\rightarrow d+d$ reaction a number of $\gamma+\text{He}^4\rightarrow p+n+d$ and $\gamma+\text{He}^4\rightarrow p+p+n+n$ reactions were observed.

Double telescope measurement

Particles detected in left,	right telescope	Number of equivalent quanta	Number of observed coincidences	Corrected number of coincidences
		$k_0=250$ MeV		
d	d	1.44×10^{13}	8	9.15
d	p	1.44×10^{13}	17	19.45
p	d	1.44×10^{13}	35	39.52
p	p	1.44×10^{13}	133	146.23
		$k_0=300$ MeV		
d	d	2.45×10^{13}	2	2.41
d	p	2.45×10^{13}	12	14.41
p	d	2.45×10^{13}	14	16.68
p	p	2.45×10^{13}	111	131.87

Single telescope measurement

Mean proton energy (MeV)	Proton angle	Number of equivalent quanta	Number of protons detected	Corrected number of protons
		$k_0=250$ MeV		
87.5	45°	3.76×10^{10}	935±11	751± 9
115.4	45°	11.21	1637±16	1361±13
127.8	45°	16.52	1753±16	1451±15
58.2	118°	3.77	1198±16	954±13
87.5	118°	8.79	653± 8	521± 6

The particle energy-bin widths were determined by the discriminator levels of counters 2 and 3. These levels relative to the peak energy losses of protons and deuterons in the counters were determined by looking at the end of the Th C'' spectrum. The fact that a plastic scintillator responds differently to electrons and stopping heavy particles was taken into account, and the data of Gooding and Pugh[15] was used for this purpose.

The above method for determining energy-bin widths was selected during the course of preliminary work for this experiment. The counting rates for protons at a given angle and mean energy were found proportional to the energy-bin widths as determined by the above procedure. Nevertheless, the uncertainty in bin widths is the source of the largest systematic uncertainty—roughly 7%.

IV. RESULTS

A. The $\gamma+\text{He}^4\rightarrow d+d$ Reaction

Two numbers of physical interest can be gleaned from the two-deuteron reaction. A direct measurement of the

---

[12] J. C. Keck and V. A. Tollestrup, Phys. Rev. **101**, 360 (1956).

[13] R. Serber, Phys. Rev. **72**, 1008 (1947).

[14] R. J. Glauber, Phys. Rev. **99**, 1515 (1955).

[15] T. J. Gooding and H. G. Pugh, Nucl. Inst. Methods **7**, 189 (1960).

TABLE II. Differential and total cross sections for the process $\gamma+\mathrm{He}\rightarrow d+d$ for two different mean photon energies. The angles for the differential cross sections are center-of-mass angles. The total cross sections were calculated under the assumption that the angular form for the differential cross section is $\sin^2\theta\cos^2\theta$.

Photon energy	Cross sections
$\bar{k}=220.5$ MeV	$\sigma_{\mathrm{tot}}=22.3\pm7.9\times10^{-33}$ cm^2 $d\sigma/d\Omega(\theta=52.4°)=(6.3\pm2.2)\times10^{-33}$ cm^2/sr
$\bar{k}=265.3$ MeV	$\sigma_{\mathrm{tot}}=5.4\pm3.8\times10^{-33}$ cm^2 $d\sigma/d\Omega(\theta=53.2°)=(1.5\pm1.1)\times10^{-33}$ cm^2/sr

differential cross section was made for two different photon energies and if one assumes the reaction to be pure electric quadrupole one can establish the total cross section by integration of the differential cross section. We chose to formally calculate the total cross section σ_{tot} with the following formula:

$$\sigma_{\mathrm{tot}}(\bar{k})=N\bigg/\left(N_t\sum_{\theta_R}\int dkN(k,k_0,\theta_R)A(k,\theta_R)\right).$$

Here N is the corrected number of $d-d$ coincidences as given in Table I of Sec. II, and N_t is the number of target nuclei per unit area in the photon beam. $N(k,k_0,\theta_R)$ is the number of photons per unit energy interval which impinged on the target when the right telescope was at θ_R and the peak bremsstrahlung energy was k_0. $A(k,\theta_R)$, the counter acceptance function, is defined as the probability that a $\mathrm{He}^4(\gamma,d)\mathrm{D}$ process was counted given that one occurred and was caused by a photon of energy k when the right telescope was at θ_R. The $\sin^2\theta\cos^2\theta$ dependence of the differential cross section is contained in $A(k,\theta_R)$. The sum is over the five right telescope positions, and the integration is over all photon energies. The formula for the total cross section was numerically integrated with the aid of the Purdue IBM 7090 digital computor. Results for the $d-d$ cross sections at the two photon energies are given in Table II. The indicated errors include systematic as well as statistical uncertainties; however, the statistical part is predominant.

