minima at those positions would be given by a coefficient which varies from 0.84 for C to 1.13 for Pb. This is again an indication of nuclear transparency.

B. Total Cross Sections for Elastic Scattering

The total cross sections for nuclear scattering, omitting the Coulomb part, were determined by counting squares on a curve of cross section per unit angle $d\sigma/d\theta = 2\pi \sin\theta d\sigma/d\Omega$, plotted as a function of angle. Although the total solid angle offered at large angles is much greater than that at small angles, the cross sections fall off rapidly enough that the contribution for angles greater than 30° is negligible in all cases. The results of the integration are consistent with the neutron results in that they fall always below the upper limits for elastic scattering indicated by the neutron experiments.

C. Nuclear Eccentricities

The high spin nuclei show no statistically important differences from their zero-spin neighbors, except that the Al minimum appears slightly sharper, but the resolution is such that nuclear eccentricities would need to be much larger than currently held values to be discernible.

IX. ACKNOWLEDGMENTS

The authors wish to express their gratitude to Professor E. O. Lawrence for his kind interest in the progress of this work. They also wish to thank the cyclotron crew and especially Mr. J. L. MacMullen for their assistance in the investigation of the structure of the emergent proton beam. Dr. S. Fernbach and Dr. K. M. Gatha have been very helpful in discussions of the theoretical aspects.

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Nuclear Photodissociation by High Energy Synchrotron Gamma-Rays*

SEISHI KIKUCHI
Cornell University, Ithaca, New York
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The stars and single proton tracks produced in photographic emulsions exposed to a beam of high energy synchrotron gamma-rays have been analyzed. The maximum energy of the bremsstrahlung spectrum was varied between 150 and 300 Mev. The following subjects were studied: 1. the cross section for star production as a function of the excitation energy; 2. the energy distribution of the protons from stars as well as single protons; 3. the angular distribution of star protons as well as single protons; and, 4. the relative number of stars associated with a meson coming out.

The cross section for the nuclear photoevents increases with increasing energy above the meson threshold. There seem to be two sorts of processes taking place in competition with each other. One is the so called free meson effect; namely, a free meson is produced inside the nucleus by the interaction of a photon with a nucleon and is then absorbed in the same nucleus. The other effect is a process in which a photon is absorbed directly by a group of nuclear particles without emitting a real meson. Evidence for the free meson effect is seen in the fact that the angular distribution of star protons of energy between 20 and 60 Mev in the case of 300-Mev excitation shows a strong forward peak. Evidence for the existence of the direct absorption of photons comes from the fact that the angular distribution of star protons of high energy, say about 100 Mev, shows a forward asymmetry.

The cross section for direct absorption is much larger than expected from Levinger's theory of nuclear photodissociation. The cross section should be at least of the same order of magnitude as the free meson effect.

I. INTRODUCTION

NOT much is known about the photodissociation of nuclei by gamma-rays whose quantum energy is above the threshold of photomeson production. The cross section for (γ,n), (γ,p), $(\gamma,2n)$, (γ,np), $\cdots$ reactions has been studied up to about 100 Mev, and the results show that the cross sections reach their maximum somewhere below 50 Mev and then decrease gradually to a very small value, which is not yet exactly measured. The purpose of the present experiment is to investigate the nuclear photodissociation when the energy of the photon exceeds the meson threshold, by studying the stars and the single proton tracks produced in a photographic emulsion exposed directly to a beam of high energy synchrotron gamma-rays.

It is expected that above the meson threshold stars will be produced by the emission and subsequent absorption of mesons in the same nucleus. Actually, it was found that the probability for star production begins to increase as the energy of the photon exceeds the meson threshold.[1] The problem is whether or not this effect can be explained in terms of the so called free meson effect alone. The present results indicate not only the existence of the free meson effect but the existence of another effect whose cross section is comparable with the free meson effect.

The production of high energy protons from any target irradiated by high energy gamma-rays has been reported, and their energy distribution and angular

* This work has been supported by the ONR.

[1] R. D. Miller, Phys. Rev. 82, 260 (1951); S. Kikuchi, Phys. Rev. 81, 1060 (1951).

TABLE I. Relative number of events produced in a photographic emulsion at different excitation energies.

Excitation energy in Mev		150	200	250	300	300–150
Single protons	<20 Mev	200±50			170±20	−30±60
	>20 Mev	35± 5			47± 8	12± 9
2-prong stars	positive	16± 2			47± 6	32± 7
	probable	9± 2			46± 7	37± 7
3-or-more-prong stars		25± 3	36±4	86±12	100	75± 3
Meson-associated stars		0			5± 2	5± 2

distribution have been studied.[2] It is expected that by the study of individual nuclear photoevents in photographic emulsions the origin of these so called photoprotons will be made clear. The advantage of the use of the photographic emulsion method lies more in the clarification of the qualitative side of the phenomenon rather than the quantitative side. In the present work a greater effort was made to take advantage of this circumstance than to get accurate values.

II. EXPERIMENTAL PROCEDURE

The photographic emulsions used were both Ilford C2 and G5. The thicknesses of emulsion used were 200, 300, and 600 microns. At the earlier stage of the work, emulsions were exposed to an uncollimated beam of synchrotron bremsstrahlung gamma-rays, 3.6 meters from the synchrotron target. Later, they were exposed to a beam in the large vacuum chamber of the pair spectrometer at about 6 meters from the synchrotron target. The electron contamination of the beam was swept away by the magnetic field of the pair spectrometer, and a pure gamma-ray beam hit the plates which were set uncovered, emulsion side facing the beam. For thick G5 emulsion this procedure helped very much to get rid of blackening due to the electron contamination of the beam. In the case of G5 emulsion there were many secondary electron tracks starting in the emulsion. Most of them were parallel to the beam and did not prevent us from finding or measuring the prongs which were not parallel to the beam. When the emulsion surface is perpendicular to the beam, the secondary electrons travel normally to the surface and the disturbance is the least.

In the case of 200-micron emulsion the maximum radiation one can give to the G5 emulsion was about $5\times 10^8\ Q$,[3] distributed uniformly over the area of a 1 in. $\times 3$ in. plate. In the case of 600-micron emulsion the limit was one third of this amount. In the case of C2 emulsion about ten times more radiation can be given than in the case of G5 emulsion of the same thickness.

[2] C. Levinthal and A. Silverman, Phys. Rev. **82**, 822 (1951); D. Walker, Phys. Rev. **81**, 654 (1951); J. C. Keck, Ph.D. thesis, Cornell University (1951).

[3] Q, the number of equivalent quanta, is a quantity defined by

$$Q = \text{total flux of gamma-rays} / \text{maximum energy of bremsstrahlung spectrum},$$

and is used conveniently in dealing with the bremsstrahlung gamma-rays. See references 5 and 6.

The processing of the plates was done according to the method developed by Occhialini[4] and others using amidol. In some cases of C2 emulsion, hydroquinone developer was used instead of amidol. It was necessary to underdevelop the plates in order to measure the energy of protons between 20 and 60 Mev by the gap density measurement. The uniformity of the development for 200-micron emulsion was very satisfactory. In the case of 600-micron emulsion there was a slight depth dependence in the degree of development.

