Production of Photostars by Bremsstrahlung of 250 to 500 Mev*

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The yield of photostars in nuclear emulsion as a function of bremsstrahlung energy has been found to increase rapidly from 6.8 millibarns per Q (total beam energy/maximum beam energy) at 250 Mev to 22.8 millibarns per Q at 500 Mev, for stars of 2 or more prongs from silver nuclei. The cross section for silver was derived by averaging the emulsion nuclei (excluding H) in proportion to their atomic weights. The total photodissociation cross section is estimated to be at most 20% larger due to the addition of one-prong and zero-prong stars. The cross section per photon is derived by the photon difference method, and is found to be about 30 millibarns per silver nucleus above 300 Mev. This very large cross section is approximately 100 times the free nucleon total photomeson cross section. Therefore, photostar production from reabsorption of real pions produced in nuclear matter requires a very short mean free path ($\lambda \approx 1 \times 10^{13}$ cm).

INTRODUCTION

THE photodissociation of nuclei by high-energy x-rays, well above the "giant resonance" at 20 Mev, has been assumed to involve explicit mesonic effects as the photon energy exceeds the 150-Mev threshold for pion production from nucleons. Indeed, early experiments on the yield of photostars in nuclear emulsions by Kikuchi[1] and Miller[2] showed a rapid increase above the meson threshold. Observations of slow pions emitted from photostars and the strong interactions of pions with nuclear matter suggested that photodissociation at high energy may be due to the reabsorption of photopions within the nuclear interior.

Special attention has been paid to the high-energy photoprotons emitted from light nuclei.[3] These protons are emitted with a strongly forward angular distribution, and the energy spectra exhibit a discontinuity in the power-law exponent suggestive of the absorption of the photon by a small nuclear subunit rather than the nucleus as a whole. This led to the proposal by Levinger[4] of a "quasi-deuteron" model, which has recently gained confirmation by the observation of neutron-proton coincidences in Li and Be at the University of Illinois[5] and the Massachusetts Institute of Technology.[6] Most, if not all, of the high-energy protons emitted from light nuclei can be attributed to photodisintegration of "quasi-deuterons."

Photodisintegration in the heavier elements has not been as extensively studied, although radiochemical analyses of some products of photospallation medium-weight elements has been studied at 370 Mev.[7] The importance of reabsorption of mesons within the nucleus increases with nuclear radius, and the concept of a "mean free path" for interaction of pions with nuclear matter becomes meaningful. The "deuteron" photodissociation cross section is small compared with the total photomeson production cross section, and thus will decrease in importance as more mesons are reabsorbed.

The study of photostars in nuclear emulsion measures most of the total photodissociation process and permits study of the photodisintegration process in detail. The present experiment extends the work of Miller and Kikuchi to 500 Mev. We have examined more than 3000 events and measured the yield of photostars of two or more prongs as a function of peak bremsstrahlung energy, in the region 250 Mev to 500 Mev. The results are compared with other experiments and an estimate of the total photodissociation cross section is obtained for photons of 250 to 500 Mev.

EXPERIMENTAL PROCEDURE

Electron-sensitive G-5 emulsions were used to insure detection of all prongs. Kikuchi[1] has shown that the correction for fast star prongs not observed in C-2 plates is 35% for 300-Mev bremsstrahlung. The disadvantage of using electron-sensitive emulsion is the reduction in the maximum allowable exposure density. This places greater stress on the reduction of pre-exposure stars due to cosmic rays and radioactive contamination.

Single emulsions, 200 or 400 microns thick and glass-backed, were exposed at normal incidence to a well-collimated beam of x-rays produced in a 0.015-in. copper target in the California Institute of Technology (CalTech) electron synchrotron (see Fig. 1). The beam area at the emulsion was about 4 cm² and considerably

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[1] S. Kikuchi, Phys. Rev. **86**, 41 (1952).
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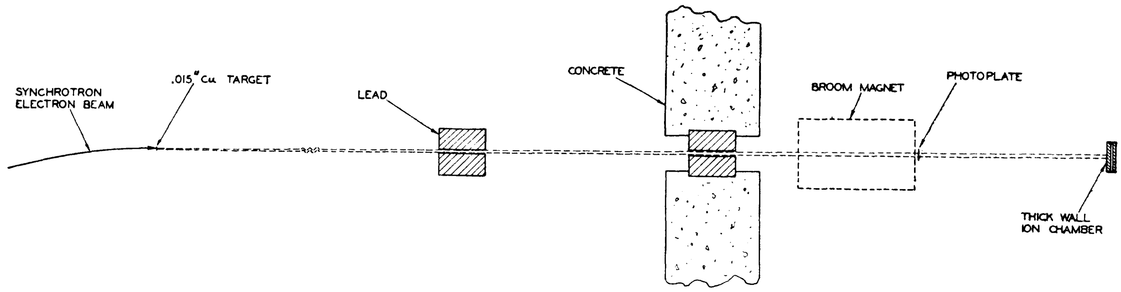

