The Emission of Slow Positive and Negative Mesons from Nuclear Disruptions Produced by Cosmic Radiation*

HERMAN YAGODA
Experimental Biology and Medicine Institute of the National Institutes of Health, Public Health Service, Bethesda, Maryland
(Received October 31, 1951)

Microscopic examination of 76 cc of thick (300 to 1800 microns) nuclear emulsion exposed in the stratosphere has revealed 168 events in which slow mesons are created and terminate their range in the recording medium. Basing the identification of sign on either π-μ decay or σ-star formation at the range terminus, 26 of the ejected particles were π^+ mesons and $145\pi^-$. The small value of the π^+/π^- ratio is attributed chiefly to the production of the ejected mesons by neutral radiation. The observational frequency of the ejected π^- mesons increases rapidly with star size and is approximately proportional to the square of the excitation energy of the parent star. In two events initiated by charged primaries several slow negative mesons were ejected as the wide angle members of large showers of particles. In general, the energy of the slow mesons is between 0.3 and 40 Mev. Corrected for escape from the emulsion the average frequency of the π^- meson production is proportional to $E^{0.6}$ for $E\leq 8$ Mev and to $E^{2.3}$ for energies between 8 and 40 Mev. Comparison of the data on ejected mesons with that available on cyclotron mesons indicates close similarity in the form of the secondary star spectra, the π^+/π^- ratio and the energy distribution of slow π^- mesons.

I. INTRODUCTION

Since the first description by Lattes, Occhialini, and Powell[1] of a double star in which the members are connected by the characteristic track of a slow negatively meson coming to rest in the emulsion, several similar events have been reported by other investigators[2–6] employing nuclear emulsions in the study of cosmic radiation. In particular, a group of 31 of these rare events has been discussed by Powell[7] in all of which the ejected meson is negatively charged. Failure to observe the emission of a slow positive meson from a star produced in thin emulsions has been attributed by the Bristol investigators to the added kinetic energy imparted to the particle by Coulomb repulsion. This increases the range and thus tends to diminish the probability of the positive meson coming to rest in the emulsion with opportunity for observation of the π-μ decay process.

The availability of thick plates and of cylindrical emulsion castings[8] of about 2-mm thickness affords better opportunity for the detection of ejected slow mesons. A systematic survey of these preparations, exposed in a series of stratosphere balloon flights, has resulted in the observation of 168 events exhibiting the ejection and termination of positive and negative mesons in the recording medium. The number of the latter is adequate for the evaluation of the frequency of slow π^- meson production, and the ranges of the particles, corrected for escape, provide several points on the energy distribution curve. While the statistics on the positive particles are still inadequate for a similar analysis, their number permits an approximate evaluation of the star-ejected π^+/π^- ratio and a comparison with the charge ratio of the cosmic-ray mesons incident from the atmosphere and the charge ratio of mesons produced by cyclotron bombardment.

II. EXPERIMENTAL

Ilford G5 plates coated 300 and 600 microns thick and emulsion castings prepared from gel of the same composition were flown in a series of stratosphere balloon flights at Minnesota ($\lambda=55°$N) described in Table I. The thick preparations were developed uniformly by means of low temperature imbibition of a bufferred amidol solution, followed by a warm stage in an aqueous medium termed an "ionic environment" which is devoid of developer but contains salts for maintaining a fixed pH and compounds to inhibit swelling of the gelatin. Details of this method, employed successfully in the uniform development of 2 mm thick castings, will be described elsewhere. All emulsions scanned recorded the tracks of fast singly charged particles at or close to the minimum of ionization.

The plates were examined with a 6.4 mm achromatic objective and 10× wide field oculars. In order to secure sufficient clarity near the bottom layers of the thick castings it was necessary to resort to oil immersion

TABLE I. Stratosphere balloon flight characteristics.

Flight	Maximum altitude, ft	Av. altitude above 60,000 ft	Time above 60,000 ft
76*S*	93,000	85,500	6.8 hr
83	95,000	91,700	6.9
110	106,000	98,500	7.3
97	99,000	90,500	6.8
108	90,000	85,200	6.7

* A preliminary report of this work was presented at the American Physical Society Meeting in New York, January, 1951 [H. Yagoda, Phys. Rev. 82, 336 (1951)].
[1] Lattes, Occhialini, and Powell, Nature **160**, 453, 486 (1947).
[2] G. P. S. Occhialini and C. F. Powell, Nature **162**, 168 (1948).
[3] L. Leprince-Ringuet, Revs. Modern Phys. **21**, 42 (1949).
[4] Cosyns, Dilworth, Occhialini, and Schönberg, Nature **164**, 129 (1949).
[5] E. Pickup and A. Morrison, Phys. Rev. **75**, 686 (1949).
[6] I. Barbour, Phys. Rev. **78**, 522 (1950).
[7] C. F. Powell, *Cosmic Radiation-Colston Papers* (Interscience Publishers, Inc., New York, 1949), p. 91.
[8] H. Yagoda, Phys. Rev. **79**, 207 (1950); **80**, 753 (1950).

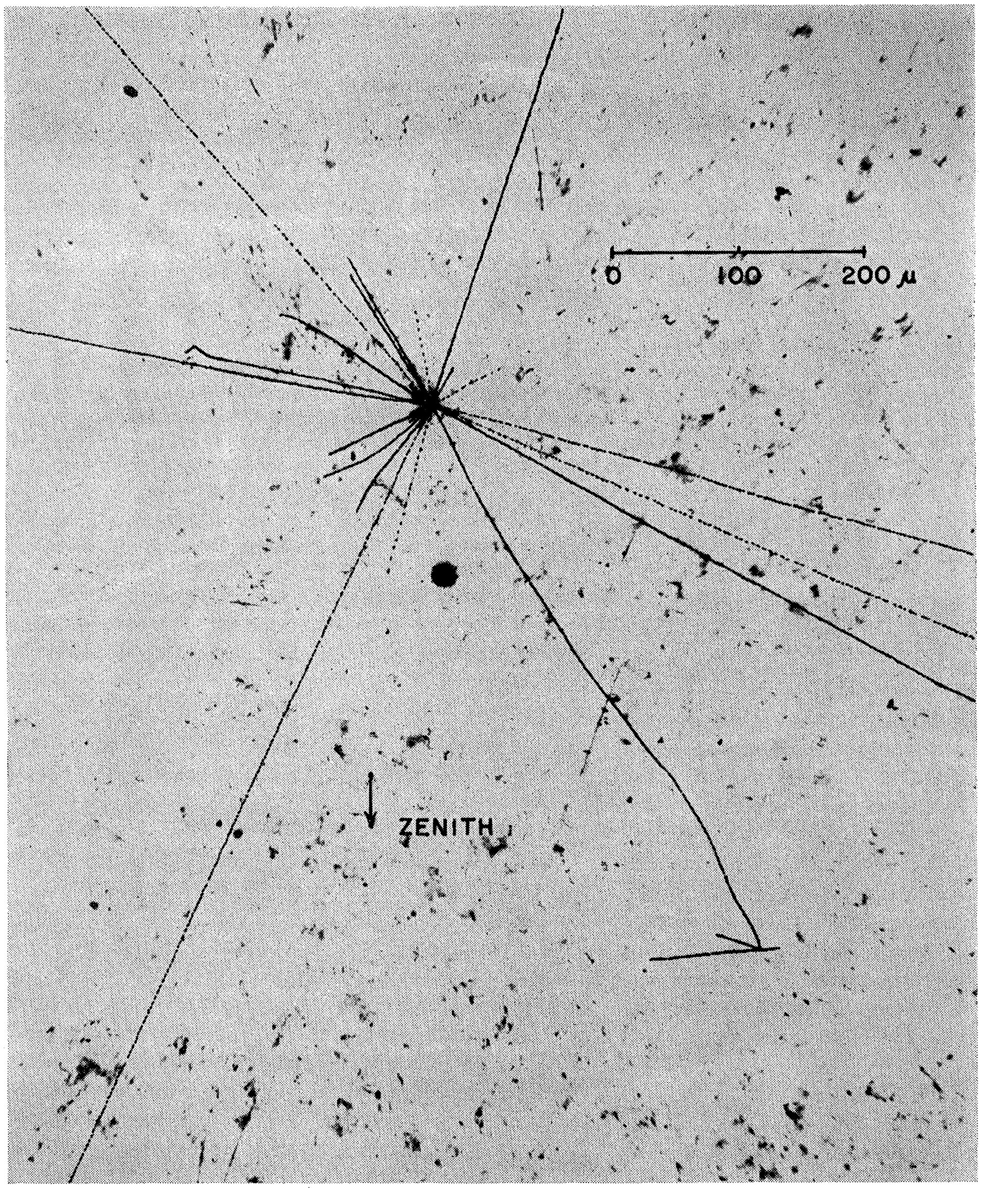

FIG. 1. Disruption of a heavy emulsion nucleus accompanied by the ejection of a 4.2-Mev π^- meson which is captured at the end of its range with the formation of a 3-prong star.

