mately Gaussian with a mean square fluctuation given by

$$\langle (X-X_0)^2\rangle_{\text{Av}}=\int_{E_1}^{E_2}\frac{4\pi e^4 NZ}{(dE/dx)^3}dE, \qquad \text{(A3)}$$

where e is the electronic charge, N is the number of atoms per cm^3 of absorber, Z is the number of electrons per atom that are effective in the ionization process, and $-dE/dx$ is the rate of energy loss of the pion at the energy E. Using Eq. (A3) the rms spread in range due to this Gaussian straggling was calculated to be $[\langle (R-R_0)^2\rangle_{\text{Av}}]^{\frac{1}{2}}=1.54$ g/cm^2 of copper.

Taking into account the multiple scattering and straggling effects discussed above and assuming that the distribution in true range of the incident beam was approximately Gaussian, the rms spread in range was estimated from the rms spread observed in the counter range curve, which was ± 4.5 g/cm^2 of copper. The mean range was taken to be the mean measured range plus the mean shortening due to multiple scattering. The resulting range of the incident beam was 124.4 ± 3.4 g/cm^2 of copper. There was also an estimated uncertainty of about 1.5 g/cm^2 of copper in the value of the mean range.

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Disintegrations Produced in Nuclear Emulsions by 1.5-Bev Negative Pions*

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The stars produced in nuclear emulsions by 1.5-Bev π^- mesons are analyzed. The numbers of stars as a function of the numbers of prongs are obtained and compared with stars produced by protons of similar energies. The angular distributions of prongs from the pion-produced stars are also derived. An example of the decay of a hyperfragment He^{5*} emerging from a pion star is described and the production of K particles by 1.5-Bev pions is noted.

FOLLOWING the Brookhaven cloud-chamber experiments[1] in which hyperons and a K particle were observed to be produced by 1.5-Bev pions, nuclear emulsions were exposed to high-energy negative pions from the Cosmotron. On account of the low intensity of pions ($\sim$1.5 per cm^2 per pulse) available at that time it was found necessary to irradiate the emulsions for a protracted period, and because of the high intensity of background radiation present it was found essential to have a clean pion beam and very good shielding of the emulsions. In the present experiment, stacks of 24 strips of 400μ G5 emulsions were irradiated in a 10-ton lead house at the end of a collimator 4 feet long. The total pion intensity in the emulsions was approximately 20 000 per cm^2. A preliminary report[2] of some of the results of scanning these emulsions has been given. Approximately 9 cc of emulsion in all were area-scanned by the three groups (B. N. L., M. I. T., and Rochester) analyzing these emulsions. Although a few K particles were observed, these experiments were not fruitful in producing observable K-particle endings within the emulsions. The results of the experiments which will be given here include, in addition to the heavy mesons, information on pion-produced stars and several hyperfragments emitted from pion stars.

PRONG DISTRIBUTIONS OF π-PRODUCED STARS

The population of π-produced stars in the emulsions can be gauged from the following details of area scanning by one group of observers. In 2.9 cc of emulsion (54.8 cm^2 of 400μ strips), 716 π-produced stars were observed, as compared with 740 neutron-produced stars.

In a sample of 75 π-produced stars, the numbers of stars as a function of the prong-number of the stars are given in Fig. 1. Also shown on the same plot and normalized to the same total number of stars, are distributions of prong numbers for 2.2-Bev protons[3] and 0.95-Bev protons.[4] It appears that the prong distribution for π-produced stars is not significantly different from that for proton stars; the 1.5-Bev π-produced star distribution lies approximately mid-

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2 Hill, Salant, Widgoff, Osborne, Pevsner, Ritson, Crussard, and Walker, Phys. Rev. **94**, 797 (1954).
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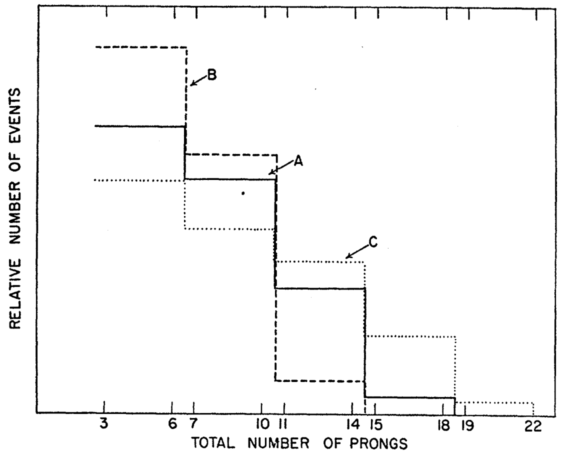

FIG. 1. Number of stars *vs* number of prongs: A, 1.5-Bev pion-produced stars, sample 75 stars; B, 0.95-Bev proton stars, sample 181 stars, reference (4); C, 2.2-Bev proton stars, sample 294 stars, reference (3). All histograms are normalized to the same total number of events.

way between the 1- and the 2-Bev proton-star distributions.