FIG. 1. The location of collimators and broom magnet during exposure.

smaller than the plate. The beam after collimation was cleared of charged particles by a strong magnetic field.

The amount of bremsstrahlung energy passing through the plate was determined by placing a thick-wall, Cornell-type air ionization chamber in the beam after the plate. This monitor is insensitive to stray low-energy radiation, and its calibration at 500 Mev has been determined at CalTech by means of a pair spectrometer and also by the shower curve method.[8] The energy dependence of the monitor calibration is known from shower theory and from calibration at 315 Mev to be about 5% per 100-Mev change in bremsstrahlung energy in this region. Effects of saturation at high beam intensities have been found to be negligible under the exposure conditions used, namely a 1-millisecond beam duration and a collection field of 1500 volts per centimeter.

The peak energy of the bremsstrahlung spectrum was determined by measuring the magnetic field at which the electron beam struck the internal target, and was controlled by the turn-off time of the rf accelerating voltage. The magnetic field integrator had been calibrated against the pair spectrometer at 500 Mev to an accuracy of about 1%. Our estimate of the accuracy of relative changes in peak energy is about ± 2 Mev.

The optimum exposure density was determined by conflicting considerations of keeping the slow-electron background low, the observer scanning efficiency high, and the number of photostars large compared with the pre-exposure star background. High star density means a large slow-electron background and reduced scanning efficiency. Very low exposure densities mean that the cosmic ray and thorium star backgrounds constitute a serious subtraction problem. Thorium stars accumulate at the rate of 1 star (3 or more prongs) per day per cm^2 of 400-micron thick emulsion. The cosmic-ray star density was 6 stars per cm^2 of 400 micron emulsion for 14-day old plates. Typical photostar densities were 50 to 60 per cm^2 when one used the "optimum" exposure density of 5×10^9 Mev per cm^2. Under these conditions the scanning efficiency, determined by scanning a second time, was 97% for stars having 3 or more prongs and 90% for 2-prong events. The lowest scan efficiencies were 85% for stars with 3 or more prongs and 67% for 2-prong events. The number of radioactive stars relative to total observed stars varied from 12% to 45%, and averaged 20%. Most thorium stars can be easily identified by the dense tracks (all shorter than 50 microns), or by the migration of the residual nucleus between decay steps, giving a disjointed star. The numbers of such identified stars during photostar scanning agreed with the control plate density to within the statistical error and we believe that the error in the photostar count due to radioactive star contamination is less than 2%. The cosmic-ray stars were, in general, indistinguishable from the photostars, and could be eliminated by statistical subtraction alone. Fortunately, their number was low (7 to 20% of the photostar yield), and the error in the correction is estimated at 1 to 3%.

An area somewhat greater than the beam was scanned on each plate, using systematic overlapping sweeps. All stars found within the area were recorded and classified as to type and prong number, if they involved two or more joined tracks. Thus, all stars with 2 or more prongs, or scatterings of single tracks were included. Single tracks starting in the emulsion *without* visible associated "recoil" (dense black track shorter than 5 microns) were not recorded. Kikuchi[1] has shown that at 700 Mev essentially all slow single protons are produced by the "giant resonance" interaction of low-energy photons, well below the energies of interest here. Light single tracks would be very difficult to detect in the electron background of these plates.

The separation of two-prong "stars" from scattering of single tracks can be done qualitatively by examination of the event, and quantitatively by estimating the scattering contributions from known cross sections. The problem is simplified by the fact that the incident x-ray beam is uncharged and hence contributes no track length, and also because the target is quite thin so that secondary interactions of star prongs are unlikely. In fact, the measured track length per star produced in a 400-micron emulsion is 1320 microns, as compared to the mean free path for nuclear interaction in emulsion of 30 cm for secondary protons. Including the 1300-micron-thick glass backing, the individual prongs from all photostars created in the plate will produce only 1.1 secondary nuclear interactions of all

[8] Walker, Teasdale, Peterson, and Vette, Phys. Rev. 99, 210 (1955).