B. The $\gamma+\mathrm{He}^4\rightarrow p+x$ Reaction

The photoproton cross sections were calculated from the relationship

$$\frac{d^2\sigma}{d\Omega dTQ}=\frac{N_P}{(N_t/A)\Delta\Omega\Delta TQ}.$$

Here N_P is the corrected number of protons listed in Table I; (N_t/A) is the average number of helium atoms per unit beam area, and Q is the number of equivalent quanta. The effective solid angle $\Delta\Omega$ subtended by the first scintillator in the counter telescope is the average of the appropriately weighted solid angles seen by the various elements of the finite target. $\Delta\Omega=0.154$ sr at 45°, 0.176 sr at 118°. ΔT is the proton energy bin of the counter telescope. In ascending order of mean proton energy, the bin widths at 45° were: 6.2, 4.7, and 4.2 MeV; at 118°: 10.2 and 6.2 MeV.

The differential cross sections are listed in Table III. The associated errors include both the statistical and the total systematic uncertainties.

V. DISCUSSION OF THE RESULTS

A. $\gamma+\mathrm{He}^4\rightarrow d+d$

The present results can be compared with those of Poirier and Pripstein,[5] and Akimov *et al.*[6] who studied the inverse process. Using a 400-MeV deuteron beam, Akimov *et al.* found $d\sigma/d\Omega=(1.6\pm0.6)\times10^{-33}$ cm^2/sr at $\theta_{\mathrm{c.m.}}=41.5°$. Under the assumption that the form of the angular dependence is the theoretically predicted $\sin^2\theta\cos^2\theta$, they concluded that $\sigma_{\mathrm{tot}}(d+d\rightarrow\mathrm{He}^4+\gamma)=(11\pm4)\times10^{-33}$ cm^2. In a similar experiment Poirier and Pripstein established an upper limit on the process, reporting $d\sigma/d\Omega\leq(0.23\pm0.06)\times10^{-33}$ cm^2/sr at $\theta_{\mathrm{c.m.}}=65°$. This leads to $\sigma_{\mathrm{tot}}(d+d\rightarrow\mathrm{He}+\gamma)\leq(1.32\pm0.34)\times10^{-33}$ cm^2 if $d\sigma/d\Omega\propto\sin^2\theta\cos^2\theta$.

The principle of detailed balance enables an immediate comparison of the above results with those obtained in this experiment. The $\gamma+\mathrm{He}\rightarrow d+d$ reaction is related to its inverse through

$$2\sigma_{\mathrm{tot}}(\gamma+\mathrm{He}^4\rightarrow d+d)=9/4(P_{dd}^2/P_{\mathrm{He}}{}^2\gamma)\times\sigma_{\mathrm{tot}}(d+d\rightarrow\mathrm{He}^4+\gamma),$$

where 9/4 is the ratio of the statistical weights, and the 2 arises from the indistinguishability of the two deuterons. The total cross sections are plotted in Fig. 5. The abscissa is laboratory photon energy k less threshold energy ϵ_0(23.9 MeV). The two values presented here are consistent with the upper limit reported by Poirier and Pripstein. The cross section of Akimov *et al.* is an order of magnitude larger than our result.

The result obtained in this experiment may be of some value in reference to the upper limit established by Poirier and Pripstein on the isotopic spin violating $d+d\rightarrow\mathrm{He}^4+\pi^0$ reaction. They have stated that their data, because of suspected background, are consistent with a zero cross section. The upper limit which they determined for $d+d\rightarrow\mathrm{He}^4+\gamma$ is consistent with our present results. Poirier and Pripstein compared their value, $d\sigma/d\Omega(d+d\rightarrow\mathrm{He}^4+\pi^0)=0.097\pm0.027\times10^{-33}$ cm^2/sr at $\theta_{\mathrm{c.m.}}=90°$ with a theoretical calculation by Greider.[16] Using the impulse approximation and leaving out any dependence on isotopic spin he obtained a cross

TABLE III. Differential photoproton cross sections for the reaction $\gamma+\mathrm{He}^4\rightarrow p+X$.

