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Photonuclear Stars in Emulsions

By

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ABSTRACT

Ilford type C-2 Nuclear Research Emulsions were exposed in the x-ray beam from the Berkeley synchrotron at four synchrotron energies. The relative yields of the photoproduced nuclear stars were determined as a function of synchrotron energy and prong number. A separation of the three and more prong stars into those produced from the light elements and those from the heavy elements in the emulsion was made. The resultant yields are expressed in terms of the cross sections of carbon and of silver, integrated over the bremsstrahlung spectrum, and also as cross sections averaged over the 80 Mev energy intervals between the synchrotron energies. These results are compared with the predictions of two different mechanisms for the photodisintegration process at high energy, and it is concluded that the present data favors the process of meson production and reabsorption as the primary process at high energies, but does not exclude appreciable yields from other processes.

I INTRODUCTION

The experimental study of the interaction of radiation with nuclei may be divided roughly into three energy regions according to the type of reactions which occur.

The lowest energy region consists of the energy range below that necessary for particle emission; with the exception of the (γ,n) reactions on H^2 and Be^9 this region extends to about 8 or 9 Mev. In this region the reduced wavelength of radiation is large compared to nuclear dimensions and one term of the multipole expansion gives an accurate description of the radiation field. Most of the experimental work has been concerned with the emission of gamma rays from excited states of nuclei, with the principal objective of giving spin and parity assignments to the excited states.

The studies of photodisintegration reactions fall in the second energy region. A great number of such reactions have been identified and studied by detecting the characteristic radioactivity of the product nucleus. The first series of such experiments were performed by Bothe and Gentner using the 17 and 14 Mev gamma rays from the bombardment of lithium and boron by protons[1]. A more complete series of reactions was studied, using the lithium gamma, by Wäffler and Hirzel[2]. The measurement of the excitation functions of these reactions, however, was only possible with the availability of the high energy bremsstrahlung from recently constructed betatrons and synchrotrons. A great deal of data has been obtained in the last three years using these machines by a number of experimenters with various techniques[3-6]. The most important general conclusion of this work is that all of the reactions studied have a resonance-like excitation function; that is, only a fairly narrow band of energies is effective in producing any given reaction. The energy at which the maximum cross section occurs depends on the particular reaction, but is generally in the region of 15 to 35 Mev. The reactions studied by this method are all of low multiplicity; the majority are (γ,n) reactions, but multiplicities up to (γ,p4n) have been observed[6]. Levinger and Bethe have given arguments that these reactions are probably electric dipole transitions[7].

Since none of these reactions has been found to give measurable yields from gamma energies much above the energy at which the maximum cross section occurs, the question arises as to what reactions do occur at mugh higher energies, and in particular whether the total photodisintegration cross sections are actually small, or whether the particular reaction cross sections are very small only because of the competition with a great many other possible reactions. A partial answer to these questions already exists in the experiments concerning the photoproduction of charged and neutral mesons[8,9]. The present experiment was undertaken to provide a more complete survey of possible photonuclear reactions at energies above those at which the low multiplicity reactions have been studied, by using photographic emulsions as both target and detector, thus making possible the observation of all reactions giving rise to charged particles, within the limitations of emulsion sensitivity.

In Section II the details of the experimental procedure are described, and in Section III the results are given. These include the prong spectrum and relative yields of all stars from bremsstrahlung spectra at four energies. An attempt was also made to separate by coulomb barrier considerations those events which were made on the light elements in the emulsion from those which were due to the silver only a fairly narrow band of energies is effective in producing any given reaction. The energy at which the maximum cross section occurs depends on the particular reaction, but is generally in the region of 15 to 35 Mev. The reactions studied by this method are all of low multiplicity; the majority are (γ,n) reactions, but multiplicities up to $(\gamma,p4n)$ have been observed[6]. Levinger and Bethe have given arguments that these reactions are probably electric dipole transitions[7].

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II EXPERIMENTAL PROCEDURES

Exposure Ilford Type C-2 Nuclear Research Emulsions, 200 microns thick, were used in this experiment. This choice of emulsion sensitivity was a compromise between the conflicting advantages of low sensitivity for the reduction of background from the large number of electrons produced in the x-ray beam, and of high sensitivity in order to see high energy protons and mesons. With the exposure and processing procedure used, the sensitivity of the C-2 emulsions was such that about 65 Mev proton or 10 Mev meson tracks were barely discernable in the single grain background.

A schematic diagram of the exposure arrangement is shown in Fig. 1. The x-ray beam from the 0.020 inch thick platinum target in the 322 Mev Berkeley synchrotron, after passing through the wall of the quartz vacuum chamber and a thin wall ionization chamber, was collimated by a 9 inch thick lead wall with an aperture 1/4 inch in diameter about five feet from the target. A small Alnico magnet was placed directly after this collimator to deflect the electrons produced at the edges of the collimator. A second lead collimator six inches thick with an aperture 1/2 inch was placed about 2 feet behind the first to shield the plate from the deflected electrons and any scattered x-rays. The emulsion itself was mounted about 6 inches behind the second collimator. The cross section of the collimated x-ray beam was 3/8 inch in diameter at the emulsion.

Exposures were made at synchrotron energies of 322, 242, 161, and 80 Mev. The energies were determined by adjusting the time at which the accelerating r.f. voltage was turned off, such that the signal pulse from a photomultiplier placed in the x-ray beam appeared at the same time that the magnet current was the given fraction of its maximum value, as observed on an oscilloscope. The peak energy of 322 Mev was determined by Powell, Hartsough, and Hill as part of an experiment to measure the bremsstrahlung spectrum[10].

