Interactions of Negative K Mesons*

J. HORNBOSTEL AND E. O. SALANT
Brookhaven National Laboratory, Upton, New York

(Received January 13, 1956)

A detailed analysis of events in nuclear emulsions caused by K^- mesons is given. Of 39 K^- mesons observed, 8 produced stars in flight, 1 underwent nuclear scattering, and 30 were captured at rest. The K^- mean free path for inelastic collisions in emulsion is 17 ± 5 cm, at most geometric. Charged hyperons and hyperfragments were seen in 12 stars; in all others, emission of a neutral hyperon is allowed by energy balance. In $\frac{2}{3}$ of the stars, a charged pion was emitted; half of the pions had kinetic energy $\geqslant 100$ Mev. 3 stars consisted only of a Σ hyperon and a pion, of such momenta as to make it obvious that K^- capture proceeded according to: $K^-+N\rightarrow Y+\pi$. Kinematic analysis shows that this reaction was the most likely process in almost all of the other captures. In 5 of the captures at rest, the pion energies were $\geqslant 100$ Mev, compatible only with $Y=\Lambda^0$. One K^- capture reaction (and possibly a few more) was: $K^-+2N\rightarrow Y+N$. In this one capture, the hyperon is either $\Sigma^\pm$ decaying by an unusual mode, possibly into an electron, or else is a hitherto unknown particle.

A. INTRODUCTION

STUDIES of negative K mesons, produced by proton bombardment of targets in the Cosmotron and detected with nuclear emulsions, have been reported for some time.[1–5] Continued examination of the same emulsions revealed a total of 39 K^- mesons; their interactions and the resulting secondaries are described in the present paper.

Attention is called to two particular features reported for the previously observed K^- captures[2,3]: (1) the appearance, in some of the disintegrations, of charged hyperparticles, a name we use to include both hyperons and hyperfragments, and (2) in the other disintegrations, an excess of K rest energy over visible star energy sufficient for creation of a neutral hyperon.

It will be seen that both of these features persist as characteristics of the more extended series of K^- captures discussed further on. Consequently, all events in this series can be described by simple reactions involving production of a hyperparticle. This situation is in accord with theory,[6] which requires creation of a hyperon, free or bound, in nuclear capture of a negative K meson. It should be noted, however, that the actual formation of a neutral hyperon is not proven by the fact that such formation is energetically possible.

B. EXPERIMENTAL ARRANGEMENT AND PROCEDURE

A sketch of the experimental arrangement, viewed from above, is shown in Fig. 1.

The circulating proton beam P of the Cosmotron strikes a fixed beryllium target T ($\frac{1}{2}$ in. high, 8 in. long, and $\frac{3}{8}$ in. thick) which is supported by the structure S. The beam of negative secondaries B, emitted at $4°\pm3°$ to P, is deflected outwards and analyzed by the magnetic field of the accelerator. It passes through the thin window W ($\frac{1}{16}$ in. aluminum) in the wall of the Cosmotron's vacuum chamber V and down a collimating channel C ($\frac{1}{4}$ in. high by 1 in. wide by 18 in. long) in a lead housing H. After leaving the collimator, the beam traverses the homogeneous field F (10 000 gauss, 10 in. long) of an electromagnet M and enters the stack of stripped emulsions E through their leading edge L. The target-to-emulsion path is 2.7 meters, of which 1.1 meters are inside the Cosmotron. Stacks were aligned so that the beam B entered parallel to the emulsion faces and normal to L.

The proton-beam energy was 2.8 Bev, and the momentum of the particles of beam B was 313 ± 3 Mev/c,[4] corresponding to a kinetic energy of 203 Mev for pions and of 91 Mev for K mesons. The K mesons travel from target to stack in a proper time of 1.4×10^{-8} sec.

During each exposure, the intensity of the proton beam was recorded by the circulating beam monitor of the Cosmotron. An exposure was limited to about 10^{13} protons, as it was found that heavier bombardments resulted in too high a track density in the emulsions. Such an exposure lasted about an hour.

The emulsions used were Ilford G5,400 microns, 2 in. by 3 in., strips. Two stacks were exposed, one of 24 and one of 36 strips.

The stacks were compressed and marked with x-ray spots for alignment. Development, by the conventional variable temperature method, was complete within 11 days after exposure. The glass plates on which the strips were mounted were cut so that the relative displacement

* Work performed under the auspices of the U. S. Atomic Energy Commission.

