Photodisintegration of Helium

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(Received May 18, 1954; revised manuscript received August 24, 1954)

Helium gas at atmospheric pressure was irradiated with 26-, 29-, 32-, and 40-Mev bremsstrahlung spectra. The energy and angular distributions of the protons produced by the photodisintegration of He^4 were studied using nuclear emulsions to detect the charged particles. Angular distributions of the protons are fitted to a differential cross section of the form $\sigma(\theta_{c.m.})\sim(a/b)+\sin^2\theta_{c.m.}[1+(\gamma/b)\cos\theta_{c.m.}]$. Over the energy range studied, the interference term may increase slowly with energy but is approximately constant ($\gamma/b=0.2\pm0.1$); the isotropic term increases rapidly with energy from 0 to 0.33 ± 0.2 at a mean photon energy of 32.5 Mev. The (γ,p) cross section reaches a peak value of about 1.8 mb at about 26 Mev. $\int_{20}^{40}\sigma dE=0.016\pm0.005$ Mev barns.

DURING the last few years it has been suggested that a modified α-particle model of the nucleus might possibly lead to an explanation of some of the features of the "giant resonances" observed in the experimental studies of the (γ,p) and (γ,n) processes.[1] Any such theory would require some information about the nuclear absorption of photons by the helium nucleus. For this reason, and also because it was felt that the structure of the alpha particle was simple enough to make possible a theoretical interpretation of the results, it was thought that an experimental study of the photodisintegration of He^4 would be worthwhile.

There have been very few experimental studies made of the photodisintegration of helium. Two studies have been made of the high-energy protons (energies greater than 45 Mev) produced by 300-Mev bremsstrahlung spectra. Benedict and Woodward[2] measured the cross section for the production of monoenergetic protons having energies between 45 and 100 Mev at 90 and 60 degrees with respect to the direction of the photon beam in the laboratory system. Kikuchi[3] has obtained the distribution in energy of the protons produced by a 320-Mev bremsstrahlung spectrum at laboratory angles of 45, 90, and 135 degrees. Both of these experiments indicate that there is a strong forward peaking in the angular distributions of the high-energy photoprotons in the center-of-mass system.

In addition to these high-energy measurements Gaerttner and Yeater[4] have made measurements with a cloud chamber using the General Electric 100-Mev betatron. Although these data suffer from a lack of statistics, they do indicate that there is a peak in the (γ,p) cross section around 27 Mev. The angular distribution of these data is compatible with a $\sin^2\theta$ center-of-mass angular distribution.

The experiment described below is an attempt to study in some detail the (γ,p) process in He^4 by photons having energies between about 20 and 40 Mev. Some of the preliminary results of this work have been reported.[5]

THE EXPERIMENTAL ARRANGEMENT

The NBS 50-Mev betatron was used as a photon source in the experiment. The target in this machine is a tungsten wire 10 mils in diameter. The effective target thickness, however, as determined by a measurement of the x-ray beam width, is only of the order of one mil.[6] Nuclear emulsions were used to detect the charged particles produced by the bombardment of a helium gas sample by various bremsstrahlung spectra produced by the betatron. The emulsion thickness was 200 microns and the helium gas was at atmospheric pressure. The geometry used in exposing the plates was the same as that used in a previous study of the photodisintegration of deuterium.[7] All exposures were measured with a 100-r Victoreen thimble chamber surrounded by a $\frac{1}{8}$-inch lead cap.

When helium is bombarded by photons having energies greater than 28 Mev, there are five reactions that can take place. These reactions and their thresholds are:

(1)	$He^4(\gamma,p)H^3$,	19.8 Mev
(2)	$He^4(\gamma,n)He^3$,	20.6 Mev
(3)	$He^4(\gamma,d)D$,	23.7 Mev
(4)	$He^4(\gamma,pn)D$,	25.9 Mev
(5)	$He^4(\gamma,2p2n)$,	28.1 Mev.