The exposures were monitored by the ionization chamber and its associated integrating electrometer circuit, and the exposures at different energies were chosen such that the single grain background from electrons would be approximately the same on all plates.

Calibration of Monitor In order to compare the yields of stars at different synchrotron energies and also to estimate absolute cross sections, an absolute calibration of the monitor ionization chamber was made at each energy by the method of Blocker, Kenney and Panofsky[11]. The calibration data were taken on the same day that the exposures were made, and the only change in the arrangement was the substitution of the calibrating ionization chamber for the photographic plate.

The calibration procedure consists in measuring the charge collected in an ionization chamber, per monitor unit of integrated beam intensity, as a function of the thickness of converter placed immediately in front of the chamber. This data is taken for a series of thin converters of both lead and copper, and is plotted using an abscissa thickness scale proportional to the number of electrons per unit area of converter. On this scale the contributions to the ionization from Compton electrons and from background electrons present in the beam is the same for both lead and copper converters; thus the difference between the lead and copper transition curves is due only to the difference in the contributions of electron pairs from the two converters. The initial slope of the difference curve is then proportional to the difference in the pair production cross sections of lead and copper integrated over the bremsstrahlung spectrum. The pair production cross sections and bremsstrahlung spectrum are known, and the proportionality constant can be calculated from the thickness of the chamber and the number of ion pairs produced per cm. of air by a minimum ionization electron.

Microscope Observation Procedure The main observation procedure was divided into two parts, an initial scan with a magnifying power of 250 to locate all possible stars with two or more prongs, and a second observation of each event with a magnifying power of 1300.

The boundary of the emulsion area which was covered by the beam was observable in the microscope by the change in the density of single grains. The area scanned on each plate included the complete area covered by the beam and extended at least 2 mm beyond the beam boundary in all directions. No events were found outside the beam boundary which could not be attributed to alpha particle tracks from naturally occurring radioactive contaminants in the emulsion.

In the second observation, the depths of all events near either surface of the emulsion were measured, and all events within 5 microns (after processing) of either surface were discarded. The purpose of not using these surface layers is to avoid missing low grain density tracks leaving the emulsion nearly normal to its surface. The minimum range of track which was counted as a star prong was 3 microns.

It was found impossible in many cases to distinguish between a two prong star and a scatter in the track of a single particle. As a result, two prong stars were classified as either possible or probable. Two prong events in which an increase in grain density was qualitatively observable in both tracks leaving the vertex, or in which there was an obvious difference in the grain density of the two tracks at the vertex, were classified as probable two prong stars. All other such events which could not be definitely established as scatters, either by a decrease in grain density of one track leaving the vertex or because one track could be traced to the origin of another star, were classified as possible two prong stars.

All three and more prong stars were observed a third time, and the ranges of all prongs less than 50 microns range were measured in order to separate those stars produced from a light emulsion element from those produced from the silver and bromine by coulomb barrier considerations.

The data shown in Section III are the results from two plates at each of the two higher energies, and one plate at each of the two lower energies. The exposures at the three higher energies were all made on the same day, and the plates were all from the same shipment and emulsion batch, but the 80 Mev exposure was made at a later date and with plates from a different emulsion batch.

In order to subtract any background of events which were not due to the x-ray exposure, an unexposed plate from the same shipment and emulsion batch was developed along with the exposed plates. An area equal to that scanned on an exposed plate was also scanned on a background plate for each of the two runs. The only events found on the background plates were "radioactive stars" from successive alpha decays of a naturally occurring radioactive contaminant. Since these radioactive stars are fairly distinctive, those events which were thought to be radioactive stars were noted and subtracted on each exposed plate, rather than subtracting the number found on the unexposed plate. In all cases, the number of such events was consistent with the number found on the unexposed plate.

A sample area on one plate of each energy was scanned for single prong stars, that is, single tracks beginning in the emulsion. The thickness of the surface layers in which events were not counted was increased to 15 microns (after processing) in this scan to eliminate the clogged tracks near the surface whose direction could not be determined.

In order to make an estimate of the validity of the two prong star data, tracks which passed completely through the emulsion were also noted in this scan. These results were inconclusive, since no attempt was made to find the energy distribution of these tracks, but reasonable assumptions indicate that the contamination of scatters in the two prong stars is probably small.

Finally, the three and four prong stars in the 80 Mev plate were examined for possible identification as $C^{12}(\gamma,3\alpha)$ or $O^{16}(\gamma,4\alpha)$ events. These results are given in Appendix A.

III RESULTS

The yields of stars are shown as a function of prong number and bremsstrahlung energy in Table I. The full energy yields are normalized to an emulsion thickness (before processing) of 200 microns, and to an exposure of 10^8 "equivalent quanta", or 322 x 10^8 Mev total energy in the bremsstrahlung spectrum. The yields at the other energies are normalized to the same thickness and to exposures that contain the same number of quanta per Mev interval at 27 Mev. This rather arbitrary choice of energy at which to normalize the exposures was made because it is in the general region in which the principal yields from low multiplicity reactions are expected, and in particular it is the value Strauch obtained for the mean energy at which the $C^{12}(\gamma,n)C^{11}$ reaction occurs. Kikuchi[12], in an experiment very similar to the present one, normalized his exposures to the yield of C^{11} beta activity in a carbon target irradiated along with the emulsion, so the choice of 27 Mev allows a direct comparison of data from the two experiments. Unless otherwise stated, all uncertainties indicated are the standard errors from counting statistics only. In addition to this there is an estimated 10 percent standard error in the 80 Mev data relative to the rest, and an additional 30 percent error in the absolute values.