In Fig. 2, the sample of 75 π-produced stars is broken down into three classes with zero, one, and two outgoing minimum or near-minimum ($g<1.25\ g_{\mathrm{min}}$) tracks. As might be expected, there are relatively fewer stars of one and two outgoing shower particles, and the latter stars have a lower total number of prongs. In the case of 2.2-Bev protons,[3] 55% of the proton stars had at least one light outgoing track. For 1.5-Bev pions this same group is only 32% of the total number of π-produced stars.

The angular distributions of the tracks emerging from π-produced stars are shown in Fig. 3. The tracks have been separated into three categories according as $g>4g_{\mathrm{min}}$ (black prongs), $4g_{\mathrm{min}}>g>1.25g_{\mathrm{min}}$ (grey prongs), and $g<1.25g_{\mathrm{min}}$ (minimum prongs). After applying a correction factor for the solid angle contained between the angles of projection, it is clear that the distribution of black prongs is consistent with an isotropic angular emergence. The distributions of grey and minimum tracks, however, indicate a strongly forward angular emergence. This is further supported by the plot in Fig. 4 of center-of-mass angles of emission of pions from small stars (number of heavy prongs <5). The transformation to the center-of-mass angles was made under the assumption that a single nucleon collision with the incident pion occurred. The distribution, which is characteristic of both elastic and inelastic processes,[5] is clearly peaked in the forward direction.

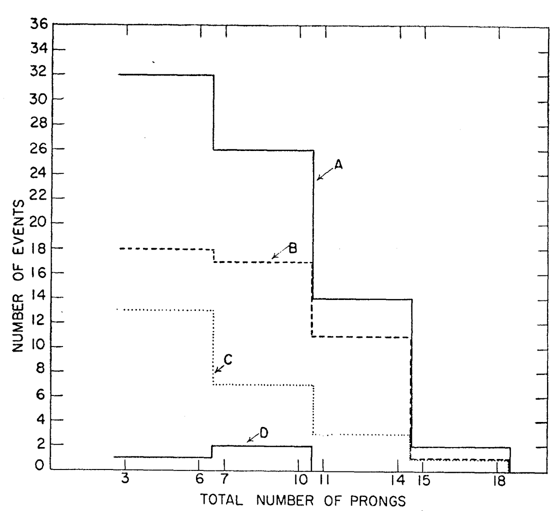

FIG. 2. Number of 1.5-Bev pion-produced stars *vs* number of prongs, for different types of stars: B, zero outgoing shower particles; C, one outgoing shower particle; D, two outgoing shower particles; A, stars of all outgoing-prong types.

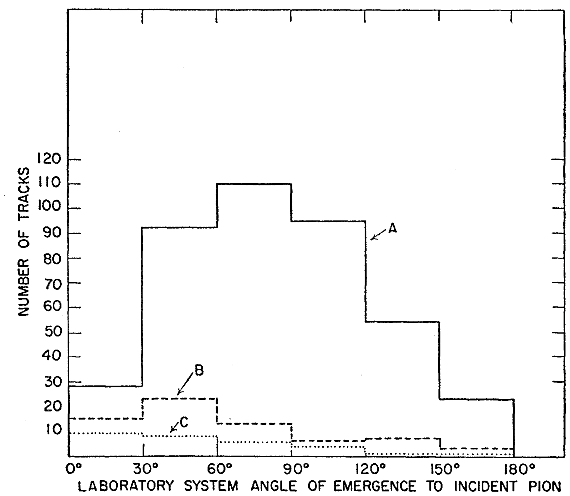

FIG. 3. Angular distributions of tracks emerging from 1.5-Bev pion-produced stars: A, outgoing black tracks; B, outgoing grey tracks; C, outgoing minimum tracks.

As might be expected (from their lower momentum and lower kinetic energy), however, the forward-to-backward ratio of light and grey prongs is not as high in the case of π-produced stars as it is in the case of proton stars. In the case of the 2.2-Bev proton stars,[3] it was found that for light tracks the forward-to-backward ratio was 16:1 and for grey tracks this ratio was 10:1. For the 1.5-Bev π-produced stars the same ratios are only 3.8:1 and 3.2:1, respectively.

HYPERFRAGMENTS

A. Mesonic Decay of Hyper-He[5]

A microprojection diagram of the event is shown in Fig. 5. The incoming 1.5-Bev π^- meson from the beam makes a primary star of four black prongs, one grey prong, and one minimum-ionizing prong. One of the black prongs appears to stop and gives rise to a secondary three-prong star.