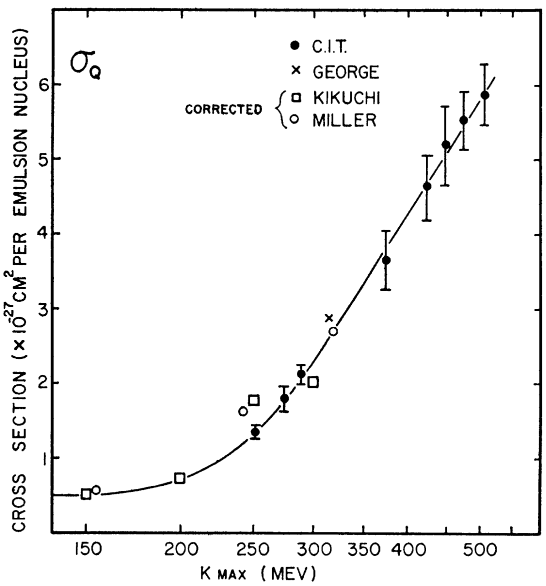

FIG. 2. The cross section per Q per emulsion nucleus for photostars with 3 or more prongs. The data of Kikuchi has been reduced 2.7 times while Miller's corrected values have been reduced by 30%, the limit quoted for his monitor error. These adjusted values are compared with the work of George and our values. The solid line is a visual fit to the experimental points and implies that the cross section per photon is constant above 300 Mev.

types in the emulsion per 100 photostars created in the emulsion. Hence, the number of spurious *2-prong* stars due to nuclear elastic and inelastic scattering is much less than 1%. Although the above track length does not include single tracks, the data of Kikuchi indicates that this will be only a slight correction.

In Table I the "definite" two-prong stars include stars in which (a) a "recoil" is observed, (b) the grain density of both prongs increases outward from the star center, and (c) both prongs have markedly different grain density. The "probable" two-prong stars are the other two-track events in which the grain density is visibly the same in both tracks, but the included angle is less than 150 degrees. Thus, the contributions to "probable" 2-prong stars from Coulomb and diffraction scattering of fast prongs from other photostars in the plate will include only scattering events beyond 30 degrees. These events are even less probable than the nuclear interactions. Hence, we have assumed all "probable" 2-prong events to be photostars, and have corrected the yield by the factor 180/150.

The thickness of the emulsion containing the photostars was measured by weighing a known area of emulsion from each batch. Variations from plate to plate were estimated from the processed thickness, and were less than 2%. It is worthwhile noting that the cross section does not depend on the shrinkage factor for this experiment where target and detector are identical.

RESULTS

The normalized yields of photostars having various prong numbers are shown in Table I as a function of peak synchrotron energy. Data from three separate series of exposures for which the plates were completely scanned are given. The number of stars of a given prong number is normalized to an exposure of 4×10^7 "equivalent quanta"[9] and emulsion thickness of 200 microns, in order to directly compare the observed yields. The actual exposure in Q is also given. The numbers are corrected for scan efficiency. The distinction between 2-prong "definite" and "probable" stars has been discussed above.

An excitation function for photostar production can be obtained by plotting the yield of stars per equivalent quantum as a function of bremsstrahlung energy, as shown in Fig. 2. In order to compare with previous experimental work by Kikuchi[1] and Miller,[2] we have plotted only stars of 3 or more prongs and calculated the cross section per emulsion nucleus (excluding hydrogen). The data of both Miller and Kikuchi, taken with C-2 plates, have been corrected for unobserved fast prongs on the basis of Kikuchi's comparisons between C-2 and G-5 emulsions at 300 Mev. In addition, Kikuchi's absolute values have been lowered by a factor of 2.7 in order to bring them into agreement with the present data and that of Miller. The reason for the disagreement in scale is not completely clear, but Kikuchi's reliance upon a single G-5 exposure at 300 Mev seems more subject to error than the series of absolute measurements made with a thick-wall ion chamber used in the current work, or the pair spectrometer used by Miller. Confirming evidence that our scale is correct is given by George,[10] who used G-5 emulsions exposed at Cornell at 315 Mev and obtained a cross section $\sigma_Q=2.9$ millibarns per Q per emulsion nucleus for stars of 3 or more prongs. (See Fig. 2.)

Figure 2 demonstrates the rapid rise in the yield of

TABLE I. Number of photostars normalized to 4×10^7 equivalent quanta per 200-micron thickness and corrected for scan efficiency.