Proton angle	Proton energy (MeV)	Differential cross section $d^2\sigma/d\Omega dT_pQ$ μb/sr MeVQ
45°	87.5	0.215 ±0.020
45°	115.4	0.170 ±0.015
45°	127.8	0.114 ±0.010
118°	58.2	0.187 ±0.017
118°	87.5	0.0710±0.0070

---

[16] K. Grieder, Phys. Rev. **122**, 1919 (1961).

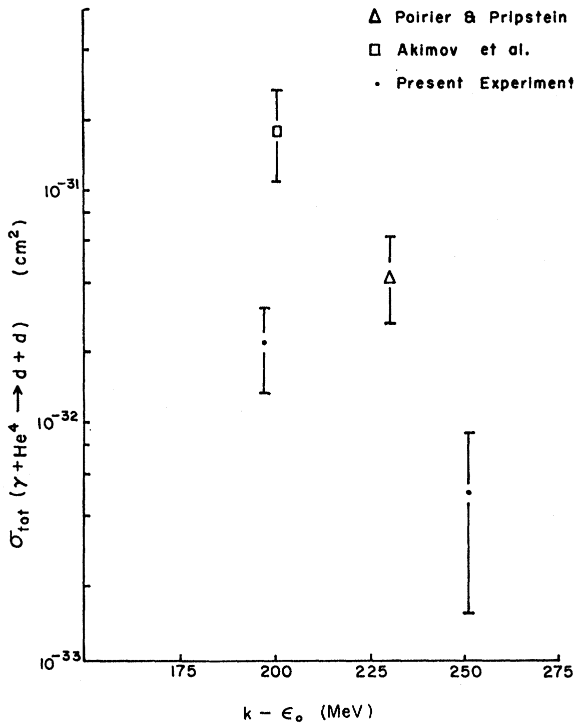

FIG. 5. The high-energy experimental cross sections for $\gamma+\mathrm{He}^4 \rightarrow d+d$. The cross section due to Akimov *et al.* and the upper limit of Poirier and Pripstein were inferred from their measurements of the inverse cross section $\sigma(d+d \rightarrow \mathrm{He}^4+\gamma)$. Threshold energy $\epsilon_0=23.9$ MeV.

section for the $d+d \rightarrow \mathrm{He}^4+\pi^0$ reaction at an appropriate angle and energy of $d\sigma/d\Omega=38\times10^{-33}$ cm^2/sr. The ratio,

$$\left.\frac{d\sigma}{d\Omega}\right|_{\mathrm{Poirier}} \Big/ \left.\frac{d\sigma}{d\Omega}\right|_{\mathrm{Greider}} = \frac{0.097}{38} = 0.0026\pm0.0008\,,$$

leads to the conclusion that isotopic spin is 99.74% conserved in the π^0 producing reaction. It seems probable in view of our results that this conservation percentage is no lower than this value.

The electric quadrupole cross section for $\gamma+\mathrm{He}^4 \rightarrow d+d$ can be compared with the quadrupole contribution to the predominantly electric dipole reaction $\gamma+\mathrm{He}^4 \rightarrow p+\mathrm{H}^3$. The angular dependence for mixed $E1$ and $E2$ transitions is

$$\begin{aligned} d\sigma/d\Omega &\propto |\sin\theta+a\sin\theta\cos\theta|^2 \\ &\propto \sin^2\theta+2\,\mathrm{Re}(a)\sin^2\theta\cos\theta+a^2\sin^2\theta\cos^2\theta\,, \end{aligned}$$

with $a^2=5\sigma_q/\sigma_d$ (where σ_q and σ_d are the total electric quadrupole and electric dipole cross sections, respectively).[17] Gorbunov and Spiridunov[3] analyzed the angular distribution of photoproducts from the He^4 (γ,p)H^3 reaction. They found the contribution of electric quadrupole absorption to be roughly 10% for $30<k<170$ MeV. On the basis of this analysis one could expect the $^1S \rightarrow {}^1D$ contribution to He$^4(\gamma,p)$H^3 to be of the order of 10^{-30} cm^2 at $k\approx220$ MeV. This would be a transition probability nearly two orders of magnitude greater than that for the $^1S \rightarrow {}^1D$ transition of the $\gamma+\mathrm{He}^4 \rightarrow d+d$ process observed in this experiment.

