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The Photodisintegration of He⁴ Nuclei by X-Rays from a 100-Mev Betatron*

E. R. GAERTTNER AND M. L. YEATER
General Electric Research Laboratory, Schenectady, New York

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The photodisintegration of He^4 nuclei has been studied in a cloud chamber, with a 100-Mev betatron as a source of x-rays. The predominant reactions observed are $He^4(\gamma,p)H^3$ and $He^4(\gamma,n)He^3$. The angles, θ, at which the protons from the (γ,p) reaction are emitted with respect to the x-ray beam are consistent with a $\sin^2\theta$ distribution. The measured average energy of the x-ray photons producing the γ-p disintegration is approximately 27 Mev. The total integrated photodisintegration cross section is 0.1 ± 0.05 Mev-barn; this value is based on an earlier determination of the absolute nitrogen cross section, obtained by a direct comparison of the number of nuclear disintegrations with the number of positron-electron pairs produced in the gas in the cloud chamber.

INTRODUCTION

AN evaluation of photonuclear effects must take into account all modes of disintegration. We have previously used a cloud chamber to survey the photodisintegration phenomena in oxygen,[1,2] nitrogen,[1-3] and carbon[4] (methane). The quantitative results of these experiments have indicated the relative importance of various modes of disintegration and the approximate values of the absolute cross sections.

In the investigation here reported we have used the same cloud-chamber technique to obtain the relative yields of the different modes of disintegration of helium. In addition, we have studied the angular distribution of protons from the (γ,p) reaction in helium, and have obtained an approximate x-ray energy distribution for this process.

The inverse reaction $H^3(p,\gamma)He^4$ has been studied by a group at Los Alamos.[5] They observe a large yield of gamma-rays with an angular distribution which is approximately $\sin^2\theta$. They attribute these gamma-rays to an electric dipole transition in He^4. The range in proton energy from their electrostatic generator was not sufficient to cover the high energy side of what they believe to be a resonance at 2.5-Mev proton energy. The energy of the emitted gamma-ray for this proton energy is 21.6 Mev. This is lower than the mean value which we obtain for the (γ,p) process.

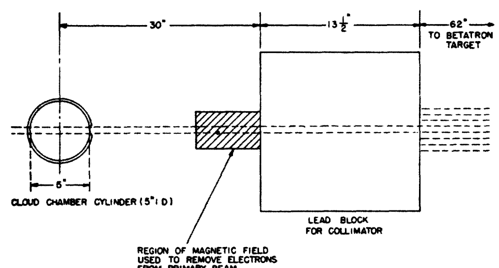


FIG. 1. Arrangement of collimator and cloud chamber in the x-ray beam.

THE EXPERIMENTAL METHOD

The experimental arrangement is shown schematically in Fig. 1. The x-rays from the 100-Mev betatron are collimated by a system of lead slits; the beam measures ⅛ inch vertically and ¾ inch horizontally at the center of the cloud chamber. The beam is cleared of electrons by a magnet and enters the cloud chamber through a window which is a 0.020-inch thick section of the Lucite wall of the chamber. The cloud chamber is filled with helium and saturated vapor from a 50–50 water-alcohol liquid mixture, at a total pressure of one atmosphere.

A single high intensity pulse of x-rays passes through the center of the cloud chamber at each expansion. The use of the cloud chamber for photodisintegration studies depends upon achieving good contrast between heavy particle tracks and the background of positrons and negative electrons, produced in the Lucite window and the gas of the chamber; the ratio of light to heavy particles is about 10^4. This has been accomplished for a number of light gases through the use of a short droplet growth time. The results obtained for two different growth times are illustrated in Fig. 2. Figure 2(a) shows the electron tracks with a growth time of about 200 milliseconds; Fig. 2(b) shows the contrast achieved for the heavy tracks against the electron background with a growth time of about 50 milliseconds.

An important feature of our technique is the use of overcompression of the cloud chamber following the initial expansion, to aid in the evaporation of the droplets.[6] This is particularly important where large pulse intensities are used and at the same time a rapid recycling of the cloud chamber is desired. With the aid of overcompression, tracks of good quality are obtained at intervals of five seconds. The photographs in this report were taken at this rate.