	Exposure	Prong number						Total	
k_{max} (Mev)	$Q\times10^{-7}$	2 probable	2 definite	3	4	5	$\geq 6p$	$\geq 2p$	$\geq 3p$
251[a]	9.55	16	51	35	16	4	1	122	56
275[b]	3.40	17	66	48	21	17	3	172	89
275[b]	3.46	16	49	41	23	8	4	142	77
294[a]	8.70	16	55	46	27	7	4	155	84
375[b]	3.72	25	68	83	45	21	8	249	156
425[b]	3.62	34	127	77	75	23	23	359	197
450[b]	2.65	...	...	94	64	31	27	...	216
475[b]	3.17	43	117	98	61	30	16	364	204
475[c]	1.79	55	104	76	108	48	26	416	258
500[b]	3.58	37	113	93	72	50	29	394	244
507[c]	1.75	34	94	100	80	47	23	376	249

[a] Run 1 (400-micron plates).
[b] Run 2 (200-micron plates).
[c] Run 3 (200-micron plates).

[9] $Q\equiv$number of equivalent quanta$\equiv$(total energy in beam)/(maximum photon energy). The cross section per Q is designated σ_Q to distinguish it from the cross section per photon σ_k.

[10] E. P. George, Proc. Phys. Soc. (London) **A69**, 110 (1956).

photostars of 3 or more prongs with increasing bremsstrahlung energy. This yield is due to the contributions of all photons in the bremsstrahlung spectrum, and when expressed "per equivalent quantum" must increase monotonically with maximum synchrotron energy. The cross section *per photon* of a definite energy can be derived from the slope of the excitation curve: for an ideal bremsstrahlung spectrum, $N(k)dk=(Q/k)dk$, the cross section per photon is $\sigma_k=d(\sigma_Q)/d(\ln k)_{\max}$. Since the integral cross section in Fig. 2 is plotted against $\ln k_{\max}$, a constant slope implies a constant cross section per photon. Above 300 Mev a constant cross section of 11 millibarns per photon per emulsion nucleus is a good fit to the experimental data.

In order to compare the experimental results with theory, it is desirable to separate the contributions from the heavy nuclei (mainly Ag and Br) and light nuclei (C, N and O) in the emulsion, which occur in approximately equal numbers. Various attempts have been made to experimentally identify photostars from light or heavy nuclei on the basis of the range of the shortest prong. The assumption used was that the Coulomb barrier prevented the emission of low-energy protons and alphas from Ag and Br. Thus, a lower limit on the number of light element photostars would be those events having a prong less than 50 microns. Using this criterion, Miller[2] found that 45% of all photostars of 3 or more prongs produced by 330-Mev bremsstrahlung should be attributed to light elements in the emulsion. Similar measurements at 500 Mev and 250 Mev from our data give 46% and 47% for the apparent lower limit of light element photostars. This result is quite surprising in view of the fact that 84% of the nucleons (excluding hydrogen) are in the heavy elements, and photon-nucleon interactions are expected to predominate with high-energy x-rays.

At least two effects tend to invalidate the above criterion for separating photostars, and in fact suggest that most of the low-energy protons come from *heavy* elements. First, it seems quite improbable that any light element excited by high-energy photons could stay together as a nucleus long enough to evaporate a low-energy prong. Secondly, the work of Debs *et al.*[7] shows that it is quite common for a heavy nucleus bombarded by high-energy x-rays to emit several times as many neutrons as protons, thus landing on the "proton-rich" side of the stability curve. Further neutron emission will be energetically forbidden for such nuclei left in low-energy states. In spite of the Coulomb barrier, proton emission will be predominant since gamma emission is competitive only for the very lowest energy states. From these arguments we conclude that the "shortest-range prong" method of separation gives, if anything, a lower limit on the number of *heavy* element photostars.