The $\gamma+\mathrm{He}^4 \rightarrow d+d$ reaction has been discussed theoretically by Flowers and Mandl.[4] Using Gaussian wave functions in the central force approximation to describe the helium nucleus, they calculated the photodisintegration cross section as a function of energy. Unfortunately, the bad asymptotic behavior of these wave functions is expected to lead to an underestimate of the cross section in the high-energy region. We have therefore calculated the energy dependence of the cross section using helium wave functions of the form

$$\Psi_{\mathrm{He}} \propto e^{-\mu_\alpha R}, \quad R=\Big(\sum_{i<j} r_{ij}{}^2\Big)^{1/2}.$$

The deuteron wave function was taken to have the form $\Psi_d \propto \{\exp(-\mu_d r)\}/r$ with μ_d consistent with a deuteron diameter equal to 2.16×10^{-13} cm. The parameter μ_α was given a value of 0.55×10^{13} cm^{-1}, which puts the calculated He$^4(\gamma,p)H^3$ cross section into good agreement with experiment. The results of the calculation are represented by Curve 1 in Fig. 6. Curve 2 shows the analytic cross section of Flowers and Mandl for their choice of parameters. The low-energy cross section is due to Zurmühle *et al.*[18] They report that the $D(d,\gamma)$He^4

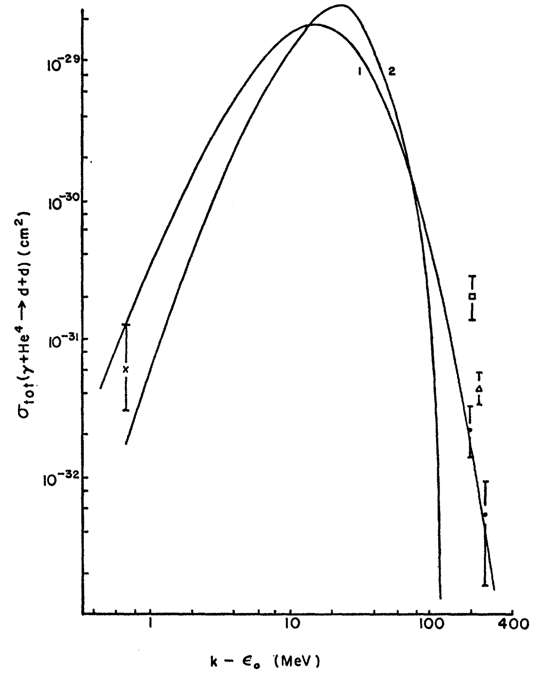

FIG. 6. Experimental and theoretical cross sections. ×–Zurmühle *et al.*, △–Poirier and Pripstein, □–Akimov *et al.*, ●–present experiment. Curve 1 was calculated using exponential He^4 wave functions; Curve 2, with Gausian He^4 wave functions. Threshold energy $\epsilon_0=23.9$ MeV.

---

[17] J. F. Marshall and E. Guth, Phys. Rev. **78**, 738 (1950).

[18] R. W. Zurmühle, W. E. Stephens, and H. H. Staub, Phys. Rev. **132**, 751 (1963).

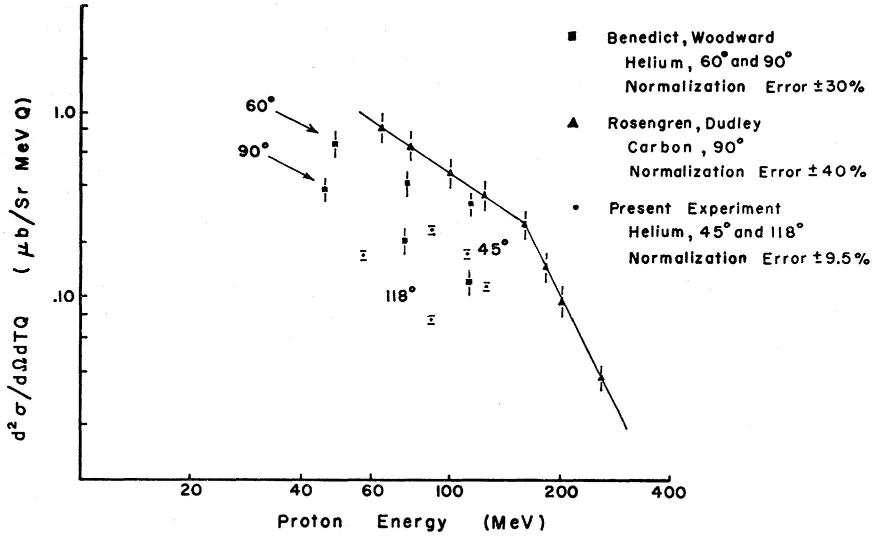

FIG. 7. Photoproton spectra.