All the star illustrations are photodrawings prepared by inking pertinent detail on an enlargement print from a low power photomicrograph. The grain densities of the tracks are not perfect facsimiles of the original developed structures.

objectives. The castings were scanned with a 26× immersion objective (N.A. 0.5, W.D. 2 mm) and details of individual events were studied with a 45× immersion objective (N.A. 0.85, W.D. 1.5 mm). In all instances the entire volume of the recording medium was examined by successive linear traversals with overlapping fields.

All stars encountered in the field of view were examined for the presence of slow meson tracks (range 6 to 300 microns) basing the identification on scatter and σ-star formation at the rest point of π^- particles, and of the characteristic π-μ decay for those of positive charge. Particles ejected with ranges exceeding 300 microns were usually located at points remote from the parent star by tracing back all meson tracks observed to be near the end of their range to their points of origin. The detection efficiency of the mesons ejected from stars was therefore dependent chiefly on the ability to discern σ-stars and π-μ events. This feedback scanning mechanism is advantageous in that it avoids the tracing of all star tracks, and tends to equalize the detection probability of long-ranged mesons ejected from both small and large stars. A duplicate scanning of a 600 micron plate showed that the detection efficiency was about 80 percent under the particular conditions of microscopy. The visibility of tracks located near the bottom of very thick gelatin layers is poor owing to the scattering of the light by the silver structures in the upper layers and hence the detection efficiency is probably lower in the 1200 and 1800 micron emulsion castings.

Studies by Adelman and Jones[9] of the tracks of negative mesons produced by the Berkeley cyclotron show that 26.8 percent of the particles produce a heavy blob of several grains at the track terminus and the remaining mesons created small stars of one to five prongs. In our observations a small number of ejected mesons were also observed to terminate in a grain cluster. However, it was decided to exclude this category from the statistics, as it is not always possible to identify a meson by inspection of its scatter, and the number of random small grain clusters in the field were too numerous for use of the blob at the rest point as an auxiliary aid in the identification.

It is also difficult to detect negative mesons when the capture of the particle results in the emission of only a single track. To avoid possible confusion with protons undergoing a large angle scatter near the end of their range, the event was not accepted unless the multiple small-angle scatter was very pronounced and the emitted prong had a range exceeding 25 microns. Also, when the range of the ejected meson was less than 300 microns, short straight tracks at the apparent rest point of the particle were interpreted as an emitted prong only when of very heavy grain density accompanied by a detectable thin-down. When the track of the 1-prong star failed to terminate the identity of the meson was determined from considerations of the grain density and small angle scatter along the recorded portion. Mesons which produce stars of more than one prong can be identified readily when the range of the ejected particle exceeds about 50 microns and the star prongs have a recorded range of at least 5 microns. A typical example of this unambiguous category is illustrated in Fig. 1. When ejected at small angles with the emulsion plane, mesons with a range of only 5 microns can be detected when their capture results in a secondary star with more than 1-prong.

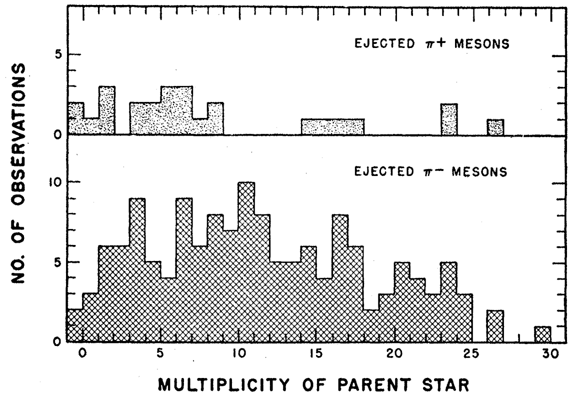

FIG. 3. Histogram of the number of events with ejected mesons as a function of the multiplicity (sum of black and gray tracks) of the parent star.

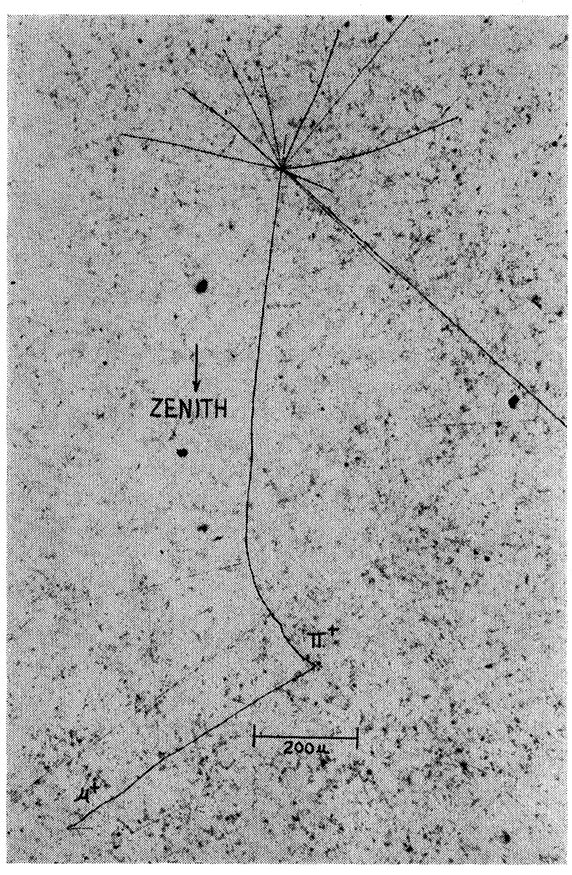

FIG. 2. Star showing the ejection of a 6.3-Mev π^+ meson which comes to rest in the emulsion and undergoes π-μ decay. The electron track from the decay of the μ^+ particle is recorded at a steep angle and appears of high grain density in the horizontal projection.

The mesons of positive charge were identified by the characteristic π-μ decay process. In many instances, as shown in Fig. 2, the track of a minimum ionization electron could also be discerned at the rest point of the μ^+ meson. In a few events the μ^+ meson track escaped from the recording medium. These were tallied only when the variation of grain density and scatter over the recorded length permitted a differentiation from the tracks of fast protons or deuterons which occasionally are produced by the capture of a slow negative meson.

The data secured by these criteria is summarized in Fig. 3 in which the number of events showing the emission of mesons of opposite charge are arranged in the order of the parent star size. In assigning a multiplicity to the parent star only black and gray tracks were counted. The multiplicity does not include the track of the ejected meson, the tracks of minimum ionization shower particles, or the track of the incident particle when its trajectory was unambiguous. The star size may thus be employed as an approximate index for differentiating between heavy (Ag, Br, I) and light (H, C, O, N) groups of nuclei by assuming that all stars of multiplicity >6 originate from the heavy nuclei.

[9] F. L. Adelman and S. B. Jones, Phys. Rev. **75**, 1468 (1949).

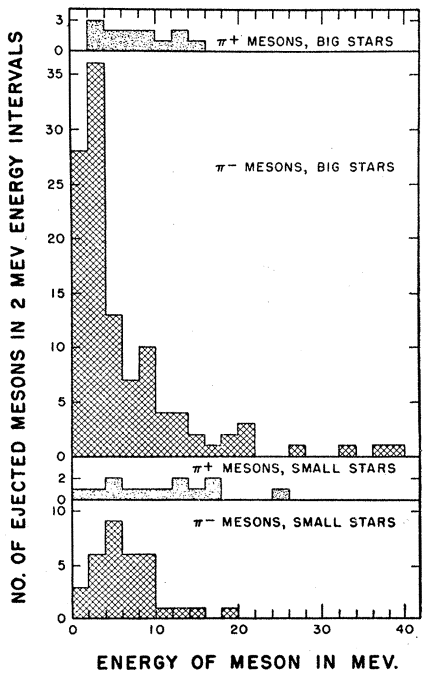

FIG. 4. Classification of mesons emitted from nuclear disruptions as a function of the ejection energy of the particles.