The fact that the stars are due to a mixture of target elements makes it impossible to reduce the yield data in Table I to cross section values unless some assumption is made concerning the relative cross sections of the various emulsion constituents. If we define an integrated cross section

$$S(E) = \int_0^E \sigma(K) N_E(K) dK \quad ,$$

where $\sigma(K)$ is the usual cross section as a function of energy and $N_E(K)$ is the number of quanta per unit energy interval in the bremsstrahlung spectrum of energy, E, normalized such that

$$\int_0^{322} K N_{322}(K)dK = 322 \text{ Mev}$$

$$\text{and} \qquad N_E(27 \text{ Mev}) = N_{322}(27 \text{ Mev}) \quad ,$$

then the yields in Table I can be expressed as

$$Y(E) = f N_o t \sum_i \frac{d_i}{A_i} S_i(E) \quad ,$$

where f is the number of "equivalent quanta", t is the emulsion thickness, and d_i and A_i are the partial density and atomic weight of the i^{th} element in the emulsion. Under the assumption that σ_i is proportional to A_i at all energies,

$$S_i(E) = \frac{A_i}{108} S_{Ag}(E) \quad ,$$

and the yields can be expressed in terms of the integrated cross sections of silver;

$$S_{Ag}(E) = \frac{108}{fN_o t \sum_i d_i} Y(E) = 0.233 \times 10^{-28} Y(E) \text{ cm}^2 \quad .$$

The integrated cross sections of silver for the production of three or more prong stars, calculated in this manner, are plotted as a function of energy in Fig. 2. Included in this figure are the data of Kikuchi, which have been normalized in absolute value for the best qualitative, overall fit with the present data. The absolute values of this cross section would be decreased by 18 percent if the cross section were assumed proportional to $A^{2/3}$ instead of A. These cross section values of silver are only rough estimates, depending as they do on such a drastic assumption of dependence of cross sections on nuclear species.

In principle, $\sigma(E)$ can be calculated from S(E); a first approximation to $\sigma(E)$ is given by

$$\sigma(E) \simeq E \frac{d}{dE} S(E) \quad .$$

However, the present data are not sufficient to define a derived curve with any accuracy. One can use the differences in the yields at two energies, though, to calculate a cross section averaged over the energy interval. The spectrum of quanta which is responsible for the difference in yields at two energies is concentrated mainly in the region between those two energies, but it also has a low energy tail. An example of such a spectrum is shown in Fig. 3, which shows the difference in the number of quanta per unit energy interval between the 242 Mev bremsstrahlung spectrum and the 161 Mev bremsstrahlung spectrum when they are normalized at 27 Mev. One can estimate what part of the difference yield is due to this low energy tail from the yields at lower energies, and from this calculate a cross section averaged over a given energy interval,

$$\bar{\sigma} = \frac{\int_{E_1}^{E_2} \sigma(K) N_{E_2}(K) dK}{\int_{E_1}^{E_2} N_{E_2}(K) dK} \quad .$$

Values of the average cross section of silver for the production of three or more prongs are shown in Table II.

As mentioned in Section II, an attempt was made to separate the light element stars from the heavy element stars by coulomb barrier considerations. The basis of the separation is that the probability of the emission of a charged particle of energy sufficiently below the barrier energy from a silver or bromine nucleus is extremely unlikely, and, thus, that any star which has one or more prongs with ranges less than some critical value must have been produced from one of the light elements in the emulsion. The application of this argument gives only a lower limit on the number of stars produced from the light elements. This procedure has been applied to only three and more prong stars, and the emission of a minimum of three charges from carbon, nitrogen or oxygen corresponds to a nearly complete disintegration of such a light nucleus. It seems reasonable to hope that at least one of the prongs will have less than the critical energy in the great majority of such disintegrations. This method of distinction has been applied to the stars produced by π^- meson capture, and gives reasonable agreement with other methods[13].

The assumed value of the critical range was 50 microns, corresponding to an alpha particle energy of 8.9 Mev. The critical range for a proton under the same assumptions is greater, but proton and alpha particle tracks of only about 50 microns residual range were not qualitatively distinguishable in the present plates. The considerations leading to this choice are given in Appendix B.

Tables III, IV, V, and VI give the range spectrum of the shortest prong of the stars in one plate at each synchrotron energy. It is seen that the fraction of events attributable to the light elements is not a very strong function of the critical range.

The results of this separation of light and heavy element stars disagrees greatly with the previous assumption of cross section dependence. The stars in the 80 Mev plate are almost completely due to the light elements, and even in the 322 Mev plate the fraction attributed to the light elements is 35 percent whereas this proportion would be

15 percent if the cross section were proportional to A, or 25 percent if it were proportional to $A^{2/3}$.

One can make use of this separation to recalculate values of S(E) for silver, and also for carbon, again assuming that the cross section is proportional to A, but in each group of elements separately. These results are plotted in Fig. 4 and are used to calculate the values of the cross sections averaged over 80 Mev energy intervals which are given in Table VIII.