III. THE RELATIVE FREQUENCY OF APPEARANCE OF DIFFERENT SORTS OF EVENTS

The nuclear photoevents analyzed were as follows:

1. Stars. In this note a star means an event such that more than two visible prongs start from a point in the emulsion. Prongs shorter than 3 microns were regarded as recoils of the residual nucleus and were not counted as prongs. The stars are classified according to the number of prongs.
2. Single prongs. This means a visible prong starting in the emulsion without association with any other visible prongs. A single prong might be a proton, deuteron, triton, alpha-particle, or meson. Some of them might be associated with neutron prongs, which are not visible. Among the single prongs only the proton prongs were analyzed. The single meson prongs were mostly light, and it was hard to obtain reliable statistics from them.
3. Meson-associated stars. This means a kind of star from which a meson comes out. If the meson is of low energy and is stopped in the emulsion, it often forms a sort of double star.

Table I shows the relative frequency with which different sorts of events were observed at different excitation energies. All the figures were taken from data obtained with G5 emulsion. In the case of 300- and 150-Mev excitation, most of the data was taken from 600-micron emulsion. In the other cases 200-micron emulsions were used. Though nothing has been said yet about the energy measurement of the protons, part of the classification of events in Table I is made according to the energy of the protons.

The numbers for the cases of different excitation energies are normalized to the same number of equivalent quanta, using the data given in the next section. The number of 3-or-more-prong stars in the case of 300-Mev excitation was taken as a standard.

There was an ambiguity about the number of two-prong stars, as such a star was easily confused with a single track suffering a large angle scattering. The use of 600-micron thick emulsion diminished this ambiguity considerably, compared with the case of 200-micron emulsion. There are still an equal number of doubtful cases and positive cases.

[4] Dilworth, Occhialini, and Vermaesen, Bulletin Du Centre De Physique Nucleaire De L'Universite De Bruxelles, No. 13a, Fevrier (1950).

The knowledge of the number of single protons in proportion to the number of stars is important in connection with the discussion of the mechanism of star production and also in connection with the relation of the present results to the results of other workers on photoprotons observed by counter experiments. To eliminate the doubt which might arise from the fact that a single proton starting in the emulsion is a rather inconspicuous event, so that the number given might be too small, the efficiency of the scanning was checked by scanning a part of the area twice. On the average the efficiency for single protons was about 80 percent, whereas that for stars was 92 percent. The figures given in Table I have not been corrected for this factor.

The method by which the percentage of meson-associated stars was determined will be mentioned in Sec. VII.

As the numbers are normalized to equal Q, the difference of the corresponding numbers at two different excitation energies indicates to a good approximation the contribution of the photons whose energies lie between the corresponding excitation energies.[5] Thus the last column of Table I shows the contribution of photons of energy above 150 Mev contained in the bremsstrahlung spectrum of maximum energy 300 Mev. It is worthwhile to note that a good fraction of the single protons in the 300-Mev case is due to photons of energy below 150 Mev. We will refer to this point again in Sec. VI.

IV. THE EXCITATION CURVE FOR STAR PRODUCTION

The experiment described in this section was carried out at a fairly early stage of the work, where only C2 emulsions had been used. The 200-micron C2 emulsions were exposed directly to the beam of synchrotron bremsstrahlung gamma-rays of maximum energy 150, 200, 250, and 300 Mev, and the numbers of stars produced in the emulsions were compared. The intensity of the beam at different excitation energies was calibrated by the intensity of radioactivity induced in a

TABLE II. The cross section per Q for the production of stars of three or more prongs.

Excitation energy in Mev	150	200	250	300
Cross section per Q, arb. units	1.95±0.18	2.55±0.19	5.63±0.56	6.04±0.41
Cross section per Q, corrected	2.05±0.20	3.00±0.22	7.20±0.72	8.15±0.57
Absolute cross section per $Q\times10^{27}$ cm²	1.5 ±0.4	2.2 ±0.2	5.4 ±0.5	6.1 ±0.4

[5] It is a special character of the bremsstrahlung spectrum that, if the spectra obtained at two different excitation energies E_1 and E_2 ($E_1<E_2$) are normalized to the same number of Q, they coincide approximately with each other in the region below E_1.

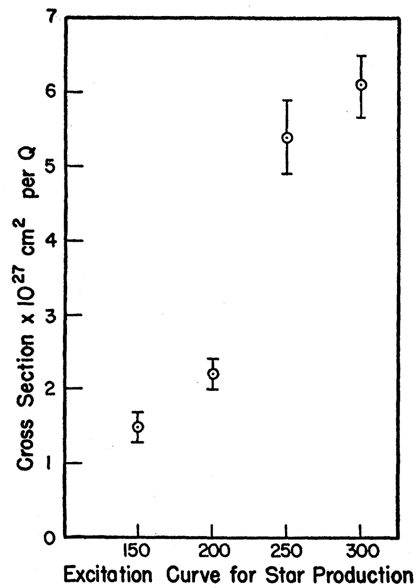

FIG. 1. Excitation curve for star production.

carbon plate exposed to the beam simultaneously with the emulsion, by the reaction $C^{12}(\gamma,n)C^{11}$. This means that the beam intensity was normalized to the same intensity at the resonance energy of the $C^{12}(\gamma,n)C^{11}$ reaction, which lies at about 25 Mev. The cross section in terms of equivalent quanta Q should be,[6] to a good approximation, proportional to the number of stars produced in the emulsion per standard intensity of the C^{11} activity. In every case the emulsion and the carbon plate were exposed to the beam for three minutes. The counting of the activity, started 5 minutes after the exposure was finished, was done with a commercial Geiger counter in standard geometry for 7 minutes. It was checked in advance that the activity in this time interval was due to C^{11}. The actual number of counts was 400 to 700 in 7 minutes, while the background count was about 140 in 7 minutes.

In counting the stars there was the ambiguity about the two-prong stars, as already mentioned. Only those events were counted as two-prong stars when it was certain that they were different particles because of the difference in the grain density of the two prongs or because of the increase in grain density of both prongs along the track as the distance from the common point increases.