This subdivision of the data into small and large stars is exhibited in Fig. 4 as a function of the kinetic energy of the ejected mesons. The energies were computed from the measured range in the emulsion basis a mass of $276m_e$ for pions employing the relationship $E_\pi = 0.250(m_\pi/m_p)^{0.419}R^{0.581}$ derived by the Berkeley group.[10]

III. THE RATIO OF POSITIVE AND NEGATIVE MESONS EJECTED FROM STARS

The observations indicate that in the low energy region under consideration (<40 Mev) the ratio of π^+/π^- ejection from all the emulsion nuclei is 0.18. On the basis of origin from large and small stars the observational charge ratio is estimated at 0.15 for heavy target nuclei and 0.37 for the light nuclei of the gelatin component. It is to be noted that ejected negative mesons terminating without visible star formation are not included in the statistics, and if it be assumed that these constitute 26.8 percent of the negative mesons, as indicated by the observations of Adelman and Jones,[9] the π^+/π^- ratios would be reduced correspondingly by a factor of 0.79.

The charge ratio of the ejected mesons is strikingly small when compared with available data on the corresponding ratio of mesons incident on plates exposed to cosmic radiation in the stratosphere. For the latter Barbour[6] observed values ranging between 1.8 and 1.4 in a series of flights with the plates exposed between the poles of a 65-lb magnet. In our flights No. 108 and 110 (Table I) a total of 520 π-μ events and 542 σ-mesons were observed to enter and terminate in the emulsions, suggesting that in essentially unscreened plates the π^+/π^- incident ratio is close to unity. In a flight at 60,000 ft elevation Fry[11] observed a π^+/π^- ratio for externally created mesons of 0.35.

The discrepancy between the ejected and the incident meson charge ratios may originate from the following factors:

(1) Geometric limitations: A study of the 26 events exhibiting the ejection of a positive meson shows that in 24 instances the μ^+ decay particle also terminated and that in the remaining two events the recorded range (about 400 microns) was adequate for the identification. The large fraction of completely terminating π-μ events suggests that the observations were limited chiefly to those events in which the decay particle was recorded at small angles with the emulsion plane. This is further indicated by the analysis in Table II which shows that the observational ratio of π^+/π^- mesons ejected from stars increases progressively with the thickness of the recording medium. Application of escape corrections to the μ^+ particle indicates that the 26 events noted microscopically probably correspond to 47 occurrences of an ejected positive meson, and that the ratio thus corrected is increased to 0.32 when all nuclei in the emulsion are considered.

(2) Ejection energies: In leaving the nucleus positive mesons will acquire an additional energy by Coulomb repulsion $E_c = Z_1 Z_2 e^2/d$. This evaluates to 9.8 and 8.1 Mev for silver and bromine nuclei, and 2.6 to 3.2 Mev for nuclei of charge 6 to 8 if it be assumed that d is of the order of the nuclear radius $1.45\times 10^{-13}A^{\frac{1}{3}}$ cm. Thus, if mesons of both charges were initially created with the same energy distributions the positive particles ejected from heavy nuclei would have their ranges extended by an amount corresponding to about 9 Mev, and hence a smaller number would terminate in the emulsion. Examination of Fig. 4 shows that this factor is not evident in our present observations, and that in contrast, a large fraction 9/13 of the positive mesons ejected from heavy nuclei appear in the laboratory system with kinetic energies well below the minimum

TABLE II. Observational intensities of ejected mesons.

Flight	Emulsion thickness microns	Volume scanned cc	No. of events with ejected mesons π^+	π^-	π^+/π^-	Intensity[a] cc per day	Total star intensity >2 prongs
76S	300	20.2	none	15	0.13	2.62	2460
83	300	15.8	3	9		2.65	2270
110	600	25.4	9	65	0.14	9.58	2680
97	1200	3.8	4	14	0.29	16.7	2540
108	1800	11.2	10	42	0.24	16.6	1910

[a] Sum of π^+ and π^- ejected mesons.

[10] H. Bradner, University of California Radiation Laboratory Report 486 (October 19, 1949), p. 60.

[11] W. F. Fry, Phys. Rev. 82, 749 (1951).

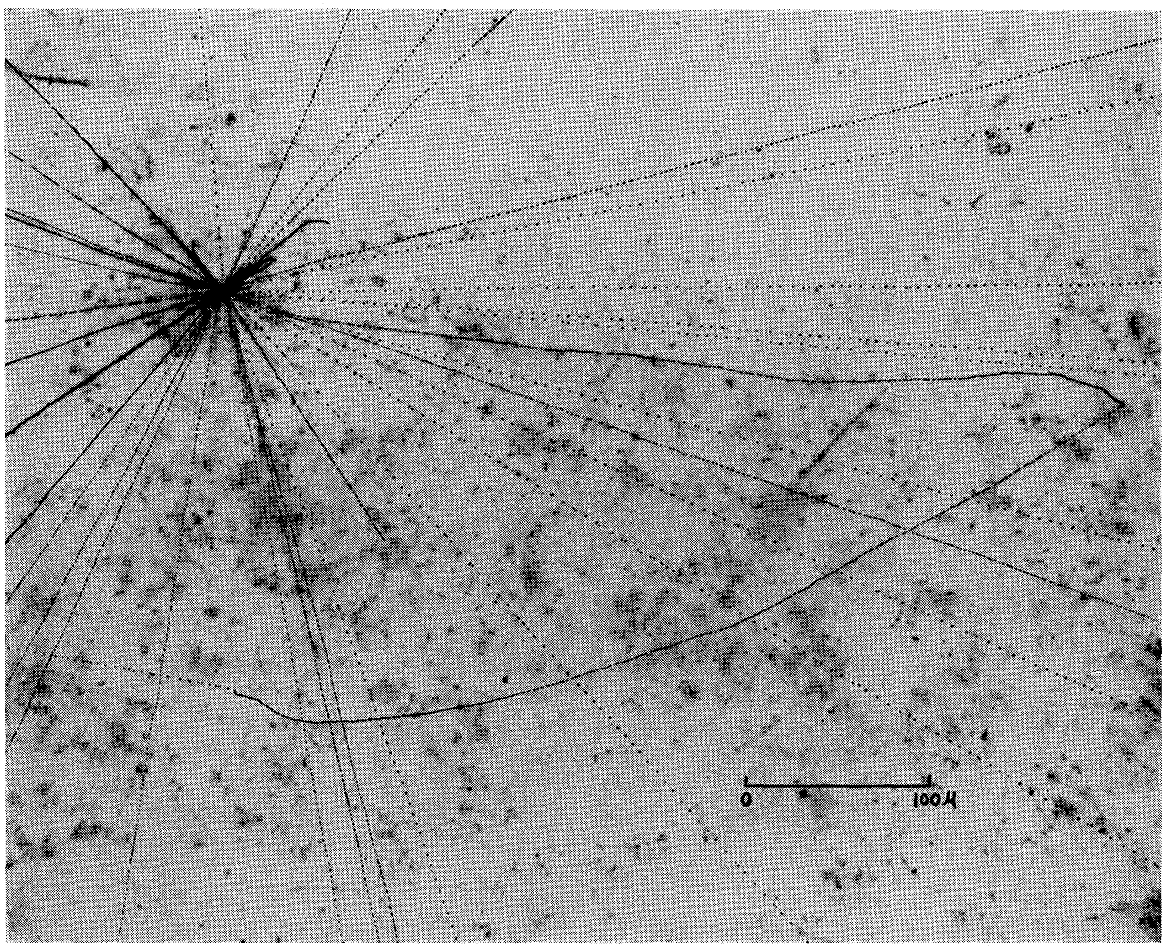

FIG. 5. Emission of a slow π^+ particle in the disruption of a heavy nucleus. The ejected meson has a kinetic energy of 4 Mev, a value markedly smaller than that imposed by the Coulomb barrier of silver or bromine nuclei. While apparently emerging in the same direction as the fast shower particles, it is probably a member of an independent group of slow mesons.

energy imposed by the Coulomb barrier.[12] Figures 2 and 5 are examples of positive meson ejection from heavy nuclei with energies less than E_c, the latter example is particularly striking in that the meson appears to emerge within the angular cone of the fast shower particles (see Sec. VI).