reaction at 1.35 MeV has a cross section $d\sigma/d\Omega = 2\times10^{-33}$ cm²/sr at 45°. This corresponds to $\sigma(\gamma+\mathrm{He}^4\rightarrow d+d) = 6\times10^{-32}$ cm² for $k-\epsilon_0 = 0.67$ MeV, if $d\sigma/d\Omega \propto \sin^2\theta \cos^2\theta$.

As evidenced in the figure, the exponential He⁴ wave function yields a striking fit to the data in the extreme energy regions. As anticipated, the Gaussian wave function leads to a gross underestimate of the cross section at higher energies. The success of the exponential wave functions for $\mu_\alpha = 0.55\times10^{13}$ cm^{-1} is especially satisfying since this value for μ_α puts the calculated cross section for the electric dipole reaction $\gamma+\mathrm{He}^4\rightarrow p+\mathrm{H}^3$ into good agreement with experiment.[7]

B. $\gamma+\mathrm{He}^4\rightarrow p+X$

The five measured photoproton cross sections listed in Table III are plotted in Fig. 7. Only the statistical uncertainties are indicated in the figure. Also shown are the helium data obtained by Benedict and Woodward,[1] and the 90° carbon spectrum found by Rosengren and Dudley.[19]

The break in the latter spectrum is characteristic of bremsstrahlung-induced proton spectra. One interpretation of these breaks is that they represent the kinematical cutoff in photodisintegration through quasideuteron absorption. The second and third points in the 45° helium data may straddle such a break.

If the effective deuteron binding energy within the nucleus is taken as 43 MeV, the deuteron photodisintegration kinematics forbid protons with an energy above 135 MeV at 45° (ignoring internal momentum in the nucleus). Similarly, protons with an energy above 66 MeV are forbidden at 118°. The 43-MeV effective binding energy is the actual binding energy of 26 MeV plus the average kinetic energy imparted to the recoil nucleus. Barton and Smith[2] put the latter quantity at roughly 17 MeV.

The kinematical break suggested by our 45° photoproton spectrum is at a somewhat lower energy than the calculated break.

Barton and Smith searched for neutrons in coincidence with roughly 100-MeV protons from helium and lithium, and concluded that virtually all the protons originated from absorption by quasideuterons. This was taken as a confirmation of the model proposed by Levinger.[20] According to this model the photodisintegration cross section σ_z should be proportional to the free deuteron photodisintegration cross section σ_D, that is

$$\sigma_z = L(NZ/A)\sigma_D\,,$$

where L is a constant introduced by Levinger.

If all the 45°, 87-MeV photoprotons observed in this experiment are attributed to quasideuteron absorption, the two-body differential cross section is 4.2 times the deuteron photodisintegration cross section observed by Keck and Tollestrup.[12] This is somewhat lower than the value $L = 6.4$ which Levinger calculated for heavy nuclei. Barton and Smith[2] found $L = 6.1$ for helium, 4.1 for lithium. Odion *et al.*[21] obtained $L = 1.3$ for lithium.

ACKNOWLEDGMENTS

The authors wish to thank Professor John Poirier, and Professor Arnold Tubis, and Dr. Robert Sprafka for several useful discussions. Technical problems concerning electronics and the cryogenic target were competently handled by Eugene Durr and M. Shrimplin. Reliable operation of the synchrotron was provided by the chief operator, Donald Banes. Film scanning was done patiently and accurately by Mrs. Jane Bell.

---

[19] J. W. Rosengren and J. M. Dudley, Phys. Rev. **89**, 603 (1953).

[20] J. S. Levinger, Phys. Rev. **84**, 43 (1951).

[21] A. C. Odian, P. C. Stein, A. Wattenberg, and B. T. Feld, Phys. Rev. **102**, 837 (1956).