* This work has been supported in part by the ONR.
[1] E. R. Gaerttner and M. L. Yeater, Phys. Rev. **77**, 714 (1950).
[2] E. R. Gaerttner and M. L. Yeater, Phys. Rev. **79**, 401 (1950).
[3] E. R. Gaerttner and M. L. Yeater, Phys. Rev. **77**, 570 (1950).
[4] E. R. Gaerttner and M. L. Yeater, Phys. Rev. **82**, 461 (1951); see also reference 2.
[5] Argo, Gittings, Hemmendinger, Jarvis, and Taschek, Phys. Rev. **78**, 691 (1950).
[6] E. R. Gaerttner and M. L. Yeater, Rev. Sci. Instr. **20**, 588 (1949).

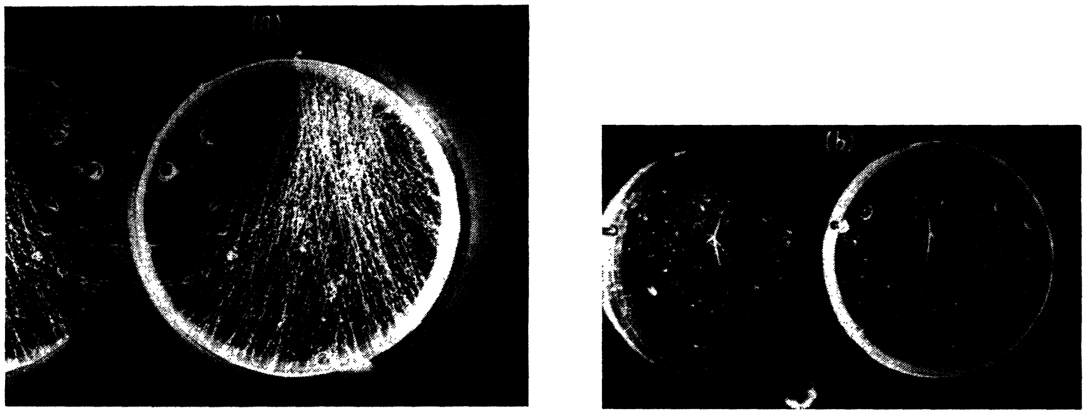


FIG. 2. Effect of growth time on track brilliance. (a) Electron tracks with 200 millisecond growth time. (b) A four-prong star, photographed with 50-millisecond growth time, against a strong electron background.

THE IDENTIFICATION OF THE HELIUM DISINTEGRATIONS

Since the gas in the chamber contains the vapor phase of water and ethyl alcohol in addition to helium, some of the observed disintegrations in the gas are to be attributed to carbon and oxygen. The separation of the flags, consisting of two charged particles, into the helium and carbon or oxygen components is possible because the maximum range of the carbon and oxygen recoils is smaller than the measured recoil track length of many of the observed flags. This conclusion is based on measurements made on carbon and oxygen flags with the cloud chamber filled with methane and oxygen respectively. The observed maximum ranges reduced to one atmosphere pressure for these cases are respectively 0.45 cm and 0.25 cm. From the relative stopping power[7] of methane and oxygen with respect to the helium-vapor mixture, the expected maximum ranges in the latter are respectively 2.0 cm and 1.4 cm. It is found that nearly all flags, in the helium-vapor mixture, for which the recoil is observed to stop have ranges less than 2 cm.

Flags with recoils longer than 2 cm are attributed to helium. Some of the helium flags are not individually identified in this way because of their orientation, which causes the visible recoil length to be less than 2 cm owing to the small depth of the illuminated region. Statistically, however, the total number can be inferred from the identifiable cases by means of a geometrical correction.

A striking characteristic of nearly all the helium flags is the difference in the track density of the two charged particles. An example is shown in Fig. 3. This characteristic is sufficient to establish the reaction as $He^4(\gamma,p)H^3$ instead of $He^4(\gamma,2d)$. It is also noteworthy that in every case of this type, the resultant momentum of the flag members is in the direction of the x-ray beam.