A low yield of positive mesons is to be anticipated if the parent stars are produced chiefly by neutrons. Thus, Bradner, O'Connel, and Rankin[13] observed a π^+/π^- ratio of 0.11 for the mesons produced by the bombardment of a carbon target with 270-Mev neutrons. The observational π^+/π^- ratio of 0.18 (or 0.32 when corrected for μ^+ escape) for mesons ejected from all the emulsion nuclei is explicable if it is assumed that most of the disruptions were initiated by non-ionizing radiation. Examination of the parent stars shows that only 13 percent of the events were initiated by a charged particle.

The charge ratio of slow mesons produced by the bombardment of targets of different nuclear charge by 390-Mev alpha-particles has been measured by Barkas.[10,14] His observations on relative meson yields, over an energy interval of 2 to 5 Mev, summarized in Fig. 6, indicates that the charge ratio falls rapidly with increasing nuclear charge and that no positive mesons were observed from indium or lead targets. Restricting our observations on mesons ejected from cosmic ray stars to an energy less than 6 Mev, yields π^+/π^- ratios of 4/18 and 5/77 for the light and heavy nuclear components of the emulsion. As seen in Fig. 6, these

[12] In a discussion with Dr. M. M. Shapiro he has suggested that lowering of the Gamow barrier for the escape of a π^+ meson might occur: (1) in a violent, more or less head-on collision of an incident particle with the target nucleus (a) if disintegration precedes the escape of the slow meson, or (b) through an increase in nuclear diameter resulting from the high excitation: (2) in a collision which imparts a high angular momentum to the target nucleus. Penetration by leaking through the Gamow barrier, which is more probable for a pion than for a heavier particle with the same energy, may account for a small proportion of the observations. Finally, the detector geometry contributes in an essential way: once a low energy meson does emerge, its chance of stopping in the emulsion is much greater than that of longer-range mesons.

[13] Bradner, O'Connel, and Rankin, Phys. Rev. **79**, 720 (1950).

[14] W. H. Barkas, Phys. Rev. **75**, 1467(A) 1949.

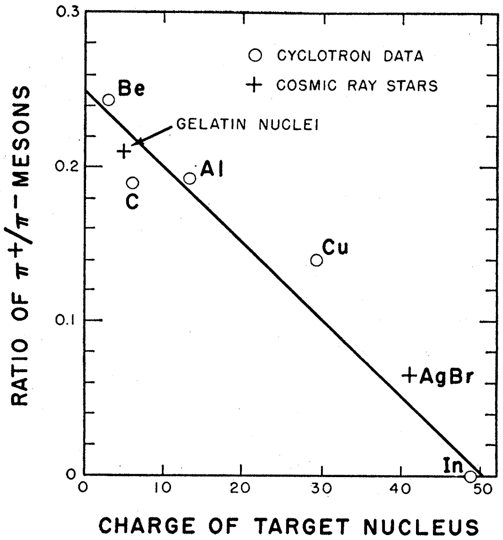

FIG. 6. Comparison of the observational π^+/π^- ratio for slow mesons produced by the cyclotron and ejected from cosmic-ray stars as a function of the nuclear charge of the target atoms.

charge ratios are in good agreement with the yield of positive and negative mesons produced by 390-Mev alpha-particles. This is rather unexpected, in that the slow mesons of cosmic-ray origin were produced chiefly by high energy neutrons and this would seem to suggest that the charge ratio of very low energy mesons is not sensitive to the energy or charge of the incident radiation.

IV. SLOW MESON EJECTION AS A FUNCTION OF STAR SIZE

Examination of Fig. 3 shows that slow mesons are ejected from stars of 2 to 18 prongs with about equal frequency. As is well known from numerous investigations of star size distribution in emulsions exposed to cosmic radiation, small stars predominate and, in general, the relative frequency diminishes exponentially with increasing star multiplicity. Our observations therefore indicate that the probability of slow meson ejection increases very rapidly with the complexity of the parent star. In order to evaluate the form of this ejection probability function an estimate was made of the total number of stars in each multiplicity class S_n (black and gray prongs) recorded in the volume of emulsion scanned for ejected mesons. On the basis of the star intensities recorded in Table II and the duration of the respective stratosphere flights it is estimated that 53,800 stars with 3 or more prongs were recorded in the volume scanned. S_n was estimated with the aid of the star spectrum based on 15,300 events analyzed in plates flown at 68,000 ft by the Bristol group,[15] and the probability $P_n=(S_\pi/S)_n$ was computed for each star class. As shown in Fig. 7, P_n is approximately proportional to the square of the multiplicity. For giant stars of 20 or more prongs there is about a 2 percent probability of a slow negative meson ($E<40$ Mev) being ejected and terminating in thick emulsions. The available data on ejected positive mesons is indicative of a similar trend in the variation of P_n with multiplicity, but the form of the function must await more abundant statistics. On the basis of ejection from large and small stars the relative observational frequency for negative mesons is 3.15 ± 0.6. Within the limitations of the present statistics slow positive mesons are observed with about equal frequency from both large and small stars. In so far as the multiplicity is a measure of the star excitation energy, and since the star excitation energy has been shown[15] to be a linear function $E_n=155n-100$, it follows that the probability of slow meson ejection is approximately proportional to the square of the excitation energy.

V. MESONS FROM STARS OF <3 PRONGS

The observations summarized in Fig. 3 show that slow mesons are also produced in simple nuclear interactions constituted of only 1 or 2 prongs, and that the meson track may begin at a point in the emulsion unassociated with the tracks of other ionizing particles, i.e., multiplicity zero. In all 4 events of multiplicity zero the points of meson origin were well embedded

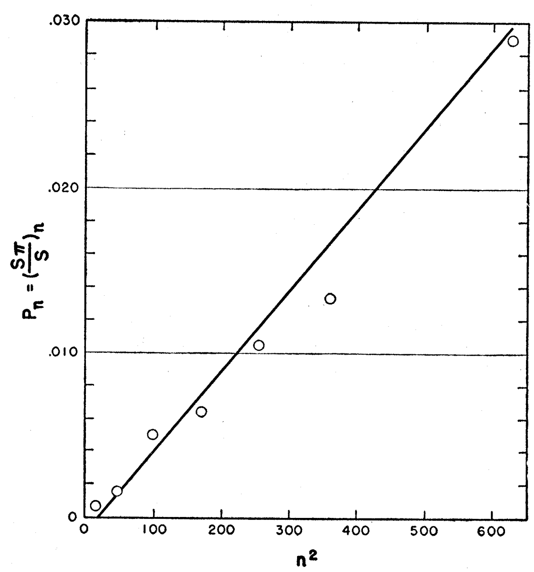

FIG. 7. Relationship between the probability of slow π^- meson ejection from a star with n-prongs and the square of the multiplicity, n^2. Because of the small number of events in individual multiplicity groups, the data has been grouped into units of three successive multiplicities. The average statistical uncertainty for the plotted points is ±25 percent on the basis of the numbers of ejected mesons in each category.

[15] Preliminary manuscript by Camerini, Davies, Fowler, Franzinetti, Lock, Perkins, and Yekutieli to be published in Phil. Mag. The star spectrum based on black and gray tracks does not vary significantly with altitude between 68,000 and 100,000 ft, as indicated by a comparison of the star size distribution of 500 stars recorded in our high altitude plates with the more statistically significant work of the Bristol group at the lower altitude.

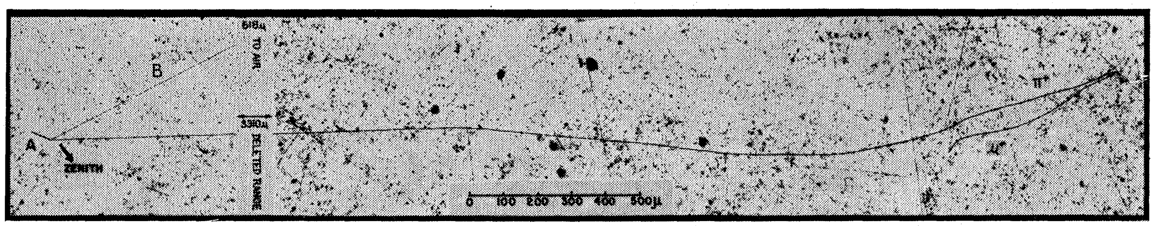

FIG. 8. Interaction exhibiting the emission of an 18.5-Mev π^+ meson, associated with a black track A and a gray track B. The latter leaves the emulsion after traversing 1300 microns without an appreciable change in grain density (less than 4× minimum); its specific ionization is indicative of either a 47-Mev pion, or a 300-Mev proton. The short black track also leaves the emulsion at a steep angle and its charge is not determinant.

within the emulsion layer and the initial grain densities of the trajectories were considerably above the lower recording limit for singly charged particles. The two positively charged mesons originating from stars of zero multiplicity are readily explicable on the basis of the interaction of neutrons or gamma-rays with hydrogen nuclei, $n+\mathrm{H}\rightarrow 2n+\pi^+$ or $h\nu+\mathrm{H}\rightarrow n+\pi^+$. The negatively charged particles, however, are not readily reconcilable with known mechanisms of meson production. The possibility must be considered that minimum ionization particles may have been associated with the π^- meson tracks, but that owing to localized fluctuations in sensitivity or unfavorable angles of incidence the tracks could not be discerned microscopically. The interpretation of these negative meson tracks must await the accumulation of more abundant statistics.