[1] J. Hornbostel and E. O. Salant, Phys. Rev. **93**, 902 (1954).
[2] J. Hornbostel and E. O. Salant, Phys. Rev. **98**, 218 (1955).
[3] J. Hornbostel and E. O. Salant, Phys. Rev. **98**, 1202 (1955).
[4] J. Hornbostel and E. O. Salant, Phys. Rev. **99**, 338 (1955).
[5] Hill, Salant, and Widgoff, Phys. Rev. **94**, 1794 (1954).
[6] A. Pais, Phys. Rev. **86**, 663 (1952); M. Gell-Mann, Phys. Rev. **92**, 833 (1953); A. Pais, Physica **19**, 869 (1953); T. Nakano and K. Nishijima, Progr. Theoret. Phys. (Japan) **10**, 581 (1953); M. Gell-Mann and A. Pais, *Proceedings of the 1954 Glasgow Conference on Nuclear and Meson Physics* (Pergamon Press, London, 1955); R. G. Sachs, Phys. Rev. **99**, 1573 (1955); M. Goldhaber, Phys. Rev. **101**, 433 (1956); the application of the theory to K^- captures observed in emulsion is discussed by Friedlander, Fujimoto, Keefe, and Menon, Nuovo cimento **2**, 90 (1955).

of tracks in adjacent plates was no more than about 0.1 mm.

Since the beam was narrowly defined ($\pm 1°$ even after scattering by a centimeter of emulsion), and since *K* particles of momentum 313 Mev/*c* have twice minimum grain density and are easily distinguished from the beam pions which traverse the stack near minimum ionization, the following procedure for scanning was adopted. Parallel to, and 7 mm from, the leading edge, each emulsion was scanned (with 600× magnification), and tracks lying within the beam and having the expected *K*-meson grain density were recorded. The scanning efficiency for these tracks, determined by rescanning several plates, was found to be 0.7. The acceptable limits of both track angle and grain density were chosen somewhat wider than necessary to reduce the chances of missing genuine *K* tracks. Any track satisfying the criteria of acceptance was then followed to its end in the stack or, sometimes, until its low-density gradient showed it was obviously a proton track. This scanning method has the obvious virtue of detecting with equal efficiency all types of K^- events, such as decays, interactions in flight and K_ρ mesons (mesons that stop without giving star prongs). About 1 out of 12 tracks followed was due to a K^- meson. (In the absence of the magnetic field *F*, contamination of the beam by protons ejected from the collimator walls increased this ratio to about 1:50, a number almost prohibitive for track scanning.) Although the plates had a heavy background of slow electrons and were crowded with all sorts of tracks (presumably from stars made by the pion beam), dark, and even light tracks could, with care, be followed unambiguously from plate to plate.

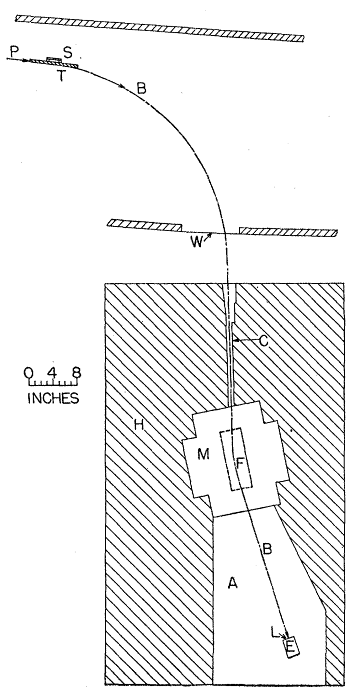

FIG. 1. Diagram of experimental arrangement. The proton beam *P* strikes the beryllium target *T* which is supported by the structure *S* in the Cosmotron's vacuum chamber *V*. From *T* is ejected the negative-particle beam *B*, which leaves *V* through the window *W*, passes down the collimator *C* in the lead housing *H*, is deflected between the pole pieces *F* of magnet *M*, and enters emulsion stack *E* through the leading edge *L*. *A* is a cavity in *H*.

All endings of tracks of *K* mesons (genuine or suspected) and of secondaries from *K* events were examined under high magnification (1400×) for light tracks.