The identification of a portion of the single tracks (one charged particle) as He^3 from the reaction $He^4(\gamma,n)He^3$ is made in a similar way. An example is shown in Fig. 4. In this case also track lengths greater than about 2 cm cannot be attributed to carbon or oxygen. Observations in a hydrogen-filled chamber indicate that long singles are not due to stray neutrons. The identification of He^3 recoils is based on track lengths greater than 4 cm.

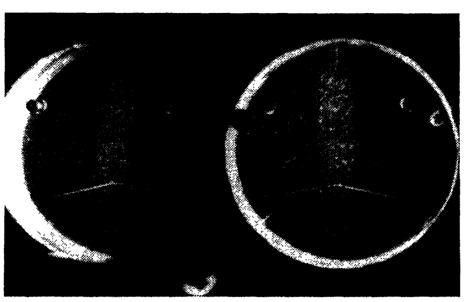


FIG. 3. A $He^4(\gamma,p)H^3$ disintegration. The band across the chamber consists of secondary electrons showing the path of the x-ray beam. Its direction is toward the bottom of the page. There is no magnetic field.

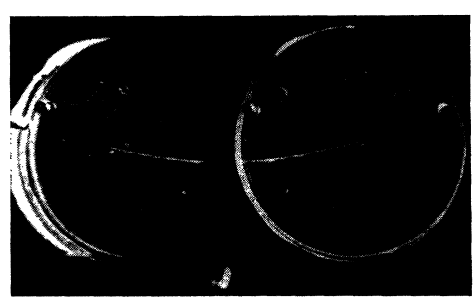


FIG. 4. A $He^4(\gamma,n)He^3$ disintegration. The magnetic field strength is about 9000 gauss.

[7] M. S. Livingston and H. A. Bethe, Revs. Modern Phys. **9**, 245 (1937). The stopping powers given are for alpha-particles of about 6 Mev. These stopping powers are valid also for heavy recoils (e.g., C^{12}) of air range less than 0.3 cm as shown by G. A. Wrenshall, Phys. Rev. **57**, 1095 (1940).

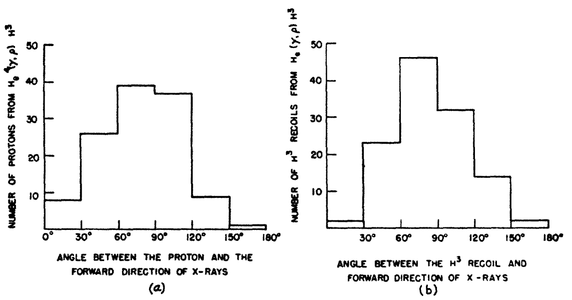


FIG. 5. Angular distribution for $He^4(\gamma,p)H^3$ in the laboratory system of coordinates. (a) Proton. (b) Triton.

THE ANGULAR DISTRIBUTION OF THE PROTONS FROM $He^4(\gamma,p)H^3$

It is observed that the protons from the $He^4(\gamma,p)H^3$ reaction are not emitted with equal probability in all directions; at right angles to the x-ray beam, the probability is much greater than forward or backward. In Fig. 5 are plotted the angular distributions of protons and tritons in the laboratory system. The angles are measured between the x-ray beam and the projection of the flag members in the horizontal plane of the chamber. The number per unit solid angle is approximately the same as the distribution in these histograms because the illuminated region of the cloud chamber is shallow ($\frac{1}{2}$ inch) and the tracks considered all have lengths greater than 2 cm. In Fig. 6 is plotted the angular distribution of tritons in the center-of-mass coordinate system. This is consistent with a $\sin^2\theta$ distribution.

X-RAY ENERGY DISTRIBUTION FOR THE REACTION $He^4(\gamma,p)H^3$

The energy of the photon which caused the (γ,p) disintegration can be computed in each case from the forward momentum which the photon imparts to the triton and proton.[8] If only the direction vectors of the momenta are known from angle measurements, as is the case here, then only the ratio of the magnitude of the photon momentum to that of the proton or the triton is determined; this ratio is not sufficient to determine the photon energy uniquely in general, but leads to two theoretical values. All cases which have one value of energy less than 25 Mev are, however, uniquely determined because the alternate value is greater than our maximum x-ray energy of 100 Mev.