[6] The cross section in terms of Q, $\sigma_Q(E)$, at the excitation energy E is defined by $\sigma_Q(E)=n/(N\times Q)$, where Q is the number of equivalent quanta corresponding to the flux which went through the area in which n events were found, and N is the number of atoms per unit area of emulsion. To get the cross section per photon, we have to take the difference, $\sigma_Q(E+dE)-\sigma_Q(E)$, and divide it by the number of photons between E and $E+dE$ for unit Q. If we use the approximation that the spectrum is given by $W(E)=Q_0/E$ for $E<E_{\max}$ and 0 for $E>E_{\max}$, where $W(E)dE$ is the number of photons between E and $E+dE$ and Q_0 is a constant, Q is equal to Q_0, as is easily shown. In this case the cross section per photon $\sigma(E)$ is simply given by

$$\sigma(E)=E d\sigma_Q(E)/dE.$$

The error caused by the fact that the C2 emulsion is not sensitive to high energy protons was estimated in the following way. First the sensitivity of the individual emulsion was determined by finding out how far the proton tracks could be followed from the end of their range. The C2 emulsion is supposed to be sensitive to protons up to the energy of 60 Mev. But in the present case they were processed rather lightly by the hydroquinone developer using the dry method, and it was determined that the emulsion was sensitive up to 30 Mev. Thus, knowing the sensitivity of C2, one can figure out from the actual prong spectrum and energy spectrum obtained by analyzing the stars in G5 emulsion, what the prong spectrum should be like and how many stars are overlooked when C2 emulsion was used. A careful study on about 300 stars obtained in 600-micron G5 emulsion showed that the prong spectrum is somewhat distorted in C2 emulsion and that the correction to be applied to the total number of the stars is about (35 ± 5) percent in the case of 300-Mev excitation. In the case of 150-Mev excitation the number of the protons above 30 Mev is relatively small compared to the case of 300-Mev excitation, and the same consideration showed that the correction should be (5 ± 3) percent.

The results are shown in Table II. The first row shows the figures proportional to the number of stars for the standard intensity of C^{11} activity before the correction for the insensitivity of the C2 emulsion. The second row shows the values after this correction. The amount of correction for the cases of 200 and 250 Mev was determined simply by linear interpolation. The ratio of the number of stars per Q produced in the emulsion at 300-Mev and 150-Mev excitation is 4.0 ± 0.5 after the correction and 3.1 ± 0.1 before the correction. The other method of determining this ratio is to determine the number of low energy single protons in proportion to the number of stars. The low energy protons, say below 20 Mev, starting in the emulsion would be due to gamma-rays of low energy through the reactions (γ,p), (γ,np), and so on. Therefore one can use the number of low energy single protons as a measure of Q values; and the ratio of the number of stars to the number of single protons of low energy gives the cross section per Q. Taking into account only those single protons and stars which start in the middle 400 microns of the 600-micron emulsion, the ratio can be determined fairly certainly. In the present case, the protons of energy below 20 Mev were counted, and the result was 4.5 ± 1.6 for the ratio. Owing to the rather small number counted, the error is fairly large. But the value is in better agreement with the corrected value from Table II than with the value before the correction.

The cross section as a function of excitation energy is plotted in Fig. 1. The value of the ordinate indicates the absolute cross section (see next section). The cross section seems to rise fairly steeply above 150 Mev. The trend is similar to the excitation curve for photomeson production. One might argue that the steep rise of the curve does not necessarily show the rapid rise of the cross section of photonuclear interaction itself. It might come from the fact that the energy of the nucleon or group of nucleons set in motion by the primary photonuclear event increases with the increasing excitation energy and therefore the probability that these particles produce a star by collision with another nucleon, inside the nucleus, increases rapidly with the excitation energy. This argument might be true if star production were a small part of all photonuclear events. However, as the figures of Table I show, the production of stars of 3 or more prongs constitutes a large part of all photonuclear events, so that the result described in this section shows definitely that the cross section for the photonuclear interaction does increase rapidly above 150 Mev.

Similar results have been obtained by Miller[1] at Berkeley. Miller used C2 emulsion and counted stars of 3 or more prongs. The relative values of the cross section at different excitation energies agree quite well with the present values before correction.

TABLE III. The energy distribution of star protons and single protons. The cross section is expressed in microbarns per Mev per Q.

Energy in Mev	300-Mev excitation Star	300-Mev excitation Single	150-Mev excitation Star	150-Mev excitation Single
20– 30	150 ± 20	155 ± 32	36 ± 6	135 ± 17
30– 40	89 ± 17	75 ± 22	17 ± 4	54 ± 11
40– 50	70 ± 15	80 ± 23	5 ± 2	20 ± 6
50– 60	64 ± 14	34 ± 15	6 ± 2	15 ± 6
60– 80	15 ± 4	7 ± 5	0	2 ± 1
80–100	10 ± 3	7 ± 5	1 ± 1	2 ± 1
100–120	12 ± 4	7 ± 5	1 ± 1	3 ± 2
120–140	8 ± 3	0	0	0
140–160	7 ± 3	0	0	0

V. THE ABSOLUTE MEASUREMENT OF THE CROSS SECTION FOR STAR PRODUCTION

The absolute cross section for star production at 300-Mev excitation was determined by measuring the integrated beam intensity sent through the emulsion with the ionization chamber and current integrator calibrated with the gamma-ray pair spectrometer[7] by Keck[2] of this laboratory. $1.08\times10^8\,Q$ was sent through a 300-micron thick G5 emulsion. Stars of 3 or more prongs were counted and the over-all average cross section σ was determined by the relation $\sigma QN=n$, where N is the sum of the number of atoms of different kinds except hydrogen per cm^2 of emulsion, and n is the total number of stars of 3 or more prongs. Since we have as yet no information about the Z-dependence of the cross section it is most reasonable to give the value of cross section in this way. As soon as we know the Z-dependence we can calculate the cross section for each element from the known data about the atomic concentration of different elements in emulsion.

[7] DeWire, Ashkin, and Beach, Phys. Rev. 83, 505 (1951).

The value obtained for the cross section per Q for the production of 3 or more prong stars at 300-Mev excitation is $(6.1\pm0.3)\times10^{-27}$ cm^2. This value will be used throughout as the basis for discussion.

The absolute cross section can also be determined[1] from the experiment described in Sec. IV by determining the absolute number of C^{11} atoms produced in the carbon plate exposed simultaneously with the emulsions, together with the value of $\int\sigma(E)dE$ determined by other workers. $\sigma(E)$ is the cross section for the $C^{12}(\gamma,n)C^{11}$ reaction for photons of energy E, and the integration is carried out over the vicinity of the resonance point where $\sigma(E)$ is appreciably different from zero. The result is consistent with the present result.

Miller,[1] assuming the cross section for star production to be proportional to the mass number, obtained the value 6.5×10^{-27} cm^2 for the silver nucleus at 322-Mev excitation. Interpolating his excitation curve, the corresponding value at 300 Mev is 5.5×10^{-27} cm^2 for silver. If we calculate the average cross section as defined here from these data, we get the value 2.5×10^{-27} cm^2, which is smaller than our value. Miller used C2 emulsion, and three-or-more-prong stars were counted. If the sensitivity of Miller's emulsion is the same as that of our C2 emulsion, the correction to be applied is a factor of 1.5. This gives the value 3.8×10^{-27} cm^2. The discrepancy is still a factor of 1.6, which is too large to be ascribed to experimental error. Errors involved in the calibration of the beam might be responsible for this discrepancy.