Ionization measurements were made by grain counting. Minimum count g_0 was about 33 grains/100μ. To make the results as independent as possible of emulsion inhomogeneity, only relative grain counts g/g_0 were used; g_0 was established from the grain density of 200-Mev pion beam tracks in the immediate vicinity of the track being measured. Errors in g/g_0 include those of the calibration tracks as well as contributions from nonstatistical sources, such as errors in dip correction in steeper tracks, inaccuracy in grain-counting steep tracks, and possible variations in counting from day to day.

Grain-count—energy calibration was obtained from grain densities of 8 σ mesons, at residual ranges between 35 and 4 mm, corresponding to a g/g_0 interval of $1.4-3.0$.

To facilitate the fitting of a smooth curve to the points of the grain-count-range calibration and to aid interpolation between 1.0 g_0 and 1.4 g_0, ranges were correlated with the specific ionization *I* by means of the range-energy relation[7] (corrected to our emulsion density) and Aron's ionization curves for copper[8] (range-energy relations for copper and emulsions are very similar). In the interval $1.0 \leqslant g/g_0 \leqslant 2.5$, the graphs of g/g_0 as a function of I/I_0 turned out to be straight lines of almost the same slope in the two stacks. The grain count-energy relation derived from these graphs was used to find kinetic energies of particles which did not stop within the stack. Quoted energy errors include the uncertainty in that relation.

In measuring the scattering of stopping particles, 20μ cells were used for residual ranges below 0.2 mm, 50μ cells for the next millimeter, and 100μ cells for longer ranges. For tracks which did not end in the emulsion, 100μ cells were used.

C. IDENTIFICATION OF PARTICLES AND PARTICLE ENERGIES

Tracks of stopping *K* particles giving capture stars (K_σ mesons) were followed for an average distance of 37 mm. Allowing for the material traversed by the tracks before being picked up, this corresponds to an average total range of 45 mm (with a mean spread of ± 3 mm and an extreme spread of ± 6 mm), the range to be expected for particles of mass about 965 m_e and momentum 313 Mev/*c*. Identification of such particles was unambiguous, since pions of the same initial grain density (about 2.1 g_0) as the *K* particles would have a range of 10 mm, and pions of 37-mm range would have

[7] Baroni, Castagnoli, Cortini, Franzinetti, and Manfredini, CERN Bureau of Standards Bull. No. 9 (unpublished).

[8] Aron, Hoffman, and Williams, U. S. Atomic Energy Commission Report AECU-663 (unpublished).

an initial grain density of 1.4 times minimum. Events produced in flight by K mesons were separated from those due to protons by the requirement that both the initial grain density and the grain density change of the incoming track be the same as found for K_σ mesons. Identification was corroborated by scattering measurements of the K tracks. Frequently the character of the star (as when it included a fast pion or a hyperparticle) made the identification obvious. Identification of K mesons stopping without producing a prong (K_ρ) required special care. Accepted K_ρ mesons had to end within the range interval previously found for K_σ mesons, and their grain density had to agree with that of a K_σ meson remeasured the same day by the same observer. Identification was confirmed by multiple-scattering measurements.

The results of the analysis of the stars caused by K^- mesons are summarized in Table I. Of the nonending light tracks from K^- stars (Column 4), only two were flat enough to permit accurate determination of $p\beta$, which, together with the grain count, gave a particle mass of $(370\pm50)\ m_e$ in the one case (NK 24) and of $(330\pm50)\ m_e$ in the other (NK 17). Accordingly, these particles were identified as pions. In the other events, the measurements were consistent with a muon as well and, in some cases, with a fast electron. (The tracks cannot be ascribed to protons, as the energy of protons with such light tracks would have increased the star energy beyond the amount provided by the K^- particle.) In the analysis which follows, all light particles (including untabulated ones from hyperon decay, except in NK 4) have been assumed to be pions, and on that assumption their energies were obtained from the grain densities of their tracks.[9] Stopping pions (NK 21, 10) listed in Column 4 were identified by ionization-range measurements, and the character of their ending; their energies were obtained from their ranges.