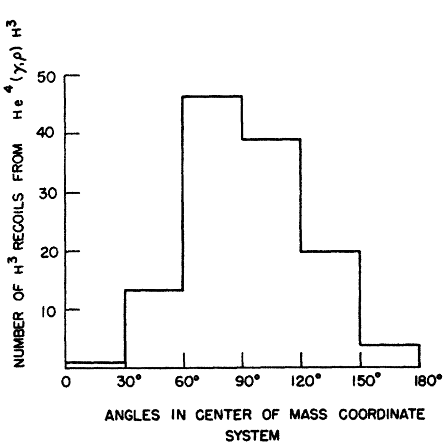


FIG. 6. Triton angular distribution, in center-of-mass system of coordinates, for the reaction $He^4(\gamma,p)H^3$. The proton distribution is the mirror image of this.

Forty percent of the identified helium flags fall in this category and, therefore, have energies definitely between 19.8 Mev (the energy threshold) and 25 Mev. For the remainder of the flags with energy in the indeterminate range, it is assumed that the smaller value of the energy is the correct one in each case. The x-ray energies for the identified helium (γ,p) flags are given in Fig. 7. In Fig. 8 are given the energy, and the angle between proton and triton, for cases with θ

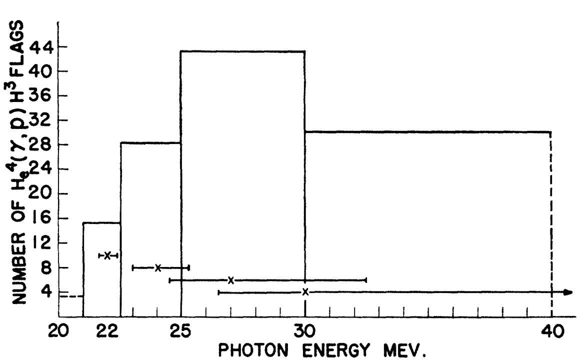


FIG. 7. Energy distribution of the photons inducing the $He^4(\gamma,p)$-H^3 reaction. The photon energy is calculated from the forward momentum imparted to the proton and triton (angle measurements only). The horizontal lines give the probable error in the energy measurement at the designated points.

between 70° and 110°, for which the energy is more accurately known.

One flag recoil with a range of 4.4 cm was observed to stop in the illuminated portion of the cloud chamber. This case is reproduced in Fig. 3. The photon energy calculated from the angles is 22.4±0.4 Mev. From this information, the approximate photon energy for a helium flag with the minimum identifiable triton range of 2 cm can be determined.[9] The result is 21 Mev.

The number of helium (γ,p) disintegrations with recoil range less than 2 cm, that is, for photon energy between 19.8 and 21 Mev, is probably less than the number in the corresponding energy interval above 21

[8] We assume that the residual H^3 nucleus from the (γ,p) reaction is unexcited. An excited state in He^3 (analogous to H^3 except for coulomb energy) has been observed by Fowler, Lauritsen, and Tollestrup [Phys. Rev. **76**, 1767 (1949)] at 6.3 Mev; however, the radiative cross section is less than one percent of the radiative cross section for the state in He^4, observed at Los Alamos (reference 5), which is probably involved in the (γ,p) interaction.

[9] See M. S. Livingston and H. A. Bethe, Revs. Modern Phys. **9**, 245 (1937) and H. A. Bethe, Revs. Modern Phys. **22**, 213 (1950).

Mev. The number between 21 and 22.5 Mev is estimated as follows.