VI. THE ENERGY DISTRIBUTION OF THE PROTON PRONGS

The energy of the protons from stars, as well as that of the single protons, were determined by measuring range, gap, or grain density, according to which one of the methods gives the most accurate value for each individual case. The analysis was carried out on 600-micron G5 emulsion exclusively. The protons or stars starting within 100 microns from either surface of the emulsion were discarded. Under these conditions the ranges of the protons remaining in the emulsion were fairly long on the average, so that a moderately accurate determination of the energy was possible. The calibration curve for the gap density as a function of energy was obtained by measuring the gap density as a function of residual range for some protons of range 5000 to 15,000 microns ending in the emulsion. The energy of protons between 20 and 60 Mev was measured mostly by this method. The gap density of a 20-Mev proton was 0.17 and that of a 60-Mev proton was 0.50. The energy of protons above 60 Mev was measured by grain counting. At 60 Mev the grain density was 100 per 100 microns. The grain density-energy curve was calibrated from some long range mesons ending in the emulsion. The longest meson track used was about 10,000 microns, whose grain density at the start corresponds to that for protons of 170 Mev. Above this energy the energy was determined roughly by extrapolation. Minimum ionization was determined by the electrons from μ-e decay and also by some high energy electrons excited by gamma-rays. It was 32 grains per 100 microns. As already mentioned, the development of the emulsion was carried out to such a degree that the determination of the energy by gap measurement was as accurate as possible for the energy region between 20 and 60 Mev.

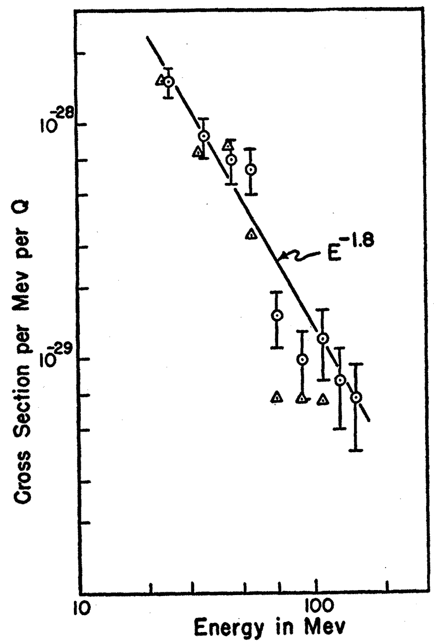

FIG. 2. Energy distribution of star protons and single protons in the case of 300-Mev excitation. The circles represent star protons and the triangles represent single protons.

The measurement was made most extensively in the case of 300-Mev excitation and less extensively in the case of 150 Mev. For other excitation energies no proton measurement was made.

There was a slight depth dependence in the degree of development. However, if we discard those prongs starting within 100 microns from either surface of the emulsion, the error caused by using the same energy gap density curve or energy-grain density curve at different depths was small enough, in so far as the higher accuracy in the definition of energy was not required. No correction arising from this circumstance was applied. Those prongs whose grain density was below 55 per 100 microns were not counted in the results. It will be shown in Sec. VII that prongs of such low grain density are mostly mesons. The results are shown in Table III.

The following conclusions can be drawn from the data shown in Table III. In the case of 300-Mev excitation, the number of single protons between 20 and 50 Mev is nearly the same as the number of star protons of the same energy range. Between 60 and 120 Mev the number of single protons is about half the

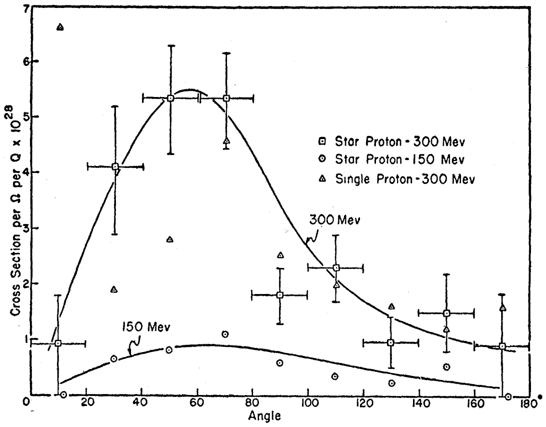

FIG. 3. Angular distribution of protons for energies between 20 and 60 Mev.

number of star protons, and above 120 Mev most of the protons are due to the stars.

Comparing the numbers at 300-Mev excitation with those at 150-Mev excitation, we see that about 75 percent of the star protons in the case of 300-Mev excitation are due to photons of energy above 150 Mev. As to the single protons, the number of protons between 20 and 30 Mev is nearly the same for 300-Mev excitation as for 150-Mev excitation, a fact which indicates that most of the single protons of this energy in the case of 300-Mev excitation are due to photons of energy below 150 Mev. Above 30 Mev the number of single protons in the case of 300-Mev excitation is twice that in the case of 150 Mev, indicating that half of the single protons observed in the case of 300-Mev excitation are due to photons of energy lower than 150 Mev.

A brief comparison of the results described in this section with the results of Levinthal and Silverman will be made here. First of all, according to the present results the photoprotons observed by Levinthal and Silverman[2] are a mixture of single and star protons. One-half of the single protons are excited by photons of energy below 150 Mev, and the rest of the single protons and most of the star protons are excited by photons of energy above 150 Mev. According to their theory the protons they observed should be due to the photons of energy much below 150 Mev.

As far as the form of the energy distribution curve is concerned, the results are in good agreement with each other. Figure 2 shows a log-log plot of the energy *versus* cross section curve in the present case. The solid line represents a function proportional to $E^{-1.8}$, where E is the energy. Levinthal and Silverman found the same distribution function, namely E^{-n}, where n is equal to 1.7 for carbon, 1.8 for copper, and 2.2 for lead. As to the absolute value of the cross section at 20 Mev, it is larger by a factor of 3 in the present case than in that of Levinthal and Silverman.

In Keck's experiment, which is concerned with much higher energy protons, mostly above 100 Mev, than in the case of Levinthal and Silverman, most of the protons seem to have come from stars. The cross section is roughly in agreement with the present results. The fact, found by Keck, that the number of protons decreases very rapidly above 150 Mev, seems to be consistent with the present result that no proton above 160 Mev was confirmed (see Sec. VIII).

VII. THE ANGULAR DISTRIBUTION OF THE PROTONS

The angular distribution of the emitted protons relative to the incident gamma-ray beam was studied by analyzing about 600 stars produced in the 600-micron G5 emulsion. The incident gamma-ray beam was sent through the emulsion at an angle of 45 degrees to the surface. The angle between the direction of emission and the incident beam was determined by measuring the dip angle of the proton track and the azimuthal angle between the proton direction and the beam direction, both projected on the emulsion surface. The shrinkage of the emulsion was taken into account. A small correction was necessary due to the distortion of the emulsion. The distortion was mostly the shearing which came from the fact that the layers near the free surface of the emulsion shrank laterally more than the bottom layers. The degree of shearing could be determined from the direction and curvature of the numerous secondary electron tracks having approximately the same direction as the incident beam. The correction due to this circumstance was 10 degrees in the worst case. In most cases it was only a few degrees.