If He^4 is bombarded by a bremsstrahlung spectrum having a peak energy from 30 to 40 Mev, a great many tracks are produced in the emulsion whose ranges are so short it is impossible to determine the type of particle producing the track. This means that a range distribution of "proton" tracks produced in such a bombardment will not only include tracks due to the (γ,p) reaction but also those due to reactions 3 through 5 and the recoil H^3 and He^3 from reactions 1 and 2. If a short-range cut-off of about 8 microns is used,

[1] H. A. Bethe and J. S. Levinger, Phys. Rev. **78**, 115 (1950).
[2] T. S. Benedict and W. M. Woodward, Phys. Rev. **83**, 1269 (1951).
[3] S. Kikuchi, Phys. Rev. **86**, 126 (1952).
[4] E. R. Gaerttner and M. L. Yeater, Phys. Rev. **83**, 146 (1951).
[5] E. G. Fuller and M. Wiener, Phys. Rev. **83**, 202 (1951).
[6] H. W. Koch *et al.*, Natl. Bureau Standards Handbook 55 (U. S. Government Printing Office, Washington, D. C., 1954).
[7] E. G. Fuller, Phys. Rev. **79**, 303 (1950).

range-energy and geometry considerations indicate that for a recoil He^3 to be included in a range distribution it must be produced by a photon having an energy greater than 32 Mev. Similar arguments indicate that recoil tritons are included in the distribution if they are produced by photons having energies greater than 25 Mev.

The (γ,d) reaction is not expected to lead to any confusion, since it has a higher threshold, and since it cannot take place in the dipole approximation. Both reactions 4 and 5, however, can take place by dipole transitions. These reactions are discriminated against both because of their higher thresholds and because of the dynamics of the three- and four-particle disintegrations. For example, in the (γ,pn) reaction if all three disintegration products have equal momenta, the proton energy in the center-of-mass system is $(1/2.5)E_a$, where E_a is the energy available for the disintegration products. The maximum possible energy for the proton is $\frac{2}{3}E_a$. For a disintegration produced by a 40-Mev photon the maximum proton energy will be the same as the energy of the proton produced in reaction (1) by a 32-Mev photon.

An attempt to sort out the effects of the various reactions listed above was made by making four different exposures with 25-, 29-, 32-, and 40-Mev bremsstrahlung spectra. In addition to the exposures made with the chamber filled with helium, background exposures were made with the chamber evacuated. In all cases the background was negligible.

TREATMENT OF THE DATA AND RESULTS

A. Proton Energy Distribution

In analyzing the data each track was treated initially as a proton. The energy of each "proton" was obtained from the observed range in the emulsion after correcting this range for a mean range in the helium gas for each track. The size of this range correction depended upon the energy and direction of each "proton." Assuming a two-body breakup for the helium nucleus, the energy of the proton producing the disintegration was calculated from the observed "proton energy" and direction. For each exposure a distribution was made of the numbers of "protons" as a function of photon energy. Assuming that for each high-energy proton there was a corresponding recoil triton, a triton distribution was calculated based on the observed high-energy proton distribution and the observed angular distributions. This calculated triton distribution was used to correct the low-energy region of the corresponding "proton" distribution.

The proton distributions for the four exposures are shown in Fig. 1, (a) through (d). The solid histograms are the distributions after correction for recoil tritons. The dashed histograms are the calculated recoil triton distributions that have been used to correct the original data. It is obvious that the triton correction becomes

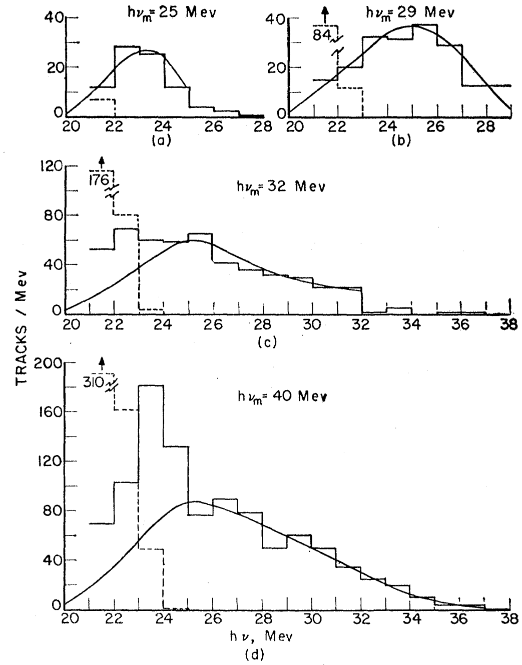

FIG. 1. Energy distributions of photoprotons. The solid histograms are the distributions corrected for recoil tritons. The dashed histograms are the recoil triton corrections. Smooth curves are free hand estimates of proton distributions (see text).

increasingly important as the bremsstrahlung energy is increased.