There are 52 (γ,p) disintegrations identified which have triton track length greater than 5 cm, from a total of 119 cases with triton track length greater than 2 cm. For these 52 cases, the primary photon energy must have been greater than 22.5 Mev. The fraction of the cases with recoil range greater than 5 cm is actually larger than 52/119, because only 7 to 10 percent of all the 5 cm tracks present will be so oriented in our shallow chamber that the full 5 cm is visible (for a $\sin^2\theta$ distribution of the emitted tritons with respect to the x-rays), whereas approximately 20 percent of all the 2 cm tracks will be measurable. The "geometrical efficiencies" quoted cannot be calculated precisely owing to the uncertainty in the measurement of the track length caused by non-uniformity of illumination near the edges of the light beam. The limiting values indicate that not more than 12 percent of the cases have recoil range between 2 and 5 cm. This is confirmed by the energy distribution, based on angle measurements, given in Fig. 7.

The average photon energy is calculated from the data in Fig. 8. The result is 27 Mev. The inaccuracy of the measured energy for the higher energy cases probably results in an average value which is somewhat too large. This error probably does not exceed 2 Mev, however, as shown by the fact that an average energy of 25 Mev is obtained by neglecting altogether these less accurate high energy cases (above 30 Mev).

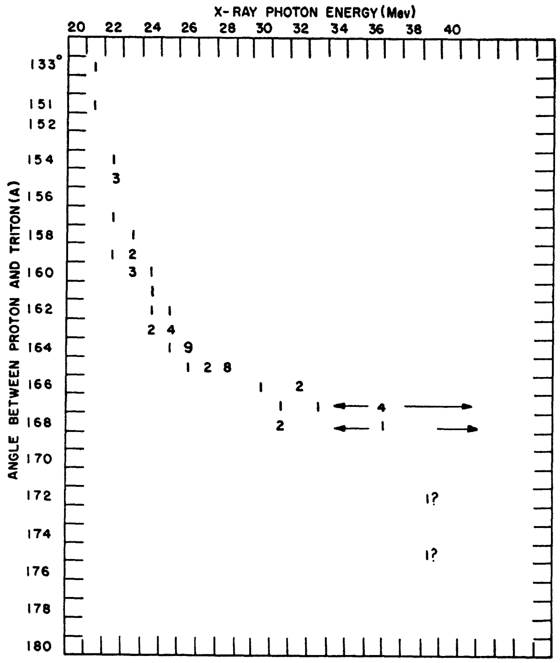


FIG. 8. Helium (γ,p) flags for which the angle between the proton and the x-ray beam is between 70° and 110°. A is the angle between the triton and the proton in the laboratory system of coordinates.

THE YIELD OF THE PHOTONUCLEAR REACTIONS IN HELIUM

(a) (γ,p)

The yield of the (γ,p) reaction in helium has been compared with that of carbon and oxygen by counting the relative numbers of helium and carbon or oxygen disintegrations produced in the mixture of helium and water-alcohol vapor in the cloud chamber. The stars, in which at least three charged particles are observed to emanate from a common point, must have originated with carbon or oxygen nuclei. An example is shown in Fig. 9. In one group of data, 67 stars and 49 identifiable He(γ,p) flags with recoil length equal to or greater than 2 cm were observed. The ratio of the yield per atom of He(γ,p) and the flags in carbon and oxygen is

$$\frac{49/\eta}{67Kb},$$

where K is the average ratio of flags to stars in carbon and oxygen, η is the detection efficiency for the helium flags, and b is the atomic ratio of helium to carbon and oxygen in the cloud chamber. The quantity K is known from our study of carbon and oxygen, and has the value $K=4$. The value of b is 6.1 at the operating temperature of 25°C. The efficiency η accounts for the cases having such an orientation in the chamber that the tracks pass out of the lighted region or out the side of the chamber with only a short section visible. For the 2 cm visible recoil length, $\eta=0.22$, calculated for a $\sin^2\theta$ distribution. The ratio of He(γ,p) to the average flag yield for the carbon and oxygen mixture in the vapor is, therefore, 0.136. From this ratio and the flag cross section for the carbon[4] and oxygen,[1] averaged according to their proportions in the vapor, the absolute cross section for the helium is obtained.[10] The integrated carbon-oxygen value, from our previous experiments, is 0.25 Mev-barn. The integrated He(γ,p) cross section obtained from this measurement is, therefore, 0.034 Mev-barn.