IV DISCUSSION OF RESULTS

The primary interest in the present data is in whether any conclusions can be drawn concerning the mechanisms of photonuclear interactions at high energies. In the energy range of the present experiment, the nucleus is large compared to the radiation wavelength; for silver $\lambda\!\!\!^{-}/R = \frac{30\text{ Mev}}{E_\gamma}$. Thus any mechanism which depends on the coupling of the radiation field with nuclear charge as a whole, such as the model of Goldhaber and Teller[14], would give very small cross sections due to interference effects.

The two coupling mechanisms which seem most reasonable are the coupling to individual protons by their charge, and the coupling with the meson fields of nucleons. The first mechanism can be regarded as the nuclear analogue of the photoelectric effect, with the modification that the proton being ejected is likely to lose part of its energy in collisions with its neighbors before escaping the nucleus. The second mechanism for photonuclear disintegration is a two step process involving the production of a meson and its consequent inelastic interaction with the nucleus in which it was produced. This process is suggested by Mozeley's measurements[15] of the relative photoproduction of π^+ mesons from a series of elements. These measurements showed a decrease in the yield per proton with mass number, consistent with the hypothesis that only the surface protons were effective in meson production. If this is so, it must be attributed to absorption of the mesons produced in the interior of nuclei, since nuclear matter is essentially transparent to high energy radiation as shown by the smallness of photonuclear cross sections compared to nuclear area. In addition, relatively low energy stars could result from the energy of the recoil nucleon associated with meson production, even if the meson escaped without loss of energy.

The features of the present data which might indicate which of these two mechanisms is predominant are the absolute cross section for star production and its variation with energy. The meson process would predict a rapid increase in cross section above meson production threshold. It is not clear, however, how the cross section would vary with energy near and below threshold since there may be some yield from the second order process which need not conserve energy in the intermediate state. The magnitude of the cross section for the meson process can be roughly estimated from measured meson production cross sections. The sum of the meson production cross sections of the appropriate number of free nucleons is a strict upper limit on the cross section for this process. For a better estimate one should make allowance for the reduction of meson production by binding and exclusion principle effects, and also subtract some part of the measured meson production cross section of the element to allow for those production events which do not leave enough nuclear excitation to produce a star. Interpolating from Mozeley's data, the yield of $\pi+$ mesons per proton from silver is about 20 percent of the free proton yield. Perhaps a reasonable estimate of the contribution per proton of $\pi+$ mesons to this process is about one third of the $\pi+$ production cross section of the free proton. Allowing an equal contribution of π^- mesons from neutrons and of π^0 mesons from both neutrons and protons, the cross section per nucleon for star production by this process is about 4/3 the $\pi+$ production cross section of hydrogen. This is about 2×10^{-26} cm^2 for silver for energies above 250 Mev.

The corresponding estimates for the nuclear photoeffect are not nearly so easy to arrive at because they depend more on the details of the nuclear model assumed. Levinger has made some calculations[16] in which he relates the nuclear photoeffect to the photodisintegration of the deuteron. He gives the total cross section as $1.6\ A\sigma_d$, where σ_d is the deuteron photodisintegration cross section. Schiff has calculated this cross section up to 140 Mev; according to his curves,[18] the cross section is roughly proportional to the inverse square of the gamma energy and is about 1.6×10^{-29} cm^2 at 140 Mev, depending somewhat on the type of n-p interaction potential assumed. This gives a cross section of 2.8×10^{-27} cm^2 for silver, or 0.31×10^{-27} cm^2 for carbon.

The comparison of the present data with the predictions above is rather indirect, because the present data does not measure the total photonuclear cross section. The cross section for photodisintegration into three or more charged particles is reasonably well defined, but the disintegrations into only one or two charged particles are likely to be an important fraction of the total number of disintegrations, especially for the heavy elements. The two complicating features inherent in this experiment, the mixture of target elements and the continuous x-ray spectrum, have effectively prohibited the measurement of the cross sections for production of one and two prong stars. Fortunately, the cross section for production of higher multiplicity stars increases with energy so that differences in the yields at two synchrotron energies are due primarily to the quanta with energies between the two synchrotron energies. For single prong stars, however, the yield from low energy quanta is so large that the relatively small change in the number of low energy quanta with the change of synchrotron energy is sufficient to mask a high energy cross section comparable to the cross section for production of three and more prong stars. In addition, the method used for separating light and heavy element stars is not satisfactory for one and two prong stars, because of the increased probability that a light element star would have no short prongs.

According to Table VII, the yield of heavy element stars falls off much faster with increasing prong number than does the light element yield, even in the 322 Mev plate. Also the ratio of the integrated cross section of carbon to that of silver is much greater than the ratio of mass numbers or two thirds power of mass numbers. These two facts indicate that the fraction of the total absorption cross section which is due to production of three and more prong stars is smaller for the heavy elements than it is for the light elements; furthermore, this inequality is progressively greater at lower energies. Thus the total heavy element integrated cross section probably does not rise nearly as rapidly as that of the three and more prong stars. The rapid increase of the slope of the yield curve of all three and more prong stars (Fig. 2) in the neighborhood of 200 Mev may be attributed to the increase in prong number of heavy element stars with energy, and does not necessarily indicate a rapid increase in total cross section above meson production threshold. On the other hand, however, it does not seem possible to make the total cross section decrease with the square of the energy, even under rather extreme assumptions about the behavior of the single prong cross section.