The several events constituting multiplicity groups 1 and 2 can be classified according to the charge of the ejected meson and the grain density of the associated tracks as shown in Table III. Most of these events can be interpreted in terms of meson production by nucleon-nucleon interaction processes. In several instances, however, where a black track is associated at the origin of the meson particle it must be postulated that the energy of the incident nucleon was only slightly above the threshold value for meson production and that the black prong represents the emergence of a slow proton. A typical example of the parent star class in which a black and a gray prong is associated with the meson track is illustrated in Fig. 8.

VI. MULTIPLE SLOW MESON EJECTION

The present observations also include two stars exhibiting the emission and termination of more than one slow meson. The first event of this character, described in detail in an earlier publication,[16] was initiated by a relativistic proton, and the two negative mesons of 3.3 and 18.4 Mev appeared as wide angle members of a collimated shower of 8 fast singly charged particles. In the second example of multiple slow meson creation, reproduced as a projection drawing in Fig. 9, three slow negative mesons were ejected from a giant star initiated by a heavy primary whose charge is estimated at 11 ± 1 by delta-ray counts. The slow mesons emerge along an independent shower axis at an average angle of 90° to the main collimated shower of about 30 relativistic particles. One of the slow mesons σ_1 appears in the horizontal projection of the event as part of the fast group, but it is directed upward at a steep angle with the principal shower axis.

[16] M. M. Shapiro and H. Yagoda, Phys. Rev. **80**, 283 (1950).

It is noteworthy that in both instances of multiple slow meson ejection the nuclear disruption shows a collimated shower of fast singly charged particles and that the slow mesons are emitted at large angles with the fast shower axis. In general, showers of fast particles (4 or more minimum ionization tracks recorded over an angular spread of $<60°$), are evident only in about 20 percent of the stars which exhibit the track of a single slow meson, and this particle is invariably the wide angle member. This orientation of the slow mesons with respect to the fast shower axis, taken in conjunction with the two instances of multiple slow meson ejection which have been observed, suggests that in stars with a fast collimated shower more than one slow meson may be produced in a fair proportion of the events, but that owing to the limited thickness of the recording medium the termination of more than one is observed very infrequently. The two occurrences suggest a lower observational limit for this process of the order of 0.09 per cc per day of exposure in the stratosphere.

The emission of a slow positive meson as a member of a group of slow mesons has not been directly ob-

TABLE III. Classification of the simple meson production processes.

Star multiplicity	Ejected meson charge	Associated tracks	Possible origin	Number of occurrences
0	+	none	$h\nu+p\rightarrow\pi^++n$; $n+p\rightarrow\pi^++n$	2
0	−	none		2
1	+	1 gray	$p+n\rightarrow n+n+\pi^+$	1
1	−	1 gray	$n+n\rightarrow n+p+\pi^-$	1
1	−	1 black		2
2	+	2 gray	$p+p\rightarrow n+p+\pi^+$	1[a]
2	+	1 black+1 gray		2
2	−	1 black+1 gray	$n+p\rightarrow p+p+\pi^-$	4
2	−	2 black		2

[a] An event similar to this, but in which the ejected meson is of negative charge, has recently been described by S. J. Goldsack and N. Page, Phil. Mag. **42**, 570 (1951). They attribute the meson production to a $n+p\rightarrow p+p+\pi^-$ reaction.

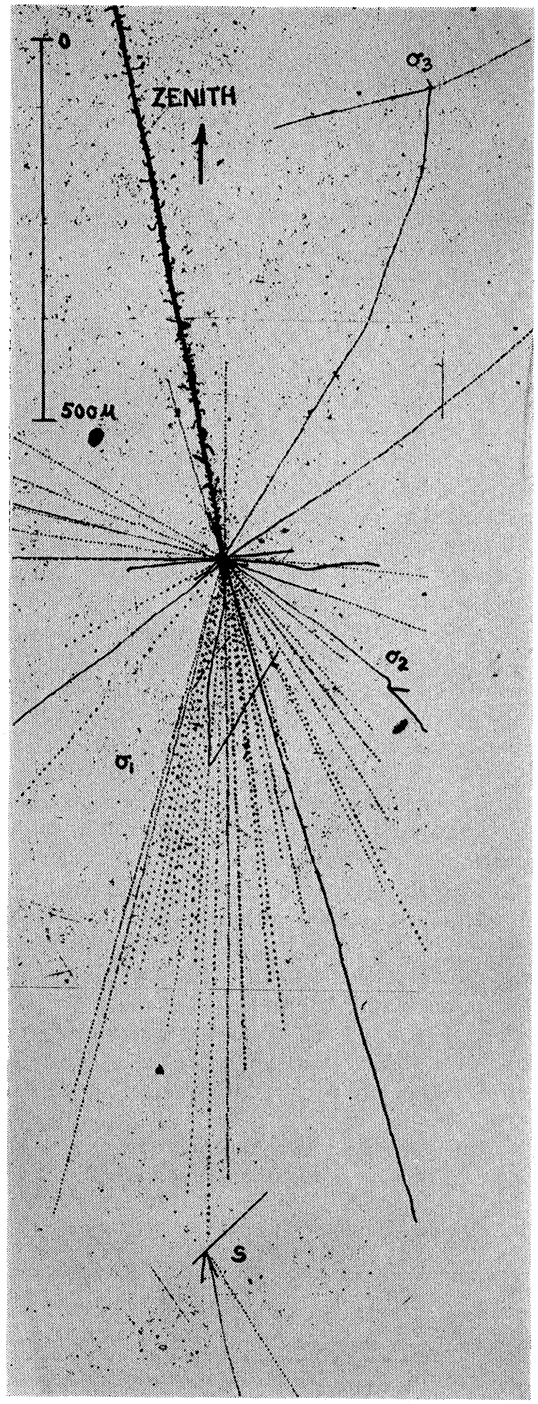

FIG. 9. Giant star initiated by a heavy primary of estimated charge 11±1, constituted of 31 black and gray tracks and about 30 relativistic particles, the latter collimated in a broom of 52° angular spread. One of the fast shower particles is captured in flight and produces a 7-prong star S. In this interaction of the incident particle with a heavy nucleus, possibly silver, three slow mesons are also ejected with energies of $\sigma_1=3$ Mev, $\sigma_2=4.9$ Mev, and $\sigma_3=8.2$ Mev. The slow mesons emerge over an angular spread of 155° and their axis is at an angle of 90° with that of the fast shower.

A number of tracks, directed at large angles with the emulsion plane, have been omitted from the horizontal projection of the event.

served. The orientation of the π^+ track in Fig. 5, however, is indicative of this process. This track seems to emerge in the same direction as the fast shower particles. It is reasonable to assume that this direction is coincidental, and that like track σ_1 of Fig. 8, the ejected positive meson belongs to an independent group of slow mesons the other members of which failed to terminate.

VII. ENERGY DISTRIBUTION OF THE EJECTED π^- MESONS

The data on slow meson ejection accumulated from observations in recording media of different thickness exposed on independent flights. Only in the exposures of flights 110 and 108 were a sufficient number of events observed to permit a rough estimate of the production rate by correcting the data for those meson tracks which originated in stars but failed to terminate in the sensitive layer. In applying geometric escape corrections it has been assumed that the probability of a meson track originating in an emulsion of thickness t and producing a σ-star or a μ^+ decay particle at the end of its range R is:

$$P_1=[1-(R+k)/2t], \quad \text{when} \quad (R+k)<t \qquad (1)$$

and

$$P_2=t/[2(R+k)], \quad \text{when} \quad (R+k)>t. \qquad (2)$$

A length k must be added to the range in order to establish the production of a secondary event at the meson track terminus. This correction is only appreciable for positive mesons where a length k of about 400 microns must be recorded to identify the secondary track as that of a μ^+ particle. For mesons of negative charge, k resides between 5 and 25 microns depending on the secondary star size and is in general negligible for most all values of R in the thick emulsions under consideration.