Uncertainties in the triton corrections and in the shape of the high energy tip of the bremsstrahlung spectrum make it impossible to obtain the exact shape of the (γ,p) cross section near threshold. The smooth curves drawn in Fig. 1 are free-hand estimates of proton distributions. These curves were drawn on the basis of the following considerations. All of these data represent the effect of the product of a cross section and the bremsstrahlung spectrum. When allowance is made for the bremsstrahlung spectrum the data in Fig. 1(a) and (b) indicate a peak in the (γ,p) cross section above 23 Mev, while those of Fig. 1(c) and 1(d) place the peak below 27 Mev. Threshold considerations show that the yield curves in Fig. 1(a) and 1(b) are free from the effects of processes other than the (γ,p) process. For this reason the general shape of the proton yield curves drawn in Fig. 1(c) and 1(d) below 25 Mev has been taken to be the same as that given in Fig. 1(a) and 1(b) when consideration is made for the differences in the bremsstrahlung spectra used in the four exposures.

The solid curve given in Fig. 2 is the result of dividing the smooth curve of Fig. 1(d) by a Schiff thin-target bremsstrahlung spectrum.[6] The normalization to an absolute cross section was obtained using the r-chamber response given in reference 6. The curve given in Fig. 3 is that obtained for the total cross section for the $T(p,\gamma)He^4$ as a function of proton energy using the principle of detailed balancing and the cross section

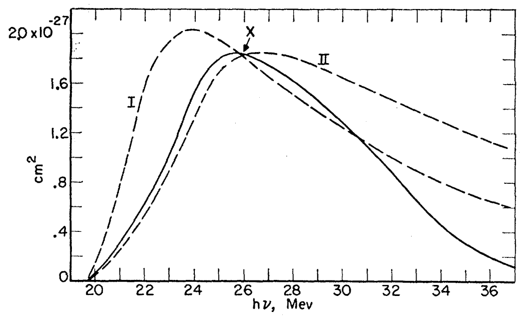

FIG. 2. Cross sections for the $He^4(\gamma,p)T$ reaction. Solid curve calculated from proton distribution given in Fig. 1(d). Dashed curves have energy dependence given by the calculations of Irving and Gunn using exponential wave functions to describe the He^4 and T nuclei (I: $1/\mu_\alpha=1/\mu_T=2.5\times10^{-13}$ cm; II: $1/\mu_\alpha=2.0\times10^{-13}$ cm, $1/\mu_T=2.5\times10^{-13}$ cm). Theoretical curves are normalized at the point ×.

for the inverse (γ,p) reaction obtained above. The circles are the points obtained from the differential cross section of Perry and Bame[8] at 90°. In obtaining the total cross section from these data the angular distribution was assumed to be $\sin^2\theta$. The discrepancy between the two measurements is not thought to be significant.

B. The (γ,d) or (γ,pn) Process

When the shape of the bremsstrahlung spectrum is taken into consideration, the distributions given in Fig. 1(c) and 1(d) have a relatively large number of short range tracks (under 25 Mev) compared to the number in the distributions of Fig. 1(a) and 1(b). These tracks could be produced by either the (γ,d) or the (γ,pn) reactions. The data are consistent with the cross section for this process having a peak at about 32 Mev. (A 32-Mev photon producing a (γ,pn) reaction in which the three disintegration products have equal momenta would give a proton having the same energy as that produced by a 23.2-Mev photon in the (γ,p) reaction.) Around 30 Mev the cross section for this process seems to be of the order of the (γ,p) cross section at 30 Mev.