The comparison of absolute values of the cross section with the predictions above is a little more significant. The silver cross section for production of three and more prong stars, averaged over the 242 to 322 Mev interval is 7×10^{-27} cm^2, a factor of three less than the total cross section estimated for the meson process. Considering the contribution from lower multiplicity events and the crudity of the theoretical estimate, this is good agreement. The values from the calculations of Levinger and of Schiff for the photoeffect process, 2.8×10^{-27} cm^2 for silver and 0.31×10^{-27} for carbon at 140 Mev, are definitely lower than would be expected from the present data (Table VIII), and the disagreement would become much worse at higher energies if the deuteron photodisintegration cross section continues to decrease with increasing energy. This is not conclusive evidence against an appreciable contribution from a photoeffect process, since these calculations were based on a fairly specific model, and the experimentally derived parameters used were quite remote.

Both the shape of the excitation function and the magnitude of the cross section for production of three and more prong stars tend to favor the meson process as the predominant mechanism of photonuclear interaction at energies above 200 Mev, but neither can exclude an appreciable yield from other processes.

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APPENDIX A

Identification of $C^{12}(\gamma,3\alpha)$ and $O^{16}(\gamma,4\alpha)$ reactions

Reactions in nuclear emulsions in which all of the final particles are charged and relatively light can be identified, and the energy of the gamma ray which produced them can be determined. The method consists in testing the momentum balance of an event under the assumption that it is a given reaction. The ranges and directions of all the prongs are measured, and the energies of the particles are found from the assumed identities of the particles and the range energy relations. The energy of the gamma ray producing the star is then calculated from the particle energies and the known Q value of the reaction. The vector sum of the momenta of all the prongs less the momentum of the incident gamma ray is then computed, and if the resultant momentum unbalance is small enough to be attributable to measurement errors, there is no doubt that the event is attributable to the assumed reaction.

All three and four prong stars in the 80 Mev plate were tested for momentum balance as $C^{12}(\gamma,3\alpha)$ and $O^{16}(\gamma,4\alpha)$ reactions. Table IX lists the events which were identified in this way, the computed energy of the gamma ray which produced the reaction, and the computed momentum unbalance. The momentum units are such that an alpha particle of 1 Mev has 1 unit of momentum. The momentum measurements were not as good as those of Goward and Wilkins.[17] Two reasons for this are that the processing procedure used is known to introduce more emulsion distortion than other methods, and the other is that the shrinkage factor was not known very accurately. However, there is little doubt that the events listed were properly identified.

The excitation function for the $C^{12}(\gamma,3\alpha)$ reaction reported by Goward and Wilkins shows a peak at about 17 Mev and a minimum at about 21 Mev followed by a second rise[17]. The yield of this reaction from quanta with energies in the region of the peak that should be expected in the present plate, according to the cross section values of Goward and Wilkins, was calculated to be 2.9, in surprising agreement with the three events found in this region.

APPENDIX B

Calculation of critical range for separation of light and heavy element stars

According to the W.K.B. approximation, the transmission coefficient, T, of a particle with energy, E, for escape through a potential barrier of height, V, is given by

$$\ln \frac{1}{T} = 2 \int_{r_0}^{r_1} \left[\frac{2m}{\hbar^2} (V - E) \right]^{1/2} dr \quad ,$$

where r_0 and r_1 are the turning points of the integrand. Substituting

$$V = \frac{zZe^2}{r} \qquad r \geq r_0$$

and integrating,

$$\ln \frac{1}{T} = \frac{2r_0}{\hbar} \sqrt{2mV(r_0)} \quad G\left(\frac{E}{V(r_0)}\right) \quad ,$$

where

$$G(f) = \frac{\cos^{-1}\sqrt{f}}{\sqrt{f}} - \sqrt{1 - f} \quad .$$

We wish to choose a critical range, R, such that a charged particle with the corresponding energy has a negligible chance of escaping from a nucleus of any of the heavy elements in the emulsion. The lightest of the heavy emulsion elements is bromine. (The very small amount of sulfur in the emulsion has been ignored in these arguments.) The choice of a value for T which makes the emission probability of the charged particle negligible compared to other modes of decay and of the values of the parameters in V which could be expected to occur from the previous particle emissions from a bromine nucleus is somewhat difficult.

If two protons and three neutrons have already been emitted from a Br^{81} nucleus, the range of an alpha particle which has a transmission coefficient of T = 0.01 is 57 microns. ($z = Z$, $Z = 31$, $r_0 = 1.5 \times 10^{-13} (72)^{1/3}$ cm.) The range of a proton under the same conditions is 82 microns. ($z = 1$, $Z = 32$, $r_0 \Delta 1.5 \times 10^{-13} (75)^{1/3}$ cm.) If, instead, two alpha particles had been emitted previously, the critical ranges for an alpha particle and a proton would be 47 and 67 microns respectively. For the latter case and T = 0.001 the alpha particle range is reduced to 36 microns.

The effect of the choice of Z and A on the critical range can be estimated by examining the derivatives of E with respect to Z and r_0. Taking R proportional to $E^{1.6}$,

$$\frac{\partial R}{\partial Z} = 1.6 \frac{R}{Z} \frac{1 + \frac{G}{\sqrt{1 - f}}}{1 + \frac{G}{2\sqrt{1 - f}}} \sim 1.9 \frac{R}{Z}$$

and

$$\frac{\partial R}{\partial r_0} = - 1.6 \frac{R}{r_0} \frac{1}{1 + \frac{G}{2\sqrt{1 - f}}} \sim - 1.3 \frac{R}{r_0} ,$$

so that

$$\frac{\delta R}{R} \sim 1.9 \frac{\delta Z}{Z} - 0.4 \frac{\delta A}{A} .$$

The configurations assumed above are quite extreme and it was decided that a critical range of 50 microns sets a good lower limit on the number of stars from the light elements. As is pointed out in Section III, the experimental results would not be changed much if the critical range were reduced to as low as 35 microns.