The upper curve of Fig. 3 shows the angular distribution of protons of energy between 20 and 60 Mev coming from stars in the case of 300-Mev excitation. It shows a strong forward peak at about 50 degrees. The decrease of differential cross section below 20 degrees seems to be real. As already mentioned, about 75 percent of the protons of this group came from photons of energy above 150 Mev. To illustrate this point more clearly, the angular distribution of star protons of the same energy region in the case of 150-Mev excitation, normalized to the same Q value, is shown in the same figure without giving the error to avoid complication of the figure. The important point is that rather low energy protons, such as 20 to 60 Mev, excited by rather high energy photons, show such a

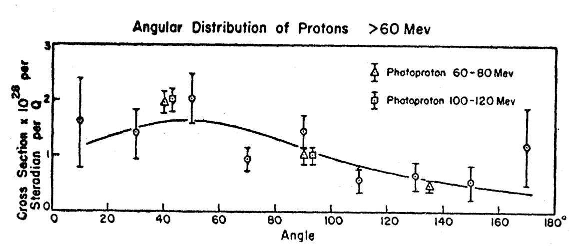

FIG. 4. Angular distribution of high energy protons in the case of 300-Mev excitation. The circles represent star protons above 60 Mev; the triangles represent photoprotons between 60–80 Mev; and the squares represent photoprotons between 100–120 Mev.

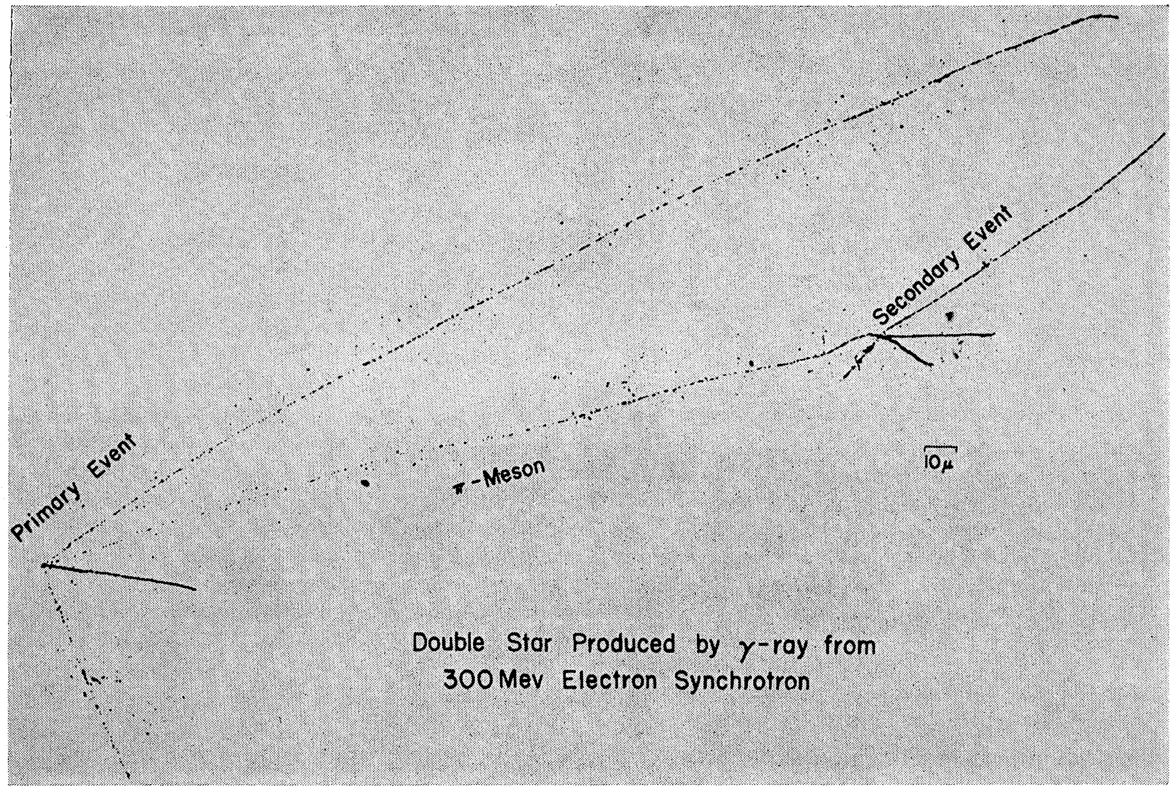

FIG. 5. A star showing production of a π-meson, which stopped in the emulsion and produced another star (Ilford C2 plate)

conspicuous forward peak. Within a fairly large statistical error, no marked difference can be observed between the angular distribution of protons of energy between 20 and 30 Mev and that of those between 30 and 60 Mev. The angular distribution of single protons of energy between 20 and 60 Mev is also shown in Fig. 3.

The angular distribution of protons from stars above 60 Mev for 300-Mev excitation is shown in Fig. 4. The prongs whose grain density was below 55 per 100 microns were not taken into account. Within fairly poor statistics one can recognize a trend towards a fairly strong forward asymmetry. It might make little sense to take an average over such a wide energy range as from 60 to 160 Mev, because it is quite possible that the angular distribution might depend strongly on the energy of the protons. To see this point more clearly, the ratio of the number of protons emitted forward ($<90°$) to the number emitted backward ($>90°$), for protons of energy between 60 and 100 Mev and between 100 and 160 Mev, is given in the following table.

Energy	60–100 Mev	100–160 Mev
Ratio	1.75±0.63	2.14±0.68

The differential cross section at 70 degrees averaged over 60- to 80-Mev protons is roughly 2±1 microbarns per steradian per Mev per Q. Keck's value for carbon at this angle and energy is 0.75 microbarn. If, assuming the proportionality of the cross section to Z and the same angular dependence for carbon and silver, we reduce this to the average cross section for atoms constituting the emulsion, we get the value 1.5 microbarns. At this energy the number of single protons is not negligibly small compared to the star protons. Therefore Keck's value should be higher than the present value. When one considers the fairly large error stated, the results are consistent.

In connection with the interpretation of the star producing process, it is important to know the angular distribution of high energy protons. The analysis of the prongs from stars by the photographic method, as was carried out in this work, is so tedious that it is almost impracticable to get more accurate results. According to the present results, however, the number of single protons in proportion to the protons coming from stars is rather small in the high energy region. Therefore, instead of analyzing stars by using the photographic method, one can get the same information from experiments on photoprotons of high energy. Keck studied the angular distribution of photoprotons excited by 300-Mev synchrotron gamma-rays at proton energies of 100, 130, and 170 Mev. The results showed that the differential cross sections at 45°, 90°, and 135° are roughly in the ratio of 4:2:1 for 100-Mev protons. The degree of asymmetry increases with the increasing proton energy.

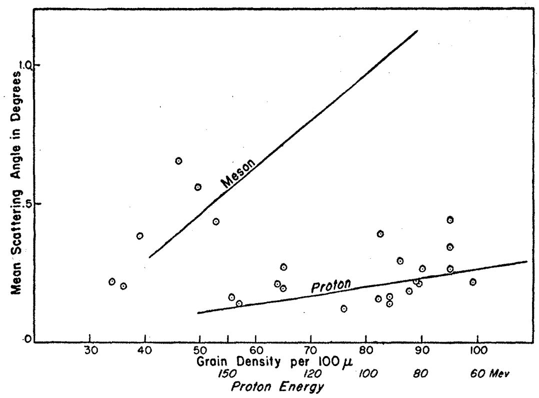

FIG. 6. The mean multiple scattering angle results.