The identity of dark prongs, Column 5, could be determined only in a few cases (especially noted in the table) where sufficient length and flatness of the track made possible scattering measurement or ionization estimate or both. In all other cases, tracks longer than 0.1 mm were assigned arbitrarily to protons, tracks 0.03 to 0.1 mm long to α particles, and shorter tracks to still heavier fragments. The lower range limits correspond roughly to the kinetic energies the particles must have to penetrate the potential barriers of the emulsion nuclei. The assignment results in approximately the usual 1:2 ratio of α particles to evaporation protons. Kinetic energies were determined according to the kind of particles and their ranges, except in few cases of nonstopping heavy particles, where the energy was found from the grain density. Binding energies were taken as 10 Mev for protons and 4 Mev for α particles. These values are intermediate between those appropriate to heavy and to light emulsion nuclei; the uncertainty introduced by ignorance of the nucleus involved is about 5 Mev per prong. Fragments longer than 0.01 mm were given 20 Mev for kinetic-plus-binding energy, a rough average for the lighter fragments of such range. For shorter tracks no energy estimate was made.

Hyperparticles, in Column 3, were identified by their decay or the characteristics of their interaction, and in part by measurements of their tracks; details will be discussed in the following section. Their kinetic energies were evaluated in the same way as for the stable heavy particles. In K^- capture, the energy needed for removal of a hyperon from a nucleus equals the difference between the total binding energies of the original and the final nuclei; hence that energy was taken equal to the nucleon binding energy. Similarly, binding energies of hyperfragments were obtained from the difference between the total binding energy of the original nucleus and the sum of the binding energies of the two final nuclei.

In some important cases, vector sums of the momenta of the charged particles (Column 6) were calculated from the particle identifications and kinetic energies given in Columns 3–5 and from the relevant angles.

The visible energies E_v in Column 7, which represent all the energy transferred to ionizing star particles in the K^- capture, are the sums of the following terms: kinetic energies of the particles in Columns 3–5, their binding energies, rest energy (139 Mev) of pions, and the difference between the rest energies of hyperon and nucleon (251 Mev for Σ, 176 Mev for Λ^0). The contribution from tracks less than 10μ long is indicated by a plus sign.

For events made by K mesons in flight, the kinetic energy T_K of the K meson at the star, in Column 2, was determined by grain count.

D. SUMMARY OF RESULTS

About 1 K^- meson was found per plate scanned. Of the 39 K^- mesons identified and listed in Table I, 24 gave stars at the end of their ranges, 6 were K_ρ mesons[10] (one of which ended in a blob), and 8 interacted in flight. In only one event (in which the K track left the emulsion) was nuclear scattering observed.

The number of K^- mesons, corrected for scanning efficiency, corresponded to a ratio of pion to K-meson flux in the emulsions of 1.6×10^4. If the K^- mesons have the same lifetime as that found for K^+ mesons, namely

[9] Pion energies were chosen to be less than the energy at minimum ionization. Observed greater-than-minimum grain densities could not correspond to energies in the range of the relativistic rise in ionization, because the resulting star energies would have exceeded the available energy.

[10] Such events were reported by S. von Friesen, Suppl. Nuovo cimento **12**, 273 (1954); Arkiv Fysik **8**, 305 (1954); Fry, Schneps, and Swami, Phys. Rev. **97**, 1189 (1955); Nuovo cimento **2**, 346 (1955); Chupp, Goldhaber, Goldhaber, and Webb, University of California Radiation Laboratory Report UCRL-3044 (unpublished).

TABLE I. Data of K^- interactions. For groups B, C, and D, the most probable reactions are listed. F refers to particles in flight, Yf refers to hyperfragments, f to stable fragments. Kinetic energies were determined from ranges, except as noted. Various methods used to identify particles or to eliminate some alternative identifications are indicated in footnotes.[a–j]