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TABLE I

Yields of stars as a function of synchrotron energy and prong number. Yields are normalized to emulsion thickness of 200 microns, and to exposures such that the number of quanta per unit energy interval at 27 Mev is equal to that of 10^8 equivalent quanta of 322 Mev bremsstrahlung.

No. of Prongs	Synchrotron Energy			
	322 Mev	242 Mev	161 Mev	80 Mev
1	760 ± 160	1130 ± 210	1050 ± 190	870 ± 170
2 possible	60 ± 4	59 ± 5	33 ± 4	11 ± 2
2 possible	85 ± 5	78 ± 5	35 ± 5	16 ± 2
3	133 ± 6	105 ± 6	40 ± 5	20 ± 3
4	73 ± 5	50 ± 4	28 ± 4	11 ± 2
5	36 ± 3	15 ± 2.3	8 ± 2	
6	13 ± 2	3 ± 1	0.6 ± 0.6	
7	3 ± 1	0.4 ± 0.4		
8	1 ± 0.5			
≥ 3	259 ± 9	174 ± 8	77 ± 7	31 ± 3

TABLE II

Cross sections of silver for production of 3 or more prong stars, averaged over 80 Mev energy intervals, i.e.,

$$\bar{\sigma} = \frac{\int_{E_1}^{E_2} \sigma(K) N_{E_2}(K)\,dK}{\int_{E_1}^{E_2} N_{E_2}(K)\,dK}$$

Energy Interval	$\bar{\sigma}$
80-161 Mev	$(1.7 \pm 0.3) \times 10^{-27}$ cm^2
161-242 Mev	$(6.5 \pm 0.7) \times 10^{-27}$ cm^2
242-322 Mev	$(7.7 \pm 1.2) \times 10^{-27}$ cm^2

TABLES III, IV, V, AND VI

Spectrum of ranges of the shortest prong of stars as a function of prong number and synchrotron energy. These yields are not normalized.

Shortest Prong Range	Prong Number 3	4	5	6	7	8	≥3
	322 Mev						
< 25μ	65	53	22	6			146
25–30μ	4	4	1				9
30–35μ	1	4					5
35–40μ	3	3					6
40–45μ	4		2				6
45–50μ	2	1				1	4
> 50μ	145	70			1		216
Left emulsion inside 50μ	9		4	1			14
	242 Mev						
< 25μ	52	34	10	3			99
25–30μ	7	3	1				11
30–35μ	4	2					6
35–40μ	3						3
40–45μ	2	2		1			5
45–50μ	2	3		1			6
> 50μ	78	33	7				118
Left emulsion inside 50μ	4	2	1				7

Shortest Prong Range Spectra (cont)

Shortest Prong Range	Prong Number 3	4	5	6	7	8	≥3
	161 Mev						
< 25μ	23	27	9	1	1		61
25-30μ	13	4	1				18
30-35μ		1					1
35-40μ		1	1				2
40-45μ		1					1
45-50μ							
> 50μ	24	6	1				31
Left emulsion inside 50μ	2	1					3
	80 Mev						
< 25μ	53	31					84
25-30μ	2	2					4
30-35μ							
35-40μ	1						1
40-45μ							
45-50μ							
> 50μ	2						2
Left emulsion inside 50μ							

TABLE VII

Relative yields of stars, normalized as in Table I. The light and heavy element yields were separated by the coulomb barrier argument as described in Section III and Appendix B.

	Synchrotron Energy							
	322 Mev		242 Mev		161 Mev		80 Mev	
Prong No.	Y_L	Y_H	Y_L	Y_H	Y_L	Y_H	Y_L	Y_H
3	50.4±5.7	98.3±7.9	47.7±5.7	55.9±6.2	22.7±3.8	16.4±3.2	19.1±2.5	0.7±0.5
4	41.5±5.1	44.7±5.3	30.0±4.5	23.9±4.0	21.5±3.7	4.4±1.7	11.2±2.0	
5	15.9±3.2	2.6±1.3	7.5±2.3	5.4±1.9	6.9±2.1	0.6±0.6		
6	3.8±1.6	0.6±0.6	3.4±1.5		0.6±0.6			
7					0.6±0.6			
8	0.6±0.6							

TABLE VIII

Cross sections of carbon and silver for production of 3 or more prong stars, averaged over 80 Mev energy intervals.

$$\bar{\sigma} = \frac{\int_{E_1}^{E_2} \sigma(K) N_{E_2}(K)dK}{\int_{E_1}^{E_2} N_{E_2}(K)dK}$$