Keck's result was confirmed by an experiment similar to that of D. Walker, using photographic emulsions placed around the target which was bombarded by the bremsstrahlung gamma-rays of 300-Mev maximum energy. The magnitude of the forward asymmetry observed by Keck was confirmed both for the protons of energy between 60 and 80 Mev and the protons of energy between 100 and 120 Mev, as shown in Fig. 4. It thus seems to be certain that the angular distribution of the high energy protons coming from stars shows a fairly strong forward asymmetry.

VIII. THE π-MESONS FROM STARS

It has been found[1] that the stars produced by gamma-rays sometimes emit a slow meson which stops in the emulsion and makes another star, or shows a π-μ decay, according as it is a π^- or a π^+. One example is shown in Fig. 5. The mesons found in this way are those of low energy, mostly below 5 Mev, and constitute only a small fraction of all mesons emitted. By extrapolating the energy spectrum obtained by Peterson, Gilbert, and White[8] down to zero energy, it is estimated that the number of mesons below 5 Mev would be roughly 0.5 percent of the total mesons. The number of stars associated with a slow meson ending in the emulsion, in proportion to the total number of stars of 3 or more prongs in the same area of emulsion, depends on the thickness of the emulsion. In the case of 600-micron emulsion there were 8 cases, compared to 1741 three-or-more-prong stars. In the case of 200-micron emulsion, the rate of observation of double stars was one case out of about 500 three-or-more-prong stars. The ratio observed in the case of 600-micron emulsion seems to be surprisingly high, because, if the mesons of energy below 5 Mev constitute only 0.5 percent of the total meson spectrum, there should be as many mesons as stars in the same area. But this was evidently not the case.

To determine the percentage of the meson-associated stars to the total number of stars the following procedure was used. It is expected that most of the meson tracks are thin, because about 80 percent of the mesons have energy of more than 20 Mev, and a 20-Mev meson corresponds to a proton of 120 Mev in its ionization power, namely 70 grains per 100 microns. The only possible way of identifying the mesons was by measurement of the mean multiple scattering angle. The trouble was the fact that when the prong had a rather large dip angle to the surface of the emulsion, the distortion of the emulsion made it difficult to carry out the multiple scattering measurement of such a track. Therefore, we measured the mean multiple scattering angles of the prongs which satisfied the following conditions: The grain density had to be smaller than 100 grains per 100 microns; the dip angle smaller than 15 degrees before processing; and the length of the prong longer than 1500 microns before going out of the emulsion. There were 26 such cases in the area where 401 three-or-more-prong stars were found. (This does not mean that the meson-associated stars are three-or-more-prong stars. Many of the mesons were associated with another prong forming a two-prong star.)

The result is shown in Fig. 6. It is clear that the 6 prongs whose grain density is smaller than 55 per 100 microns are all mesons. A proton whose grain density is 55 corresponds to an energy of 160 Mev. The above result is not surprising because the cross section for the production of such a high energy proton is exceedingly small.

We therefore assumed all prongs with grain density less than 55 to be mesons. There were 19 such prongs in the area where 401 three-or-more-prong stars were found. This means that the cross section for the production of mesons of energy above 20 Mev associated with a star is (5.0 ± 1.5) percent of the cross section for the production of stars of three or more prongs.

There were also mesons of intermediate energy, which did not end in the emulsion, but it was very easy to identify them as mesons from the wiggling of the tracks. There were 4 such cases out of the area where 1741 three-or-more-prong stars were found. Summarizing the results, the number of meson-associated stars found in a certain area of emulsion is 5.7 ± 2.0 percent of the number of three-or-more-prong stars found in the same area.

As has already been mentioned, the single meson tracks starting in the emulsion were not counted, because they are inconspicuous events and difficult to take reliable statistics about. However, we occasionally noticed a single meson starting in the emulsion without being associated with any star. Some of them were low in energy and stopped in the emulsion. Some of them were of high energy, and the identification was possible only by the mean multiple scattering angle measurement. Roughly speaking, the number of single meson tracks are of the same order of magnitude as the number of mesons associated with stars.

[8] Peterson, Gilbert, and White, Phys. Rev. 81, 1003 (1951).

The cross section for the production of meson-associated stars is thus 6.1×10^{-27} cm^2 times 0.05, which is equal to 3×10^{-28} cm^2. The value expected from the data on the meson production is 7×10^{-28} cm^2 for the total cross section, assuming[5] the cross section for carbon and silver to be 4.0×10^{-28} cm^2 and 1.7×10^{-27} cm^2. Therefore, if there are twice as many single mesons as mesons from stars, which is probable, the results are consistent.

It might be worthwhile to mention here that there was one case where a slow meson came out of a star and stopped in the emulsion, decaying into what was probably a μ-meson whose range was only 200 microns.

IX. DISCUSSION OF THE RESULTS, AND CONCLUSIONS

The consistency or inconsistency of the present results with those of other workers with related problems was discussed in each section from case to case, and might be summarized as follows. In general the present results are consistent with the results of the experiments on photoprotons done by Levinthal and Silverman,[2] Walker,[2] and Keck[2] both in energy distribution and angular distribution of the protons. In the case of Levinthal and Silverman, about half of the protons seem to have come from stars excited by photons of energy above 150 Mev and the rest of the protons seem to be single protons, half of which are excited by photons of energy above 150 Mev and the rest by photons of energy below 150 Mev. In the case of Keck, where higher energy protons are concerned, most of the protons came from stars excited by photons of energy above 150 Mev. In the case of Walker the excitation energy was 200 Mev. Although no precise analysis was made in the present experiment at this excitation energy, it is clear that the origin of the protons was the same as in the other cases, with the difference that the contribution of the single protons excited by photons of energy below 150 Mev is larger than in the case of 300-Mev excitation.

For the absolute cross section, the value of Levinthal and Silverman is smaller by a factor of 3 than the present value, which is in good agreement with Keck's value. For the cross section for star production, the present value is 1.6 times larger than the value obtained by Miller[1] at Berkeley, although the relative values at different excitation energies are in close agreement with each other.

As for the interpretation of the results, the theory of Levinthal and Silverman seems to be good only for a part of the protons they observed. According to their theory the protons of energy E should be produced by photons of energy $E+25$ Mev. This means that most of the protons they observed should be due to photons of energy below 100 Mev. According to the present result, three-fourths of the protons they observed should have come from the photons of energy above 150 Mev and therefore cannot be accounted for by their theory. As will be discussed later, the free meson effect seems to be responsible for these protons.