Accordingly, we have chosen to weight the contribution of the emulsion constituents proportional to their atomic weight. With a straight A dependence, only

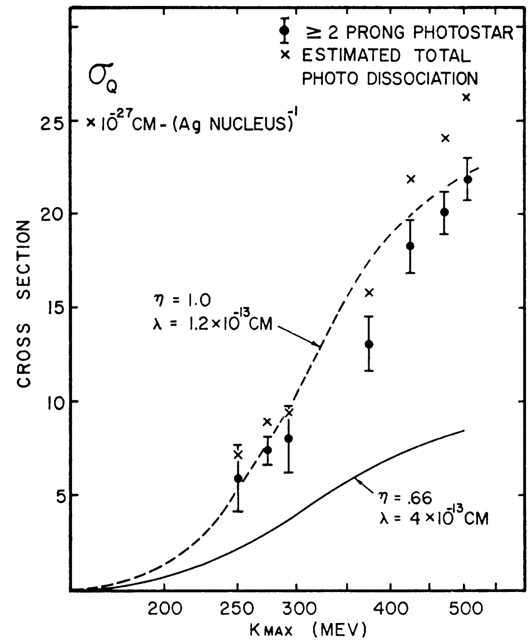

FIG. 3. Photostar cross sections per Q per equivalent silver nucleus. Star yields, due to photons below the meson threshold, have been subtracted. The solid curve gives the values predicted by the optical model using parameters from other experiments. The dotted curve assumes no nuclear binding and a short mean free path for pions in nuclear matter.

16% of the stars come from the lighter elements, which compose the gelatin. Consideration of any model for photostar production, which involves meson production and subsequent reabsorption, will only increase the relative contribution of the heavy element photostars.

The photodisintegration cross section for photostars with two or more prongs, still expressed per equivalent quantum, but given per "equivalent Ag nucleus" (total number of emulsion nucleons÷108) (excluding H) is shown in Fig. 3. The yields due to photons below the 150-Mev meson threshold have been subtracted.

The total cross section for photodisintegration would include photostars with "one prong" and "zero prongs" (neutron emission only) in addition to the stars with two or more prongs. We have estimated that the yield of zero-prong and one-prong events is less than 20% of the two-or-more prong yield when only high-energy photons above 150 Mev are considered. Kikuchi searched carefully for 1-prong events in G-5 emulsion irradiated with 300-Mev bremsstrahlung and found that, although the number of single prongs was fairly large, most of the single protons were produced by photons below 150 Mev. The single prong events from higher energy photons constituted 10% of the two-or-more-prong yield in Kikuchi's case: we have assumed that the same fraction will apply in our case. A correction of 10% was also made for the zero-prong stars, on the assumption that the photostar prong distribution would be the same as that of charged pion emulsion

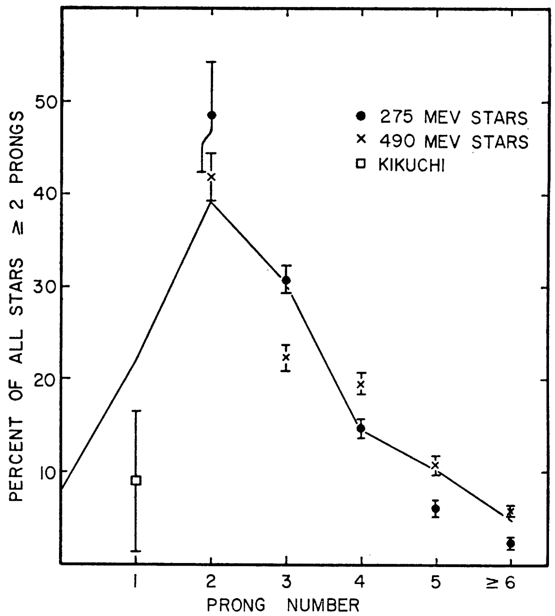

FIG. 4. Prong distribution for photostars made by 275-Mev and 490-Mev bremsstrahlung. These distributions are compared with the prong distribution from pion stars, shown as a solid line. The percent of one-prong photostars produced by photons between 150 and 300 Mev is taken from Kikuchi. All data was normalized for the same number of 2-or-more-prong stars.

stars. Since the average prong number increases with bremsstrahlung energy, the correction for zero- and one-prong stars may be less than 20% at 500 Mev. The total cross section for photodissociation shown in Fig. 3 is 1.20 times the cross section for 2-or-more prong photostars.

Prong distribution is given in Fig. 4 for photostars made by "high" (475–503 Mev) and "low" (251–294 Mev) bremsstrahlung energies. The distributions have been normalized to the same number of 3-or-more-prong stars to eliminate any uncertainty in the 2-prong stars. There is a significant increase in the prong multiplicity for "high"-energy photostars, since they produce 2.5 ± 0.8 times as many stars with more than 6 prongs as do the "low" bremsstrahlung energies. This increase can probably be explained on the basis of increased nuclear evaporation, or the $+/-$ photomeson production ratio. The π^+/π^- ratio is known to increase with photon energy[11] and the absorption of π^+ mesons has been observed to make stars with more charged prongs than the absorption of π^- mesons.[12,13]

The weighted average of all of the fast charged-pion star prong distributions in G-5 emulsions[12–14] has been plotted as a solid curve in Fig. 4. The agreement with the photostar distributions is reasonably close considering the energy dependence of the prong distributions and the fact that nothing is known about stars made by neutral pions. Our assumption that the zero- and one-prong photostars constitute only 20% of the two-or-more-prong photostars is in agreement with the pion star prong distribution. The basic similarity of the pion and photostar prong distributions for events with 2 or more prongs constitutes additional evidence for the importance of mesonic processes in photostar production.