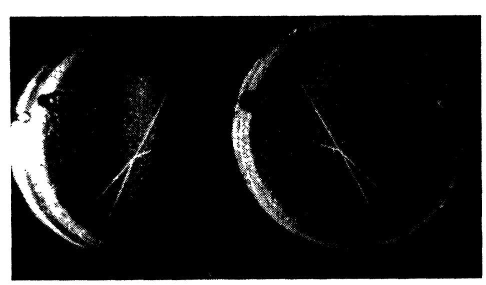


FIG. 9. A "star" in helium-vapor mixture in the cloud chamber.

[10] This assumes that the disintegrations in carbon and oxygen are produced by x-rays in approximately the same energy range as in helium.

The helium cross section has also been evaluated by comparison with the yield of flags in nitrogen, for which we have previously[1] determined the integrated cross section by comparing the number of nuclear disintegrations with the number of electron pairs produced in an air-filled cloud chamber. For this purpose, the relative x-ray intensities in the two experiments have been compared with an ionization chamber, using the same instruments, geometry, and betatron peak energy. For 195 helium flags (corrected for efficiency), an ionization of 108 units was obtained; for 430 flags in nitrogen at one atmosphere pressure, the same ionization chamber gave a reading of 15.6. The ratio of yields per atom for He(γ,p) and nitrogen flags is, therefore, 0.131. The integrated cross section for the He(γ,p) reaction from this measurement is, therefore, 0.04 Mev-barn, based on a nitrogen cross section of 0.3 Mev-barn. The agreement in the two measured values of this cross section is satisfactory for this type of experiment and indicates the internal consistency of the flag data involving the elements helium, carbon, nitrogen, and oxygen.

The accuracy of the He(γ,p) cross section depends on the accuracy of the nitrogen cross section and on the uncertainties in the yield ratio. The former is estimated to be accurate within about 20 percent. The accuracy of the yield ratio is determined mostly by statistics and the accuracy of the geometrical efficiency; the estimated error is 35 percent over all.

(b) (γ,2d)

This reaction should be observed as a "flag" having tracks of equal ionization and with resultant momentum in the forward direction. This yield is no more than one percent of the (γ,p) yield.

(c) (γ,n)

The (γ,n) yield can be evaluated in the same way as the (γ,p) yield. In a portion of the data in which 45 flags with recoil lengths greater than 4 cm were counted, there were observed 59 singles of length greater than 4 cm. Our helium (γ,n) to (γ,p) ratio is, therefore, about 1.3.

(d) (γ,pn or γ,2p,2n)

The yield of the reactions $He^4(\gamma,pn)H^2$ or $He^4(\gamma,2p,2n)$ can, in principle, be estimated from those disintegrations for which the resultant momentum is not in the forward direction of the x-rays. Such flags have been observed in oxygen and methane and account for about 15 percent of the total. When the helium data are corrected for the expected contribution from oxygen and carbon in the vapor, a few cases remain which might be attributed to helium; but within the statistical accuracy of the data, these might still be attributed to carbon and oxygen. On the assumption that these cases are due to helium, the upper limit for their yield is about 20 percent of $He^4(\gamma,p)H^3$.

DISCUSSION OF RESULTS†

The theory of Levinger and Bethe[11] gives the total integrated photonuclear cross section for helium as

$$\int \sigma dW = 0.06(1+0.8x) \text{ Mev barn},$$

where x is the fraction of the nuclear force which is of the exchange type. Our experimental result is 0.1 ± 0.05 Mev-barn. This value, although not sufficiently accurate to indicate the amount of exchange force, gives strong support for the dipole type interaction discussed by them. This conclusion is supported by the observed angular distribution of the protons from the (γ,p) reaction.