Equations (1) and (2) assume that R is small compared to the linear dimensions of the recording medium, and hence are not applicable to the data of flight No. 108. In the region of 10 to 40 Mev the long ranges of the mesons necessitate an additional correction owing to the limited size of the castings (diameter 5 cm). For cylindrical disks of diameter D and thickness t the probability of a particle of range $R>t$ terminating is as a first approximation:

$$P_3=(t/2R)[(D-R)/D]^{\frac{1}{2}}. \qquad (3)$$

Application of these corrections to the data observed in the 600 micron plates and the 1800 micron thick castings shows (Fig. 10) that within the limitations of the available statistics the yield of negative mesons increases progressively with their ejection energy. The close agreement between points from the two flights indicates that the meson ejection phenomenon is of a reproducible character, and that the form of the spectrum is independent of altitude between 90,000 and

106,000 ft. Points A, B, and C on Fig. 10 are from the energy spectrum of π^- mesons produced by 390-Mev alpha-particles on a carbon target measured by Jones and White and described in the Bradner Report,[10] normalized to the stratosphere data. This comparison indicates a close similarity in the form of the negative meson spectra over the region of 3.8 to 12.5 Mev suggesting that the distribution is not sensitive to the charge of the target and projectile nuclei.

A detailed analysis of the present data is not warranted owing to the limited statistics. It appears, however, that even in the region below 40 Mev, the spectrum cannot be fitted by a single power law. The negative meson production frequency in the region between 8 to 40 Mev is significantly greater than for the 1 to 8 Mev region. The points below 8 Mev are based on good statistics, the geometric escape corrections are small and hence the relationship $I_\pi \propto E^{0.6}$ is dependable for the production intensity of negative mesons ejected with energies ≤ 8 Mev. For energies >9 Mev the intensity appears to be proportional to $E^{2.3}$, but the statistical uncertainty is large and the significance of the rapid increase in intensity must await more abundant observations.[17] The intensities of meson production in the stratosphere shown in Fig. 10 have not been corrected for those particles which stop in the emulsion without visible star formation, or for the over-all factors which govern the detection efficiency as discussed in Sec. II.

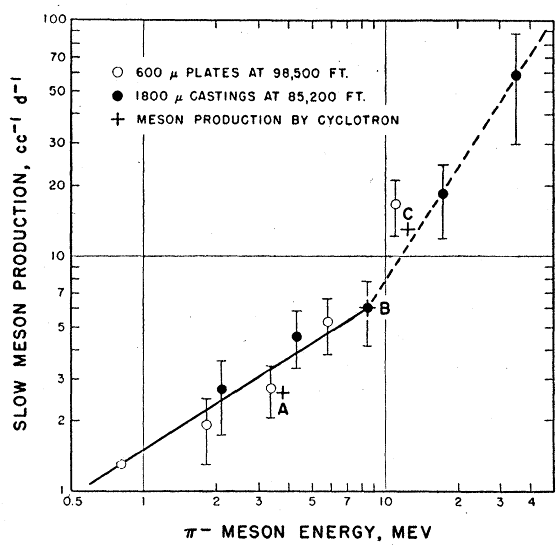

FIG. 10. Slow π^- meson production intensity, corrected for escape, as a function of meson ejection energy. Points A, B, and C from the energy distribution of cyclotron mesons (intensity in arbitrary units) have been normalized to the stratosphere cosmic-ray data at point B.

[17] Disks of emulsion 2.5 mm thick and 90 mm in diameter have been cast and processed successfully. One of these has been recovered after a level flight at 95,000 ft. Measurements on this preparation should improve the statistics in the region of 8 to 40 Mev and provide some additional points on the range distribution of ejected mesons with energies up to about 80 Mev.

TABLE IV. Star size distributions produced by ejected and cyclotron mesons.

Exposure No. of events	Stratosphere 148	Cyclotron 3366
	percentage of stars	
1-prong	32.4 ±4.7	32.4±1.0
2-	26.3 ±4.2	32.7±1.0
3-	27.0 ±4.3	22.3±0.8
4-	12.2 ±2.9	10.5±0.6
5-	1.35±1.0	2.0±0.2
6-	0.68[a]	0.1±0.1

[a] Based on only a single observation. Combining the data on 5- and 6-prong stars indicates a frequency of 2.0 and 2.1 percent for σ-stars produced by cosmic-ray and cyclotron mesons, respectively.

VIII. SECONDARY STARS PRODUCED BY THE CAPTURE OF EJECTED MESONS

The distribution of secondary stars produced at the range terminus of the 148 negative mesons ejected from cosmic-ray disruptions is compared with the prong size distribution obtained with π^- cyclotron mesons in Table IV. The latter data is taken from a compilation by Adelman[18] based on a total of 3366 σ-stars recorded in plates exposed to the negative mesons produced by the Berkeley cyclotron. Within the limitations of the comparatively scant cosmic-ray statistics the two groups of observations appear to be comparable. This can be interpreted that most all of the mesons ejected from cosmic ray disruptions are identical in mass with the π^- mesons produced by the cyclotron, as a large admixture of heavy mesons ($\sim 1000m_e$) might favor the production of the more complex σ-stars constituted of 4 to 6 prongs.

In the course of these observations more than 2000 meson tracks were followed back to their points of origin. No examples of the decay of a heavy τ-meson into 3 light mesons were detected by this scanning mechanism.[19] In descriptions of τ-meson occurrences[20,21] the plates were exposed at mountain altitudes surrounded by large thicknesses of lead or ice. It thus appears that the production of τ-mesons is favored by

[18] F. L. Adelman, University of California Radiation Laboratory Report 1005 (1951).

[19] The decay of a $1000m_e$ particle at rest into three π-mesons releases 86 Mev available as kinetic energy. If shared equally, the decay particles will have ranges of about 10 mm and a termination probability of only 0.072 per track in the 1800 micron castings. When the energy is shared unequally the probability of detecting the slower decay particles is considerably improved ($P=0.3$ to 1 for energies of 12 to 1 Mev). If the three respective ranges are considered equally probable, the average detection probability per event is estimated at about 0.5. Since no instance of ternary τ-meson decay was noted the upper limit for the process is of the order of 1 per 500 π-μ decays.

[20] Brown, Camerini, Fowler, Muirhead, Powell, and Ritson, Nature **163**, 82 (1949).

[21] J. B. Harding, Phil. Mag. **41**, 405 (1950).

a preponderance of secondary radiation, and that very few interactions at stratosphere elevations result in the formation of τ-mesons.

ACKNOWLEDGMENTS

Opportunity is taken to thank the ONR and the aeronautical staff of General Mills for the exposure and recovery of the several emulsion preparations. The casting of emulsion disks of adequate sensitivity was greatly facilitated by Dr. C. Waller of Ilford Limited through provision of a supply of G5 gel. Appreciation is expressed to Dr. M. M. Shapiro for many helpful discussions of meson production mechanisms, and for providing space in the gondola on several balloon flights.

PHYSICAL REVIEW VOLUME 85, NUMBER 5 MARCH 1, 1952

Emulsion Cloud-Chamber Study of a High Energy Interaction in the Cosmic Radiation*

M. KAPLON, B. PETERS,† AND D. M. RITSON
University of Rochester, Rochester, New York
(Received November 16, 1951)

A new technique is described for studying high energy interactions utilizing photographic emulsions as detectors. A detailed study has been made with this technique of one very high energy mixed shower. Evidence is obtained for the multicore structure of the soft component at depths of several radiation lengths in this mixed shower, along with the existence of a finite lifetime for the decay of the neutral π-meson into two photons of the order of 1×10^{-14} sec.