COMPARISON WITH THEORY

The Levinger "quasi-deuteron" model appears to account for very few of the photostars observed. The deuteron photodissociation cross section[15] is 350 times smaller than the photostar cross section for a silver nucleus at 300 Mev. While experiments show that "quasi-deuteron" photodissociation may be the predominant process for light nuclei, the single proton yield per nucleon from oxygen is only 1.6 times higher than from deuterium.[6] If the "quasi-deuterons" in light nuclei are each assumed to have 1.6 times the cross section of the free deuteron, the light nuclei contribute less than 4% of the photostars. The small yield of one-prong stars observed by Kikuchi[1] is in agreement with this calculation. Furthermore, the photostar cross section is very small at 100 Mev, while the deuteron photodisintegration cross section at 100 Mev is considerably larger than at 300 Mev.

The large photostar yield, and the steep rise of the photostar cross section above 150 Mev, have led a number of authors to suggest an intimate connection with mesonic processes. Wilson[16] suggested that the photodisintegration process consists of the photoproduction of pi mesons from each nucleon, followed by reabsorption by a system consisting of the parent nucleon and its nearest neighbor. This process incorporates the large cross section for meson photoproduction, and provides the interaction of the photon with a small nuclear subunit required to explain the forward peaking of the angular distribution of high-energy photoprotons. In this latter respect Wilson's model is similar to that of Levinger, the difference being that in the real deuteron the nucleons are interacting strongly for only a small fraction of the time so that mesons can escape.

An alternative picture of photodissociation based on the optical model with a finite mean free path for meson reabsorption in nuclear matter was first given by Brueckner, Serber, and Watson[17] and later developed further by Watson,[18] Francis and Watson,[19] and Reff.[20]

The assumed values of the mean free path must be compatible with data analyzed on the same model for

[11] Motz, Crowe, and Friedman, Phys. Rev. **99**, 673 (1955).
[12] G. Bernardini and F. Levy, Phys. Rev. **84**, 610 (1951).
[13] H. Bradner and B. Rankin, Phys. Rev. **87**, 547 (1952).
[14] Bernardini, Booth, Lederman, and Tinlot, Phys. Rev. **80**, 924 (1950); Bernardini, Booth, Lederman, and Tinlot, Phys. Rev. **82**, 105 (1951).
[15] J. C. Keck and A. V. Tollestrup, Phys. Rev. **101**, 360 (1956).
[16] R. R. Wilson, Phys. Rev. **86**, 125 (1952).
[17] Brueckner, Serber, and Watson, Phys. Rev. **84**, 258 (1951).
[18] K. M. Watson, Phys. Rev. **88**, 1163 (1952).
[19] N. C. Francis and K. M. Watson, Phys. Rev. **89**, 328 (1953).
[20] I. Reff, Phys. Rev. **91**, 150 (1953).

meson-nucleon and meson-nucleus absorption experiments. The observed $A^{\frac{2}{3}}$ dependence of the photomeson production cross section can be used to find values for the mean free path which are, in general, shorter than the absorption mean free paths found from meson interaction experiments.[21]

Butler[22] has proposed a way to circumvent the mean-free-path difficulties, which at the same time contains the features of meson-exchange effects between strongly coupled nucleons as proposed by Wilson. The "surface nucleons" which make up the less dense outer atmosphere of the nucleus are assumed to account for most of the free-meson production, while meson production is strongly suppressed and photodisintegration enhanced in the "core" nucleons. This model provides very accurately an $A^{\frac{2}{3}}$ photomeson production dependence, independent of the value of meson-nucleon mean free path for scattering and absorption on the surface nucleons.