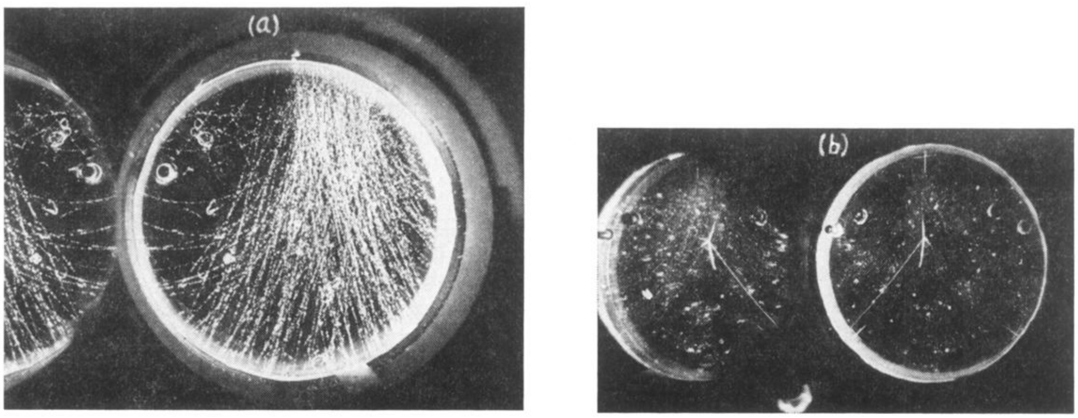
The energy of the x-ray photons producing the $He^4(\gamma,p)H^3$ disintegrations has been determined approximately from the momentum imparted to the disintegration products. The resulting energy distribution has a mean value not less than 25 Mev. For a detailed analysis of the excitation function more accurate data are needed—possibly from triton range measurements in a cloud chamber filled with helium at high pressure.

It is a pleasure to acknowledge the support of Dr. E. E. Charlton and the betatron group. We are indebted to Professor H. A. Bethe and Professor P. Scherrer for helpful discussions.

† *Note added in proof.*—Since this work was submitted for publication, it has been brought to the authors' attention that the photodisintegration of helium is being studied by E. G. Fuller and M. Wiener at the National Bureau of Standards (private communication) and by Prof. J. R. Atkinson at the University of Glasgow (private communication from E. W. Titterton). Fuller and Wiener, using photographic emulsions for a detector, find an energy distribution and integrated cross section for the (γ,p) process in approximate agreement with ours. However, their angular distribution for 550 photoprotons is not compatible with a pure $\sin^2\theta$ distribution; they observe about one-half as many forward as at 90° to the x-ray beam.

A theoretical treatment of the photodisintegration of helium has also appeared since our work was submitted for publication: B. H. Flowers and F. Mandl, Proc. Roy. Soc. (London) **206A**, 131 (1951).

[11] J. S. Levinger and H. A. Bethe, Phys. Rev. **78**, 115 (1950).



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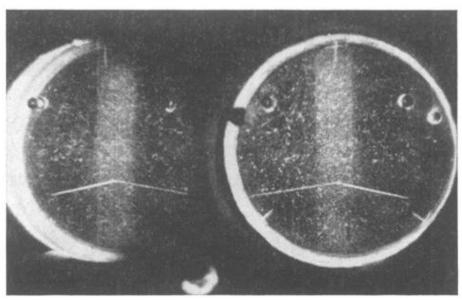

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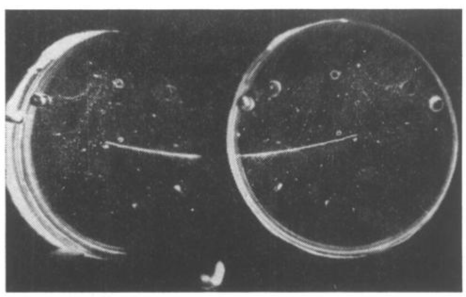

FIG. 4. A $He^4(\gamma,n)He^3$ disintegration. The magnetic field strength is about 9000 gauss.

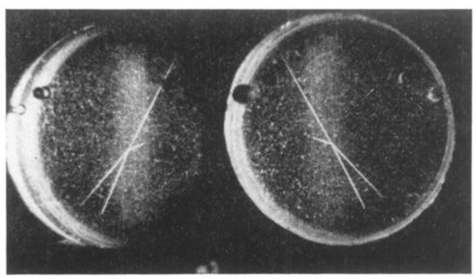

FIG. 9. A "star" in helium-vapor mixture in the cloud chamber.