HIGH energy nuclear interactions lead to the production of mixed showers of mesons, nucleons, and electronic components. Such interactions with energies above 10^{12} ev have been previously studied both by observing the resultant electronic and nucleonic cascades in Auger showers and by directly observing the primary interactions in the photographic emulsions. Observations on Auger showers are necessarily indirect. While on the other hand the photographic plate allows a detailed study of the primary interaction to be made as to distribution and multiplicity, the energies of the products cannot be determined, and the primary energy can only be approximately estimated from kinematic considerations. Hitherto, such events have very rarely been found and only in the course of random surveys.

We have made observations with a technique which allows a much more detailed study to be made of the interactions, and at the same time permits the events to be found with relative ease. The events are observed in a so-called emulsion cloud chamber consisting of alternate layers of photographic emulsions and absorber. An interaction in the stack starts a mixed shower. The plates near the interaction show just the charged mesons and nucleons formed in the primary interaction. Later in the stack the electronic component begins to multiply and form well-marked electronic cores. From these cores and their degree of multiplication can be determined the numbers, and energies of the neutral mesons resulting from the initial interaction. It is further possible to measure the lifetime of the neutral mesons from the finite path lengths they transverse at high energies. To find such an event, one of the emulsions in the emulsion cloud chamber is scanned for high energy electronic cores. If the plates are well aligned it is possible to predict the position of a core in succeeding and preceding plates and thus trace the event back to the first plate in which it appears; this plate is usually near the origin of the shower and the tracks reproject back to the point of origin.

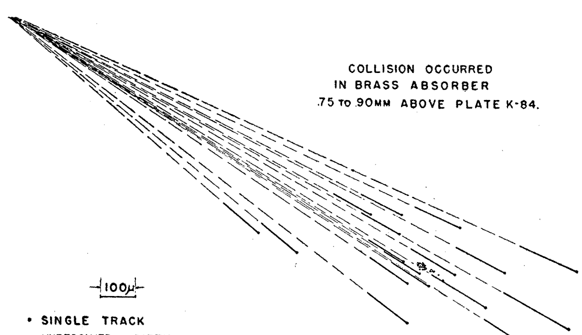

FIG. 1. Target diagram of hard shower in first plate (plate 8) showing reprojection of tracks to a common origin.

One important advantage of this technique over cloud-chamber techniques is the high resolution of the photographic plate in which tracks are resolved within $\frac{1}{2}\mu$ and cores of electronic showers can be resolved which would completely "swamp" a cloud chamber and permit no detailed structure to be discernible.

The energy range for which the technique is applicable depends on the material of which the stack is constructed. The core of an electronic shower does not show above the background of random tracks in the experiment described below unless its energy is in excess of 10^{11} ev. If we had used a stack exclusively of photographic plates, this limit would have been about 5×10^{12} ev; with high Z materials the limit would have been as low as 10^{10} ev.

* This work was supported by the AEC.
† Now at Tata Institute, Bombay, India.

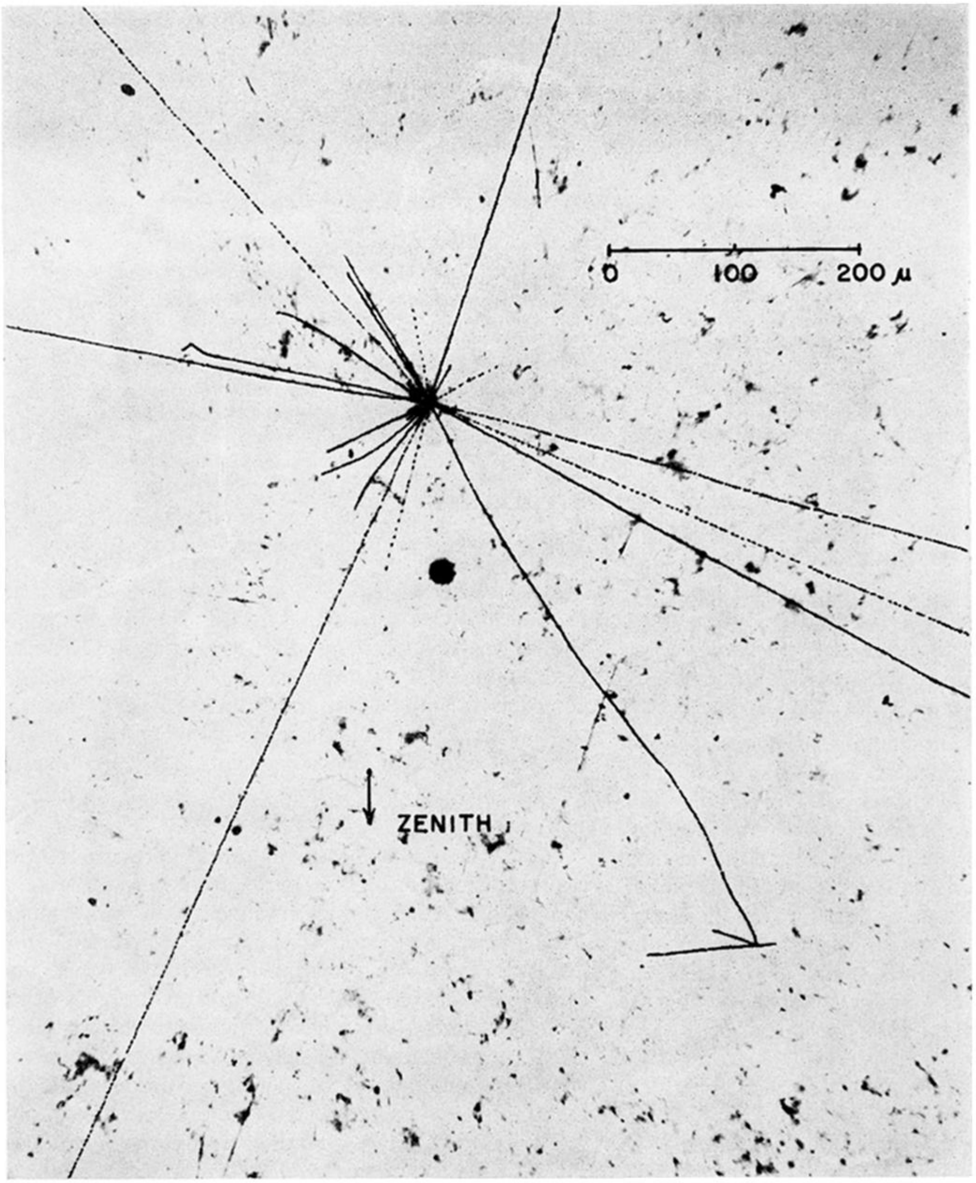

FIG. 1. Disruption of a heavy emulsion nucleus accompanied by the ejection of a 4.2-Mev π^- meson which is captured at the end of its range with the formation of a 3-prong star.

All the star illustrations are photodrawings prepared by inking pertinent detail on an enlargement print from a low power photomicrograph. The grain densities of the tracks are not perfect facsimiles of the original developed structures.

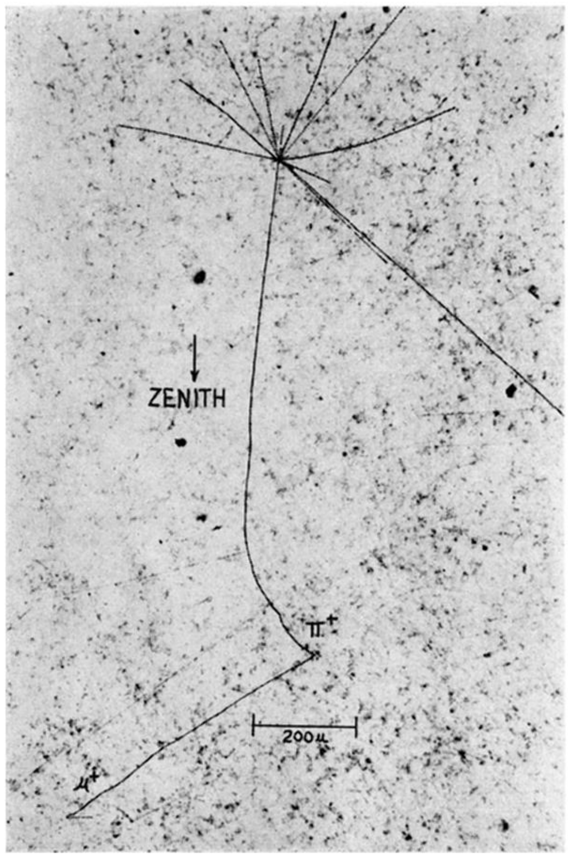

FIG. 2. Star showing the ejection of a 6.3-Mev π^+ meson which comes to rest in the emulsion and undergoes π-μ decay. The electron track from the decay of the μ^+ particle is recorded at a steep angle and appears of high grain density in the horizontal projection.