[5] W. D. Walker and J. Crussard, Phys. Rev. 98, 1416 (1955).

The black track connecting the stars has a length of 262μ. It is thicker than a stopping proton of similar dip in the same emulsion strip. The track shows two δ rays of length $>1\mu$. This number is normal for a helium particle. A lithium fragment of this range would show an average of ten such δ rays.[6]

The characteristics of the secondary star are given in Table I. Track 1 has been followed through eight emulsions, a total length of 5950μ, before it escapes from the stack. Its grain density, g, referred to plateau grain density, g', measured in three different emulsions is: first emulsion, $g=(2.2\pm0.16)g'$; seventh emulsion, $g=(2.8\pm0.18)g'$; eighth emulsion, $g=(2.9\pm0.2)g'$. The scattering of track 1 in the seventh emulsion, where distortion was practically negligible, gave $p\beta=33\pm7$ Mev/c. The mass of the particle, calculated from scattering-ionization in the seventh emulsion, is $m=(265\pm70)m_e$, and from grain density variation *vs* range in emulsions 1–8 is $m=(275\pm60)m_e$. Track 1 is therefore ascribed to a π meson and its initial energy deduced from grain density measurements is (25.4 ± 0.7) Mev; the corresponding momentum is (88 ± 1.3) Mev/c.[7]

TABLE I. Characteristics of secondary star caused by hyper-He^5.

Prong number	Projected angle with track 1	Angle of dip	Range (μ)	Identification
1	0°	$-32°\pm2°$	5950 (escapes)	π^- meson
2	$74°\pm1°$	$-16°\pm1°$	198 (ends)	proton
3	$136°\pm2°$	$+24°\pm6°$	12.5 ± 1.5 (ends)	He^4

Track 2, as judged from its appearance, is due to a particle of unit charge. If it is a proton, from its range, it has an energy of 5.48 Mev and an initial momentum of 101.5 Mev/c.[7] If track 1 is a π^- meson and the hyperfragment has charge 2, then track 3 also has charge 2. No beta decay at the end of track 3 is observed and, from momentum balance, it will be shown that it is very probable that track 3 is due to a He^4 particle. If it is assumed that track 3 arises from He^4 the initial momentum is 161.0 Mev/c.[6,8]

From the measured angles of Table I it can be readily shown that the three tracks are very nearly coplanar. However, accurate coplanarity of the three tracks can be gained by allowing the angle of dip of track 3, which is the least accurately measured of all angular quantities, to be 28° instead of 24°. This deviation is well within the limiting accuracy of the measurement. The space angles between the three tracks are then: tracks 1–2, 65.7°; tracks 2–3, 147.6°; tracks 3–1, 146.8°. From the observed momenta of the pion and proton, the resolved momentum in the direction of the He recoil is then 159 ± 8 Mev/c, in excellent agreement with the observed value of 161 ± 8 Mev/c for an assumed He^4 recoil. For a He^3 recoil, the observed initial momentum would be only 135 ± 6 Mev/c.[6,8] The momenta of pion and proton transverse to the He recoil are 48.2 and 54.1 Mev/c, respectively, and are therefore reasonably well balanced. There seems little doubt but that the three particles emitted from the hyperfragment are pion, proton, and He^4 and that these particles represent all that are emitted.[9]

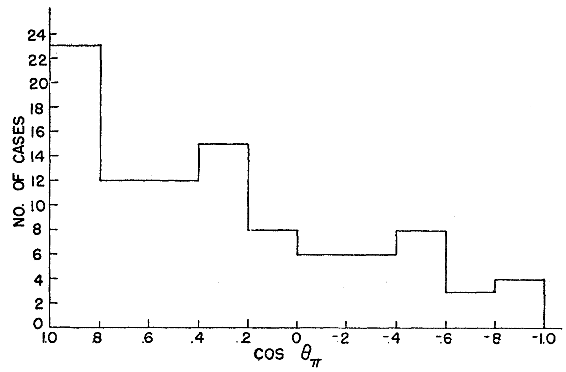

FIG. 4. Angular distribution, in the center-of-mass system, of singly emergent pion tracks from small stars produced by 1.5-Bev pions.