C. Angular Distributions

The data from the four exposures were divided into three energy intervals and angular distributions plotted corresponding to each energy group. The lowest energy used (23 Mev) was high enough so that recoil tritons could produce only a negligible effect. These data are plotted in Fig. 4 as a function of the angle θ. As indicated in Fig. 4(a), the angle θ is the projection into the plane of the emulsion of the angle θ_l between the direction of the photon and the direction of emission of the proton in the laboratory system. The projection angle β is 15 degrees.

In analyzing these data the angular distribution in the center-of-mass system was assumed to be of the form:

$$\sigma(\theta_{\text{c.m.}})d\Omega_{\text{c.m.}} = b\left[\frac{a}{b}+\sin^2\theta_{\text{c.m.}}\left(1+\frac{\gamma}{b}\cos\theta_{\text{c.m.}}\right)\right]d\Omega_{\text{c.m.}}. \quad (1)$$

This differential cross section when transformed to the laboratory system and projected into the plane of the emulsion gives the following approximate expression for the number of events to be expected as a function of the angle θ:

$$\begin{aligned}N(\theta)d\theta \simeq [&a\sin\theta(1+2c\cos\beta\cos\theta+\sin^2\beta\cos^2\theta)\\ &+b\sin^3\theta(1+4c\cos\beta\cos\theta+2\sin^2\beta\cos^2\theta) \quad (2)\\ &+\gamma\cos\beta\sin^3\theta\cos\theta(1+4c\cos\beta\cos\theta+5/2\sin^2\beta\cos^2\theta]d\theta.\end{aligned}$$

In this expression c is the ratio of the velocity of the center of mass to the velocity of the proton in the center-of-mass system ($c\simeq\hbar\omega/[24Mc^2(\hbar\omega-B)]^{\frac{1}{2}}$, where B is the proton binding energy), and β is the projection angle indicated in Fig. 4(a). The constants a, b, and γ and the probable errors in these constants were determined by fitting (2) to the experimental data by the method of least squares. The values obtained by this procedure are given in Table I. These data are not sufficiently accurate to determine the form of the angular distribution function. If, however, the differential cross section is assumed to be of the form given by (1) the data do indicate the general trend of the constants in this expression over the energy interval studied. The dashed histograms in Fig. 4 are those obtained using (2) and the constants determined from the least-squares fit of the data.

DISCUSSION

The integrated cross section from threshold to 40 Mev determined from Fig. 2 is $\int\sigma dE=0.016\pm0.005$ Mev barns. The error quoted is principally due to uncertainties in the geometry and in the determination of the absolute photon flux. Within the experimental errors this value is in agreement with the value estimated by Gaerttner and Yeater[4] from their data. It is in very

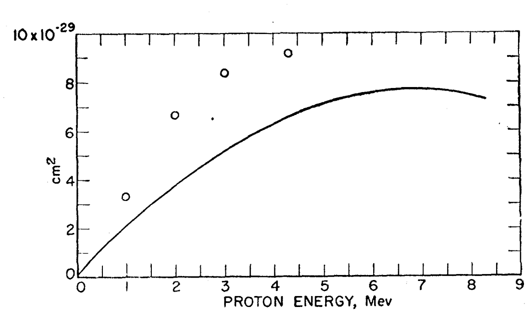

FIG. 3. Cross section for $T(p,\gamma)He^4$ reaction. Solid curve is that obtained from the photodisintegration cross section using the principle of detailed balancing. Circles are total cross sections from the work of Perry and Bame assuming a differential cross section of the form $\sigma(\theta_{\text{c.m.}})\sim\sin^2\theta_{\text{c.m.}}$.

[8] J. E. Perry, Jr., and S. J. Bame, Jr., Phys. Rev. 90, 380 (1953).

good agreement with the value of 0.015 Mev barns obtained by Nicolai and Goldwasser.[9] In agreement with the recent measurements made of the inverse $T(p,\gamma)He^4$ reaction,[8,10] the data given in Fig. 2 do not show any indication of a "resonance level" in He^4 around 21 Mev.[11] Rather, the data seem to indicate a "resonance" curve similar to those obtained for the photon processes in the heavier nuclei.