Analysis of the present photostar production cross sections for a Ag nucleus using the optical model concept of mean free path as outlined by Reff[20] leads to a formula for the photostar cross section from a nucleus of atomic number A and radius $R=r_0A^{\frac{1}{3}}$ ($r_0=1.2\times10^{-13}$ cm), as follows:

$$\sigma_{\text{star}}=\sigma_f\eta A\left(1-\tfrac{3}{4}\lambda/R\right),$$

where σ_f is the average of the charged and neutral free-pion photoproduction cross sections from hydrogen,[8,23] and λ is the mean free path for absorption in nuclear matter. Francis and Watson[19] have defined η as a factor incorporating the effects of nuclear binding, and from analysis of photoproduction and absorption of mesons have determined the product,

$$\eta\lambda=2.6\times10^{-13}\text{ cm}.$$

"Reasonable" values of η and λ given by Francis and Watson are $\eta=0.66$ and $\lambda=4\times10^{-13}$ cm. The lower solid curve in Fig. 3 was obtained by using these values, and is clearly inadequate to account for the photostar yield.† In fact, only by ignoring nuclear binding entirely, and taking the mean free path to be r_0, can one provide sufficient absorption to provide a fit to the two-or-more-prong events. This ignores the additional 20% photodissociation yield of one- and zero-prong stars at the higher energies.

This very short mean free path is equivalent to complete absorption for mesons produced in the "core," and is also in agreement with Butler's model. The extent of the "core" can be calculated from Butler's model, but an absolute upper limit would be to consider the entire nucleus as the "core"; i.e., to reabsorb all mesons produced from 108 separate nucleons in a silver nucleus. The "integral" cross section in Fig. 3 can be differentiated to give the cross section per *photon* for photodissociation of the silver nucleus, as shown in histogram form in Fig. 5. The average slope over 100-Mev intervals has been used to calculate an average cross section for photons in the interval. For comparison, the total neutral and charged pion photomeson production cross section from hydrogen, multiplied by 108, is shown as the solid curve.[24] Because of limitations of the difference method, the statistical errors are too great to accurately define the curve, but the absolute scale and general rise of the cross section are clearly correct. The solid curve represents an *upper limit* on photostar production due to reabsorption of real mesons produced from 108 individual nucleons, since it assumes

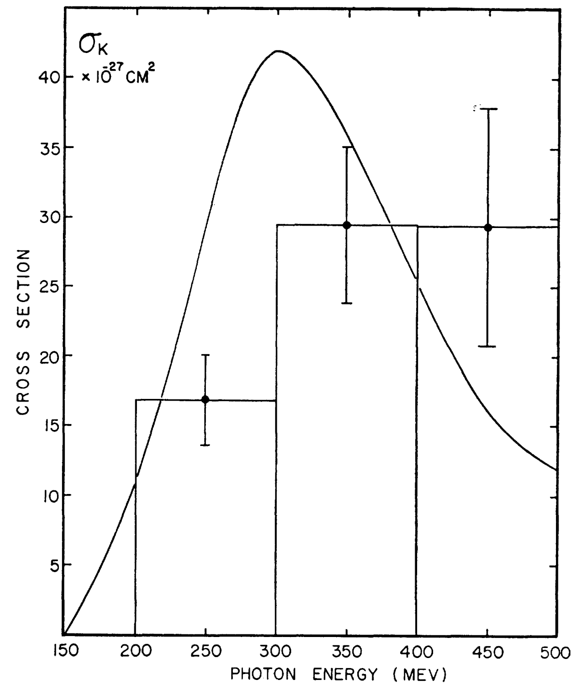

FIG. 5. The photostar cross section per photon per equivalent silver nucleus. The histograms represent the differentiation of the total excitation cross section in Fig. 3. The solid curve is 108 times the photomeson cross section from free nucleons.

[21] W. Imhof, University of California Radiation Laboratory, Report UCRL-3383, 1956 (unpublished); Chedester, Isaacs, Sachs, and Steinberger, Phys. Rev. **82**, 958 (1951); D. H. Stork, Phys. Rev. **93**, 868 (1954); F. H. Tenney and J. Tinlot, Phys. Rev. **92**, 974 (1953).

[22] S. T. Butler, Phys. Rev. **87**, 1117 (1952).

[23] D. C. Oakley and R. L. Walker, Phys. Rev. **97**, 1283 (1955).