The total kinetic energy of particles 1, 2, and 3 of the hyperfragment decay assuming the above scheme is (34.4 ± 1.0) Mev. If the hyper-He^5 fragment is assumed to contain a bound Λ^0 having a Q value of (36.9 ± 0.2) Mev,[10] then the binding energy of the Λ^0 in He^{5*} is (2.5 ± 1.3) Mev. The observed time of flight of the hyperfragment is of the order 10^{-11} sec. It is of interest to point out that the present interpretation, unlike that given earlier,[2] of the hyperfragment being He^{5*} is entirely consistent with the existence arguments of hyperfragments recently put forward by Dalitz.[11] The binding energy of the Λ^0 in He^{5*} obtained in the present case is in excellent agreement with the value of

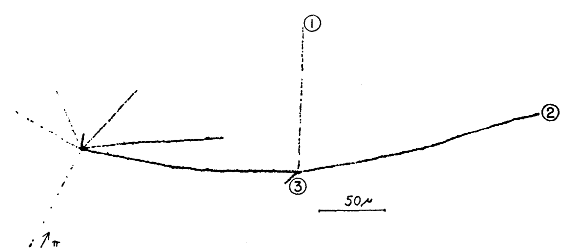

FIG. 5. Decay of ${}_2He^{5*}$ hyperfragment ejected from a 6-prong star produced by 1.5-Bev pion.

[6] J. Crussard, thesis, Paris, 1952 (unpublished).

[7] Fay, Gottstein, and Hain, Nuovo cimento **11**, Suppl. 2, 234 (1954).

[8] W. H. Barkas, Phys. Rev. **89**, 1019 (1953); Barkas and Young, University of California Radiation Laboratory Report UCRL 2579 (unpublished).

[9] If one were to consider that the possibility of the hyperfragment being a singly-charged ${}_1H^{4*}$ was not yet ruled out and that the decay took place according to the reaction: ${}_1H^{4*}\rightarrow\pi^-+p+{}_1H^3$, then the range of the ${}_1H^3$ recoil balancing π^- and p momenta would have to be 78μ.

[10] Report of Padua Conference, Nuovo cimento **12**, Suppl. 2, 461 (1954).

[11] R. H. Dalitz, Phys. Rev. **99**, 1475 (1955).

TABLE II. Characteristics of three connected stars.

Primary star	Length of connecting track (μ)	Secondary star (black prongs)	Total visible energy secondary star (Mev)
4 black prongs, 1 grey prong	5	3	10–20
3 black prongs, 1 grey prong	2–3	5	30
6 black prongs	4	5	50

2.1 ± 1.0 Mev for a similar case reported recently at the Pisa Conference.[12]

B. Nonmesonic Decay of Other Hyperfragments

Three other cases of "double stars" were observed, in which the incoming 1.5-Bev π^- meson made a primary star connected to a secondary star by a short black prong. The three secondary stars show only black prongs (evaporation particles). The characteristics of these stars are given in Table II. Except in the first event, in which the connecting track has the appearance of a short thin-down track, the secondary stars could be capture stars of very slow outgoing π^- mesons. However, from the observations of Fry, Schneps, and Swami,[13] it is much more likely that these very short tracks represent the decay of excited fragments. These nuclei can be rather heavy and it is not surprising that they show non-mesonic decay.[14]

K PARTICLES

In the 9 cm³ of emulsion area scanned, two stopping K^+ mesons were observed. One K meson had its origin outside the emulsion stack and traveled 11 mm before decaying into a near-minimum ionizing secondary particle. The other K meson emerged from a 9-pronged 1.5-Bev π star at an angle of approximately 172° to the direction of the incident pion. This K particle travelled 8 mm in the one emulsion strip before decaying into a near-minimum secondary particle.

In the light of later experience with the production of K particles using 2- and 3-Bev proton bombardment,[15] it is of interest to compare the K-particle production rates for pion and proton bombardments. In the case of proton bombardments, it was found that on the average approximately one K-particle decay was observed per 400 observed π mesons that ended in the emulsion. In the case of the present pion bombardment, two K mesons were observed per 700 π-meson endings, so that the intensity of K mesons observed on this basis of measurement is not in disagreement with the proton bombardments. The difference in the proton and pion experiments, however, was in the efficiency of finding the K particles. The areas (and volumes) of emulsion scanned in both proton and pion experiments were approximately the same (157 cm² and $\sim$170 cm², respectively), yet only two K mesons were observed in the pion experiment as compared with twelve in the proton case. To a large extent this difference was attributable to the lower pion intensity available and to the fact that compensatingly longer exposures could not be made because of the high background of radiations present.

ACKNOWLEDGMENTS

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[12] Crussard, Fouché, Kayas, Leprince-Ringuet, Morellet, Renard, and Trembley, Report of Pisa Conference, 1955 (unpublished).
[13] Fry, Schneps, and Swami, Phys. Rev. **97**, 1189 (1955).
[14] W. Cheston and H. Primakoff, Phys. Rev. **92**, 1537 (1953).
[15] Hill, Salant, and Widgoff, Phys. Rev. **99**, 229 (1955).