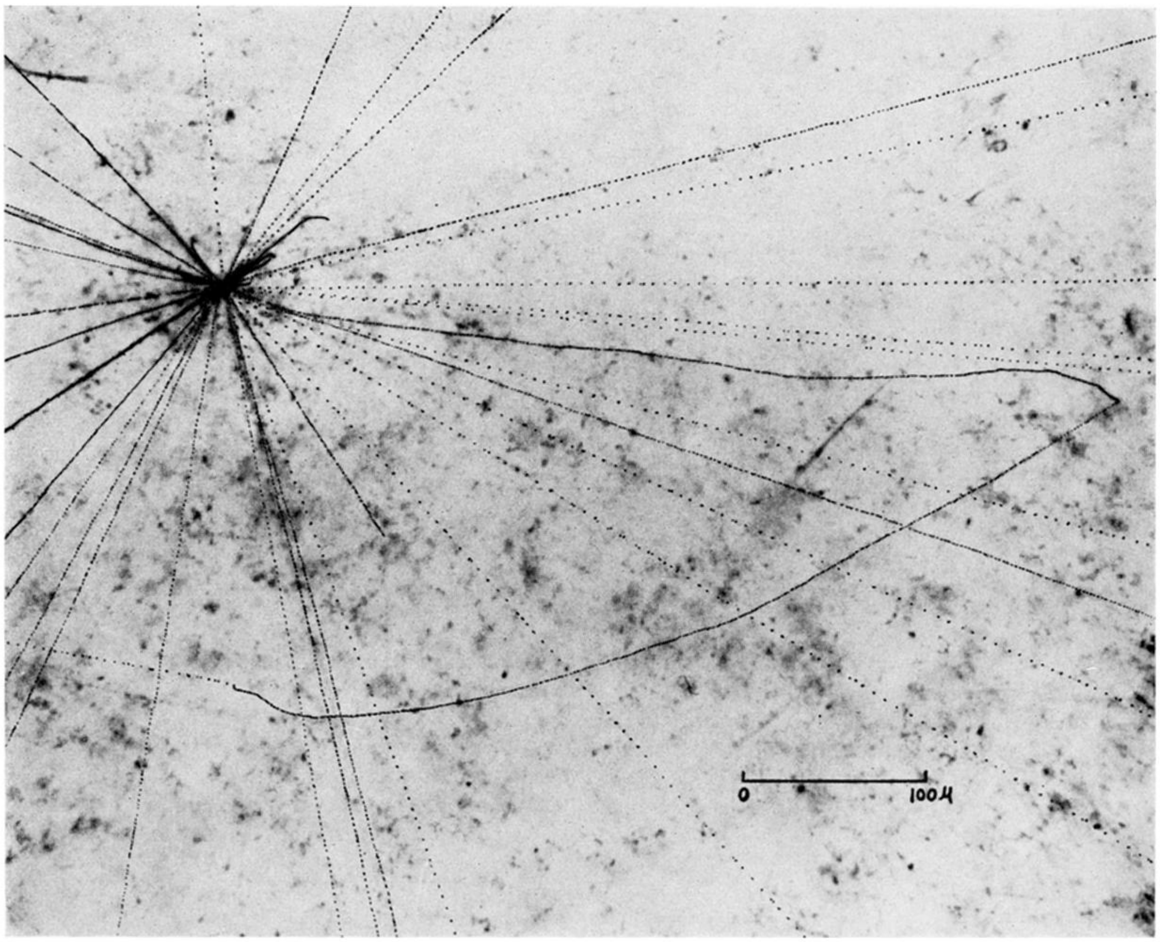

FIG. 5. Emission of a slow π^+ particle in the disruption of a heavy nucleus. The ejected meson has a kinetic energy of 4 Mev, a value markedly smaller than that imposed by the Coulomb barrier of silver or bromine nuclei. While apparently emerging in the same direction as the fast shower particles, it is probably a member of an independent group of slow mesons.

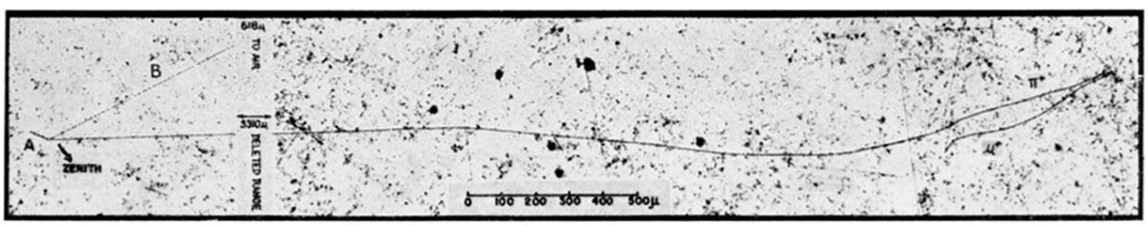

FIG. 8. Interaction exhibiting the emission of an 18.5-Mev π^+ meson, associated with a black track A and a gray track B. The latter leaves the emulsion after traversing 1300 microns without an appreciable change in grain density (less than 4× minimum); its specific ionization is indicative of either a 47-Mev pion, or a 300-Mev proton. The short black track also leaves the emulsion at a steep angle and its charge is not determinant.

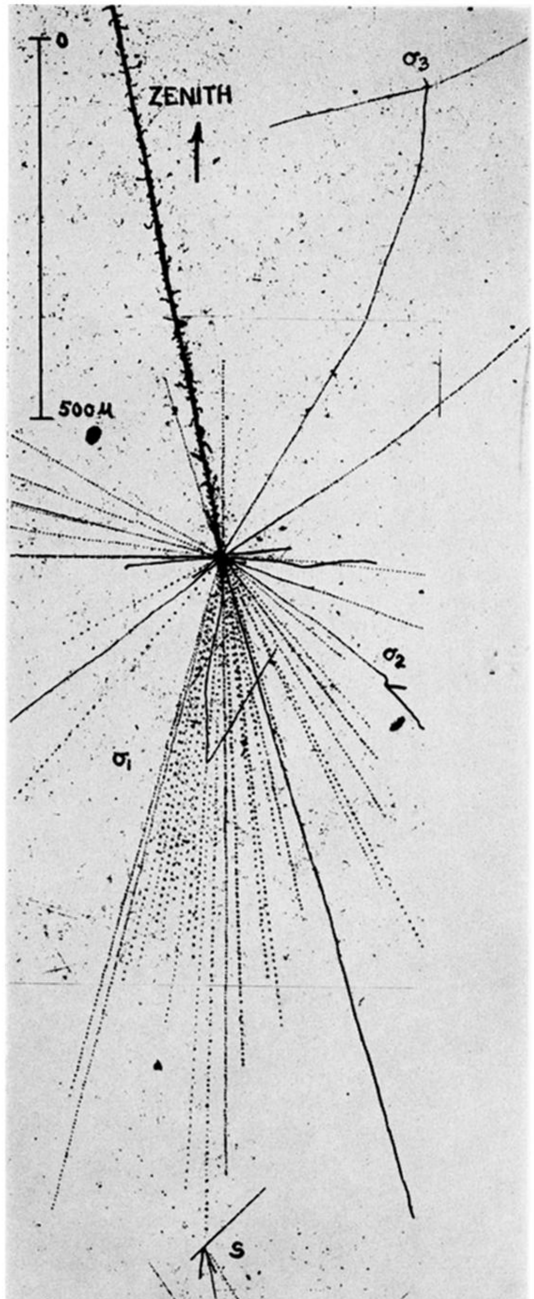

FIG. 9. Giant star initiated by a heavy primary of estimated charge 11±1, constituted of 31 black and gray tracks and about 30 relativistic particles, the latter collimated in a broom of 52° angular spread. One of the fast shower particles is captured in flight and produces a 7-prong star *S*. In this interaction of the incident particle with a heavy nucleus, possibly silver, three slow mesons are also ejected with energies of $\sigma_1=3$ Mev, $\sigma_2=4.9$ Mev, and $\sigma_3=8.2$ Mev. The slow mesons emerge over an angular spread of 155° and their axis is at an angle of 90° with that of the fast shower.

A number of tracks, directed at large angles with the emulsion plane, have been omitted from the horizontal projection of the event.