Keck tried to explain his results mainly on the basis of Levinger's theory of photodissociation of the nuclei by high energy photons. The approximate form of the angular distribution curve fitted well with the theory, but the cross section was a few times larger than the prediction of the theory. As will be discussed below, the present result seems to show that the Levinger approximation fails to explain the production of high energy protons excited by photons of energy between 150 and 300 Mev.

There are, among others, the following three evident experimental facts which should be explained.

1. The cross section for photodissociation increases above 150 Mev, and for bremsstrahlung of maximum energy of 300 Mev, the cross section per Q is about 6.1×10^{-27} cm^2 plus the cross section for the production of the two- and one-prong stars. From the data given in Table I, the difference between the total cross sections at 150-Mev and 300-Mev excitation is estimated to be about 9×10^{-27} cm^2 per Q.

2. The angular distribution of protons of energy between 20 and 60 Mev coming from stars shows a conspicuous forward peak between 45 and 70 degrees, and 75 percent of these protons are produced by photons of energy above 150 Mev.

3. The angular distribution of star protons of energy above 60 Mev shows a fairly strong forward asymmetry.

The above-mentioned result 1 shows clearly that some kind of photonuclear process which does not occur in the low energy region begins to take place above 150 Mev. It is quite natural to consider that this is due to the free meson effect, namely the effect of production of a meson in the nucleus: Suppose the nucleons in the nucleus are free and that a photon interacts with one of them and produces a meson. The meson thus created will sometimes get out of the nucleus without interaction, but sometimes it will be absorbed in the nuclear matter before getting out. The latter case obviously results in the production of a star. Even in the former case, the chance would be large that the emitted meson form a star with the nucleon knocked out by the meson-producing process and/or with secondaries of the recoil nucleon.

According to this picture, the excitation curve for star production is nothing else but the excitation curve for photomeson production. As for the absolute value of the cross section for the star production, it is expected to be approximately equal to $\sigma_0 A$, where σ_0 is the cross section for the production of photomesons, including neutral mesons, by a nucleon and where A is the mass number.

On the other hand, experiments[9] show that the cross section for photomeson production is proportional to $\sigma_0 A^{\frac{2}{3}}$. This fact is to be explained by the absorption

[9] R. F. Mozley, Phys. Rev. 80, 493 (1950); R. M. Littauer and D. Walker, Phys. Rev. 82, 746 (1951).

of the meson inside the nucleus and by the Pauli exclusion principle for the recoil nucleon. The numerical value of $\sigma_0 A^{\frac{2}{3}}$ is 4.0×10^{-28} cm^2 for carbon[8] and 1.7 $\times 10^{-27}$ cm^2 for silver for charged mesons. Multiplying these values by $A^{\frac{1}{3}}$ and taking an average over the light and heavy atoms in the photographic emulsion, we get 3.7×10^{-27} cm^2. Adding the part which comes from neutral meson production, assuming that the cross section for neutral meson production is the same as for charged mesons, we get the value 5.5×10^{-27} cm^2 for $\sigma_0 A$. This value should be compared with the value 9×10^{-27} cm^2 obtained above. At present, it is not possible to say anything about the reality of the difference. The fact that the values are fairly close to each other seems to indicate the appropriateness of the assumption.

Results 2 can also be explained, at least qualitatively, on the basis of the picture used to explain result 1, if we consider that the protons of energy between 20 and 60 Mev belonging to the strong forward peak are those protons knocked out by the process in which a meson is produced. If we neglect the internal motion of the nucleons and consider them at rest, the energy of the recoil nucleon is calculated easily as a function of the angle of emission and of the photon energy, simply by applying the laws of conservation of energy and momentum. In this case protons are always ejected into the forward direction. In the case of 300-Mev bremsstrahlung there should be no protons above 20 Mev making an angle greater than 45 degrees with the incident gamma-ray beam. The energy of the protons should be a maximum at 0 degrees and should be about 70 Mev. The energy decreases as the angle of emission increases.

To predict the angular distribution exactly, we need to know the angular distribution of π-mesons emitted at the same time. The angular distribution of photomesons produced on protons by photons of energy 250 Mev has been studied by Bishop, Steinberger, and Cook.[10] According to their results the angular distribution shows a backward asymmetry and a broad maximum at 130 degrees referred to the laboratory system. The meson emitted at 130 degrees is accompanied by a recoil nucleon emitted at an angle of 20 to 35 degrees according to the energy of the photon. Anyway, the recoil nucleon should show a very steep forward asymmetry if we neglect the internal motion of the nucleons inside the nucleus.

The observed forward peak of protons is much broader than this, and moreover the angular distribution curve seems to show a decrease at very small angles. The broadening of the peak might be accounted for by the internal motion of the nucleons before the interaction and the subsequent scattering of the proton inside the nucleus. The decrease at very small angles, if it is true, seems to be hard to understand by the internal motion. Although a quantitative study of the effect of the internal motion of the nucleon on the broadening of the angular distribution is necessary before a final conclusion can be drawn, it seems reasonable to guess that the protons in question are recoil nucleons kicked out by the meson-producing reaction, because there is no other process so far known, which can explain such a conspicuous forward peak of low energy protons down to 20 Mev produced by such high energy photons.

Now, if we want to explain result 3, namely the forward asymmetry of the angular distribution of high energy protons, by the free nucleon model as in the case of 1 and 2, we meet a serious difficulty: The high energy protons, according to the free nucleon model, should be produced by the absorption of a meson inside the nucleus and, as the angular distribution of the mesons shows no sign of forward asymmetry, the protons also should be more or less isotropic in angular distribution. Such is not the case, as Fig. 4 and other experimental evidence show.

This is the point that Levinger[11] tried to explain in terms of electromagnetic photodissociation based on the theory of Schiff[12] for the photodissociation of the deuteron. The idea of Levinger is to describe the nucleus as an aggregation of "quasi-deuterons" and apply the theory of Schiff to them. According to his result the angular distribution is essentially the same as predicted by Schiff in the case of the actual deuteron, and the total cross section per photon should be equal to $1.6\times A\times\sigma_s$, where A is the mass number and σ_s is Schiff's cross section. Therefore, the dependence of the cross section on the photon energy is the same as that of Schiff's deuteron cross section, which decreases steadily with increasing photon energy.

It is interesting to examine how far the observed facts can be explained by the Levinger theory, because it might give some information indirectly about the applicability of Schiff's approximation at photon energies as high as 300 Mev. In Schiff's calculation the effect of the virtual meson field is taken into account through the nuclear force between the proton and a neutron, and the interaction of the photon with the deuteron takes place through the electric moment of the proton. The reason that this approximation is supposed to be good up to fairly high energy is that the electric dipole and quadrupole moment due to the virtual meson field almost vanish. Schiff set the limit of applicability below the photon energy of 140 Mev. Above this energy the effects of the interaction due to the magnetic moment of the virtual meson field and due to the electric moments of higher order, together with the free meson effect, might make the above-mentioned approximation invalid.

As already mentioned, the Levinger cross section is given by $1.6\times A\times\sigma_s$ per photon. Using this result, extrapolating Schiff's value of σ_s up to 300 Mev, as

[10] Bishop, Steinberger, and Cook, Phys. Rev. **80**, 291 (1950).