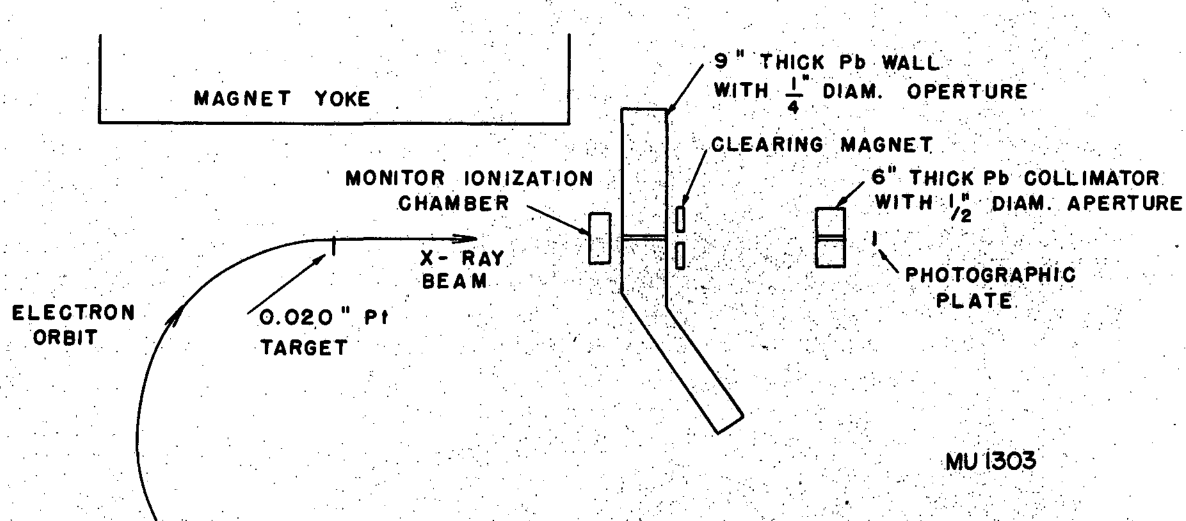
These values were derived using the coulomb barrier argument to separate light element stars from heavy element stars, and assuming that the cross section is proportional to mass number in each group of elements separately.

Energy interval	$\bar{\sigma}_C$	$\bar{\sigma}_{Ag}$
80-161 Mev	$(0.49 \pm 0.12) \times 10^{-27}$ cm^2	$(0.94 \pm 0.16) \times 10^{-27}$ cm^2
161-242 Mev	$(1.7 \pm 0.4) \times 10^{-27}$ cm^2	$(3.6 \pm 0.5) \times 10^{-27}$ cm^2
242-322 Mev	$(1.4 \pm 0.6) \times 10^{-27}$ cm^2	$(7.0 \pm 1.2) \times 10^{-27}$ cm^2

TABLE IX

Summary of momentum balance measurements

$C^{12}(\gamma,3\alpha)$		$O^{16}(\gamma,4\alpha)$	
Momentum unbalance	γ Energy	Momentum unbalance	γ Energy
0.11	25.4	0.17	26.8
0.24	17.1	0.17	32.5
0.30	24.9	0.22	23.8
0.31	24.6	0.23	31.5
0.36	19.8	0.26	22.2
0.58	25.9	0.29	22.8
0.63	17.1	0.35	33.0
		0.37	27.3
		0.74 (doubtful)	39.7


MAGNET YOKE
9" THICK Pb WALL
WITH 1/4" DIAM. OPERTURE
CLEARING MAGNET
MONITOR IONIZATION
CHAMBER
6" THICK Pb COLLIMATOR
WITH 1/2" DIAM. APERTURE
X- RAY
BEAM
PHOTOGRAPHIC
PLATE
ELECTRON
ORBIT
0.020" Pt
TARGET

MU 1303

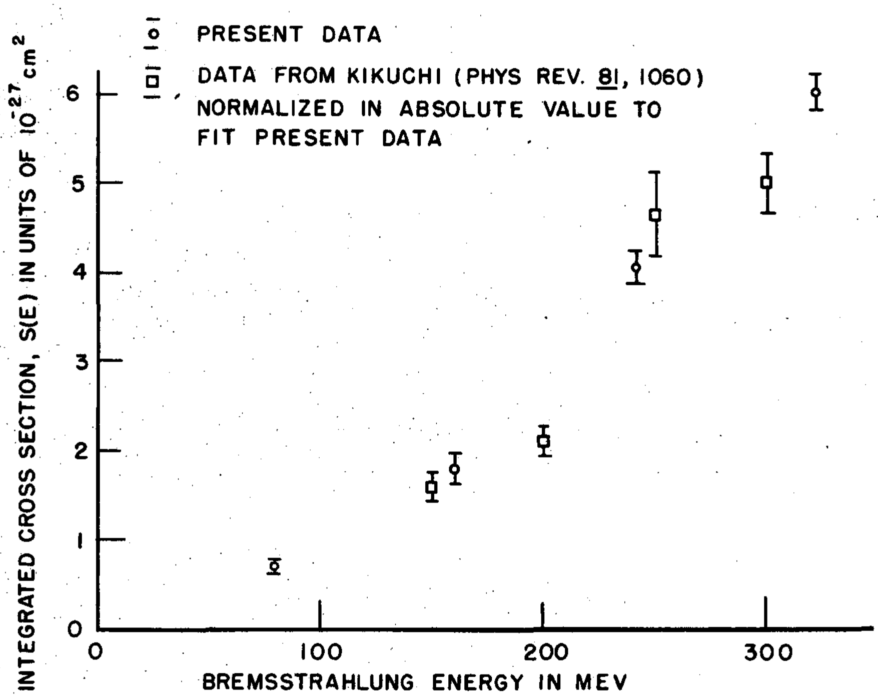


FIG. 2

INTEGRATED CROSS SECTION OF SILVER FOR PRODUCTION OF 3 AND MORE PRONG STARS.