† *Note added in proof.*—Professor K. M. Watson has pointed out that these values apply only to pions of 85 Mev. At higher pion energies the resonance in pion-nucleon interactions leads to a sharp decrease in the mean free paths for absorption and inelastic scattering. The energy of the pions "within the nucleus" should also include the well-depth. [See Frank, Gammel, and Watson, Phys. Rev. **101**, 893 (1956).] Under these assumptions the optical model gives excellent agreement with the observed short mean free path. The predicted photostar yield is approximately the same as the dotted curve shown in Fig. 3. Since the optical model in its present form gives basic agreement with the experimental results, there appears to be little need to postulate a new mechanism which increases photodisintegration in the "core" nucleons, as proposed by Butler.[22]

[24] It is worthwhile noting that the same monitor was used for both the photomeson and photostar measurements.

that *all* mesons are reabsorbed. A direct measurement of the ratio of photostars (3 prongs) to free mesons produced in emulsion by 315-Mev bremsstrahlung was made by George[10] who found 7.6 when single-meson tracks as well as mesons with associated prongs were included. When photostars of all prongs and neutral mesons are included, the total meson yield is 12% of the total photostar yield. Calculations from Butler's model by George[10] give 8–13%, whereas the optical model gives a much higher (50–60%) meson yield. Reduction of the solid curve by this amount would improve agreement with the lower energy photostar yields, but would account for only approximately half of the 400–500 Mev photostars. Experiments at higher bremsstrahlung energies would help decide whether the photostar cross section continues to remain high.

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Cosmic-Ray Bursts under Lead at Sea Level*

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The integral size-frequency distributions of ionization bursts near sea level were measured in a thin-walled ($\frac{1}{16}$ inch steel), 8-inch diameter, spherical ion-chamber filled with argon at 50 atmos pressure, under 14 different thicknesses of lead ranging from 0.11 cm to 22 cm. The measurements, along with those already published for the ion chamber with no shield and with a 27-cm lead shield, represent some 15 000 hours of recording. The range of size covered extends from about 3×10^4 to 10^8 ion pairs. In a subsidiary experiment the size-frequency distributions of bursts directly associated with extensive air showers were measured and to these were added, at each thickness of the shield, the bursts due to single μ mesons, protons, and stars derived from the analysis already published. These totals were then subtracted from the gross size-frequency distributions. The bursts remaining are almost wholly due to the electrons and photons of the soft component and to the radiative and knock-on processes of μ mesons. Transition curves of these bursts (Rossi curves) are given for selected sizes, corresponding (on the average) to showers of 1, 2, 4, 8, $\cdots$, 512 electrons crossing the ion chamber. There is no sign of a second maximum in these transition curves. There is strong evidence that the cascades which give rise to the "first" maximum originate from *single* electrons or photons incident on the lead shield and hence these experimental results are suitable for a straightforward comparison with cascade theory in an energy range extending to some 50 Bev. Indications of a transition effect of the bursts attributed to stars are noted.

1. GENERAL

WE reported in I[1] the cosmic-ray ionization pulses or bursts observed in an unshielded, thin-walled, 8-inch diameter, spherical ion-chamber (volume 4.4 liters, with 50 atmospheres argon at 0°C) at 400 feet above sea level at Deep River, Ontario (lat 46° 06′ N, long 70° 30′ W). The wall of the ion-chamber was steel, $\frac{1}{16}$-inch thick. The pulse-recording equipment was capable of dealing, in the same experimental run, with bursts of a range of size of nearly four decades and the bursts due to single cosmic-ray mesons and electrons were measurable. The bursts observed in the ion chamber under a 27-cm-thick shield of lead were also reported in I and a comparison of the two size-frequency distribution curves, unshielded and shielded, permitted analysis of both curves into separate components representing the size-frequency distributions of the bursts due to single μ mesons, electrons, single protons, stars, extensive showers, and cascades originating in the lead.

In continuation of this work, bursts have been measured with 14 other thicknesses of the lead shield, ranging from 0.11 cm to 22.0 cm, and it is the purpose of this paper to present these observations. It should be noted that the measurements are basic in the sense that there was no preselection of the events by counter telescope or other means, so that the results comprise *all* the ionization bursts that arise, in a spherical vessel, from the omnidirectional flux of the cosmic radiation at the site of the experiment. In a subsidiary experiment the bursts that occurred in coincidence with extensive air showers were directly measured for several thicknesses of the lead shield.

An analysis of the results is given which yields as its principal result a family of transition curves showing

* A preliminary report of some of these measurements was given at the Chicago Meeting of the American Physical Society, November, 1953 [H. Carmichael and J. F. Steljes, Phys. Rev. **93**, 913(A) (1954)].

[1] H. Carmichael and J. F. Steljes, Phys. Rev. **99**, 1542 (1955).