[11] Private communication.

[12] L. L. Schiff, Phys. Rev. **78**, 733 (1950)

Levinger did, and assuming the bremsstrahlung spectrum to be of the form Q/E, we can calculate numerically the difference between the cross section per Q for the Levinger process at 300 and 150 Mev. This difference comes out to be 3.6×10^{-28} cm^2.

Now it is not fair to compare this value directly with the observed cross section for the production of high energy protons, because only a fraction of the high energy protons produced by the primary process leave the nucleus retaining their energy. To avoid the ambiguity caused by the correction due to this circumstance as far as possible, let the above value, 3.6×10^{-28} cm^2, be compared with the corresponding cross section for star production. From Table I we see that the difference of the cross section per Q for star production including two-prong and one-prong stars at 300 Mev and 150-Mev excitation is about 9×10^{-27} cm^2. This is about 25 times larger than the cross section for the Levinger process. Therefore, if we assume that the Schiff-Levinger approximation is correct, most of the star-producing process should have come from the free meson effect and only about 4 percent of all the stars are due to the Levinger process. If this is so, it is difficult to understand the observed forward asymmetry of high energy protons, unless we assume that the number of high energy protons produced by each absorption of a meson is 25 times smaller than the number produced by each Levinger process, which is impossible. It is expected that there are a few more protons per elementary process in the case of the Levinger process than in the case of meson absorption. But it seems to be impossible that there will be a difference by a factor of more than 2.

Now, looking either at Fig. 5 or at the angular distribution curve obtained by Keck, it is quite natural to assume that the number of protons constituting the asymmetric part of the curve is at least the same as, and probably larger than, the number of protons belonging to the isotropic part. Therefore the process responsible for the asymmetric protons should have a cross section of at least the same order of magnitude as the process responsible for the isotropic part. This means that, besides the free meson effect, there should be another effect which gives rise to the forward asymmetry of protons and has a cross section at least ten times bigger than that predicted by the Schiff-Levinger approximation. It is understandable that in any kind of process in which more than one particle participates in the interaction with a photon, there should be a forward asymmetric distribution of protons relative to the laboratory system, because the momentum of the photon is transferred directly to the participating particles through the emission and absorption of a virtual meson.

One can consider another process which might give rise to the forward asymmetry of high energy protons, although it is somewhat hypothetical. Namely, a photon is first absorbed by a nucleon resulting in the formation of a nucleon isobar, which has been postulated by Fujimoto and Miyazawa[13] and Brueckner and Case to account for the cross section for the production of neutral mesons.[14] The lifetime of the nucleon isobar might be long enough to collide with the other nucleon before decaying into a π-meson and a normal nucleon. The result might be that the excited nucleon makes a transition to the normal state, giving a part of the energy released to the particle with which it collides. In this way the energy and momentum of the photon can be transferred to two nuclear particles without emitting a meson. The cross section for such a process should show a resonance at the energy corresponding to the energy of excitation of the nucleon. A more elaborate study of the excitation function for star production might be of interest in this connection.

In any case the study of the cross section for the photodisintegration of deuterons or alpha-particles is very important to clarify the phenomena discussed in this note. All the results obtained by the present experiment can be understood if the cross section for the photodisintegration of deuterons or alpha-particles associated with the production of high energy protons increases above the meson threshold with increasing photon energy.

In conclusion the author wishes to express his cordial thanks to Professors R. R. Wilson and H. A. Bethe for enabling the author to stay at Ithaca as well as for valuable discussions. Thanks are also due to Professor K. Greisen and Dr. S. Hayakawa for valuable discussions and to the crews of the microscope laboratory for scanning the plates.

[13] Y. Fujimoto and H. Miyazawa, Prog. Theor. Phys. **5**, 1052 (1950).

[14] K. A. Brueckner and K. M. Case, Phys. Rev. **83**, 1141 (1951).

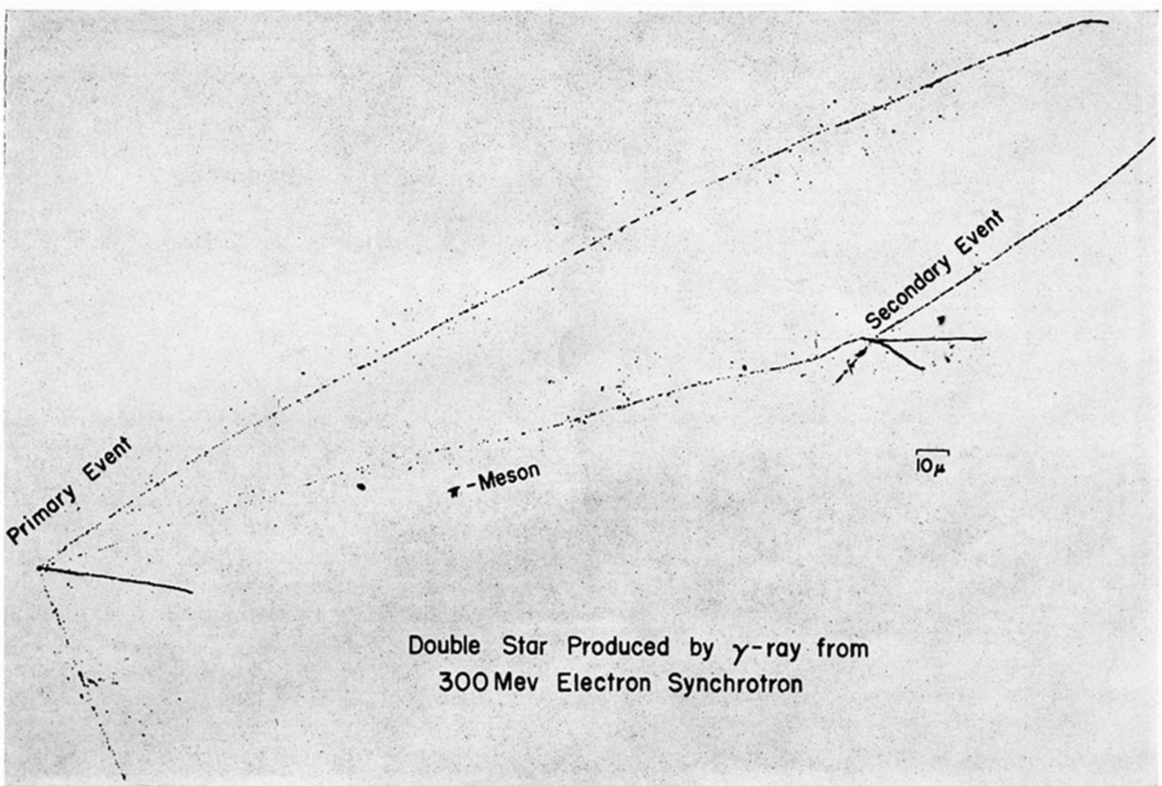

FIG. 5. A star showing production of a π-meson, which stopped in the emulsion and produced another star (Ilford C2 plate)