MU 1962

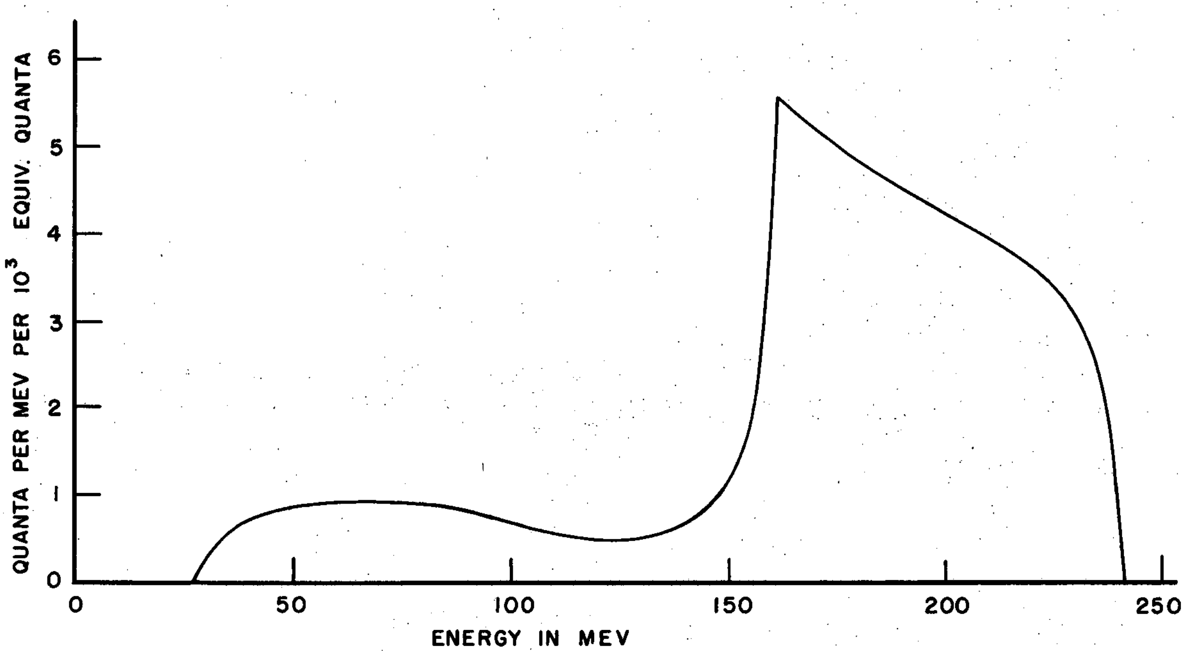


FIG. 3

DIFFERENCE BETWEEN 242 MEV AND 161 MEV BREMSSTRAHLUNG SPECTRA

MU 1963

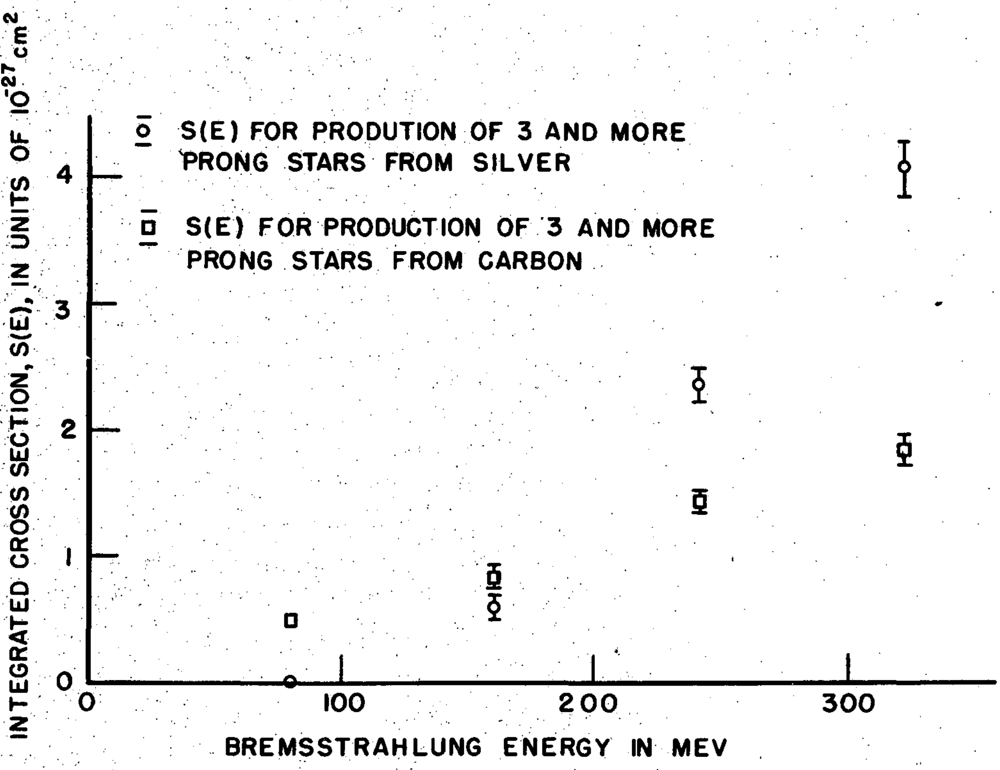

S(E) FOR PRODUTION OF 3 AND MORE PRONG STARS FROM SILVER
S(E) FOR PRODUCTION OF 3 AND MORE PRONG STARS FROM CARBON
INTEGRATED CROSS SECTION, S(E), IN UNITS OF 10^{-27} cm^2
0
1
2
3
4
0
100
200
300
BREMSSTRAHLUNG ENERGY IN MEV

FIG. 4

MU 1964