The errors in the constants determined for the angular distributions are large. Some general conclusions, however, can be drawn about the trend of the angular distribution with increasing photon energy. The "isotropic term" a/b increases rapidly with energy over the energy range considered. The coefficient of the "interference term" γ/b, however, is either constant or only increases slowly with energy. The value obtained for the "interference term" is in agreement with that found by Perry and Bame in their study of the inverse reaction.

The theoretical curves giving the (γ,p) cross section as a function of photon energy as given by the calculations of Flowers and Mandle[12] and by the work of Gunn and Irving[13] can be brought into qualitative agreement with the curve given in Fig. 2 by making the proper choice of a parameter used in these calculations which determines the radial extent of the He^4 nucleus. The calculations of Flowers and Mandle make use of Gaussian wave functions to describe the helium and tritium nuclei. Gunn and Irving made calculations using both Gaussian and exponential type wave functions. For reasonable values of the nuclear parameter involved, the energy dependence of the (γ,p) cross section given in Fig. 2 is in better agreement with the calculations made by Gunn and Irving using the exponential type wave functions than with those using Gaussian functions. The theoretical curves given in the work of Gunn and Irving that best fit the experimental data are given in Fig. 2. The theoretical curves are normalized to the experimental data at the points indicated. Although the statistics are poor and there are uncertainties in the shape of the bremsstrahlung spectrum it is felt that, for energies above 26 Mev, the experimental shape of the cross-section curve given in Fig. 2 is much more reliable than the shape indicated below 26 Mev. In the region above 26 Mev a discrepancy is indicated between the energy dependence given by Gunn and Irving and that given by the experimental curve. Although it is not considered likely, this may be entirely due to the crudeness of the experiment. It may also be due to the crudeness of the approximations used in the calculations (i.e., exponential wave functions for the triton and helium nuclei and plane waves to describe the motion of the proton and triton in the final state) or due to the neglect of noncentral forces in the calculations. The neglect of noncentral forces results in the omission of transitions from ground state components that are not present in the pure central force approximation. Irving[14] points out the need for the inclusion of a tensor force in the nuclear interaction in order to obtain the correct binding for the helium nucleus. It may also be necessary to include a tensor force to explain the behavior of the angular distributions.

TABLE I. Values of the parameters in Eq. (1).

Photon energy range (Mev)	23–26	26–30	30–40
$\langle\hbar\omega\rangle_{Av}$ (Mev)	24.5	28	32.5
a/b	0.004±0.05	0.21±0.08	0.33±0.2
γ/b	0.13 ±0.05	0.25±0.09	0.35±0.2

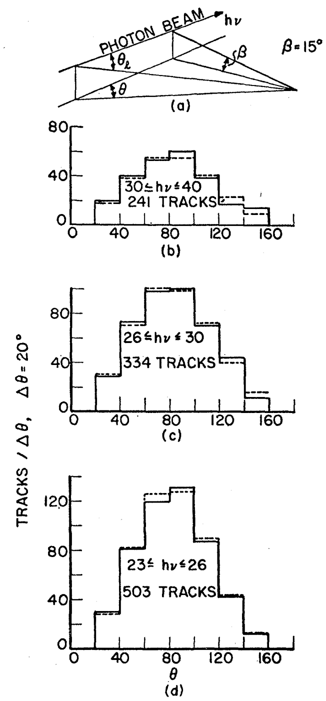

FIG. 4. Proton angular distributions. In (a) the angle θ is in the plane of the emulsion, the angle β is in a plane perpendicular to the emulsion. Solid histograms are experimental results. The energy interval for each distribution as well as the numbers of tracks in each distribution are indicated. Dashed histograms are calculated for a differential cross section in the center-of-mass system of the form

$$\sigma(\theta_{c.m.})=b\left[\frac{a}{b}+\sin^2\theta_{c.m.}\left(1+\frac{\gamma}{b}\cos\theta_{c.m.}\right)\right].$$

Values of the constants are taken from Table I.

The author wishes to acknowledge the help of M. Wiener and J. Godfrey in the analysis of the nuclear emulsions. He gratefully acknowledges the many helpful discussions of the work held with members of the Radiation Physics Laboratory, in particular those with Dr. C. H. Blanchard.

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