	1	2	3	4	5	6	7	8
Group	Event	K^- kinetic energy T_K Mev	Kinetic energies, Mev and identity of star particles: Hyperparticles	Pions[l]	Stable heavy prongs[m]	Residual momentum Mev/c	Visible star energy[q,r] E_v, Mev	Reaction
A	8		10, Σ^+ [a,b]	66 ± 7		60	476 ± 9	$K^-+p\rightarrow\Sigma^++\pi^-$
	1		34,[k] $\Sigma^\pm$ [a]	57 ± 6		170	491 ± 8	$K^-+p\rightarrow\Sigma^\pm+\pi^\mp$
	14F	74 ± 6	58, Σ^- [a,b,c]	100^{+60}_{-30}		86[p]	558^{+60}_{-30}	$K^-+p\rightarrow\Sigma^-+\pi^+$
B	25		3.5, Σ^- [a]		10,p; 8,p; 8,p	165	321 ± 20	$K^-+n\rightarrow\Sigma^-+\pi^0$
	4		125 ± 6, $Y^\pm$ [a,b,c]		11,p [b]	410	406 ± 12 [s]	$K^-+2N\rightarrow Y^\pm+n$
	5		{ 18, $_\Lambda H^4$ [a] or 10, Σ^- [a] }		8,α; 50,d[f]; 23,p[b]; 8,p		{ 359 ± 40 401 ± 27	$K^-+N\rightarrow Y+\pi^0$; π^0 scattered $K^-+N\rightarrow\Sigma^-+\pi$; π absorbed
	35F	40 ± 12	31, $_\Lambda H^4$ [a]		5,p; 13,α; ~45,p		327 ± 27	$K^-+N\rightarrow Y+\pi^0$; π^0 scattered
	12		Yf [a,d]		19,p; 12,p; 12,p; 13,p; 6,p		$288\pm20+$	$K^-+N\rightarrow Y+\pi^0$; π^0 scattered
	26		Yf [a,d]	41 ± 4	28,p[g]; 45,p[g]; 20, f		$469\pm15+$	$K^-+N\rightarrow Y+\pi^-$; π^- scattered
	23F	50 ± 8	Yf [a,d]		11,p; 66,p[g,h]; (22,p,?; 9,α,?)		$273+$; $(318+)$	$K^-+N\rightarrow Y+\pi^0$; π^0 scattered
	16F	70	Yf [a,d]	100^{+40}_{-20}	~40,p; (12,p)		$465^{+40}_{-22}+$; (487)	$K^-+N\rightarrow Y+\pi^-$
	21		Yf? [d]	13,π^- [a,c]	125[n]±8,p[c,i]; 80,d[j]; 28,p[c]; 9,p; f; f			$K^-+N\rightarrow Y+\pi^-$; π^- scattered
C	19 {		13,Σ^-[e]?	5; π^-[e]?	25,p; 12,α; 21,p; f	470	$226\pm12+$ $355\pm17+$	$K^-+n\rightarrow Y^0+\pi^-$; π^- scattered $K^-+N\rightarrow\Sigma^-+\pi$; π interacts
	17			74 ± 8	6,p	216	229 ± 10	$K^-+n\rightarrow\Sigma^0+\pi^-$
	28			~60	5,p		~214	$K^-+n\rightarrow\Sigma^0+\pi^-$
	24F	72 ± 6		66 ± 2			205 ± 2	$K^-+n\rightarrow\Sigma^0+\pi^-$
	2			100^{+50}_{-25}	20,p		269^{+50}_{-25}	$K^-+n\rightarrow\Lambda^0+\pi^-$
	3			120^{+70}_{-25}	f		$259+$	$K^-+n\rightarrow\Lambda^0+\pi^-$
	6			120^{+70}_{-25}	6,p; 14,α; 10,α; 10,α		321^{+70}_{-31}	$K^-+n\rightarrow\Lambda^0+\pi^-$; π^- scattered
	11			$\gtrsim100$	8,α; 6,p; 5,p; 20,f; f		$\gtrsim312+$	$K^-+n\rightarrow\Lambda^0+\pi^-$; π^- scattered
	13			100^{+40}_{-20}	20,f; 45,p		314^{+40}_{-22}	$K^-+n\rightarrow\Lambda^0+\pi^-$; π^- scattered
	9F	45 ± 5		100^{+40}_{-20}	7,p; 29,p		295^{+40}_{-22}	$K^-+n\rightarrow\Lambda^0+\pi^-$
	10			11.5,π^- [a,c]	103[n]±5,p[c]; 32,t[f]		320 ± 16	$K^-+n\rightarrow\Lambda^0+\pi^-$; π^- scattered
D	29				180 ± 20[n],p[c,i]; 33,p[h]	376 ± 42	233 ± 23	{ $K^-+p+p\rightarrow\Lambda^0+p$ $K^-+N\rightarrow\Lambda^0+\pi$; π absorbed
	15				20,f; 14,α; 8,p; 5,p; 18,p[b]; 4,p		113 ± 24	$K^-+p\rightarrow Y^0+\pi^0$; π^0 scattered
	7				40,p[g]; 12,p; 14,α		90 ± 12	$K^-+p\rightarrow Y^0+\pi^0$; π^0 scattered
	18				11,α; ~7,p; ~10,p		~52	$K^-+p\rightarrow Y^0+\pi^0$
	20				24,p; ~7,p; f		~51+	$K^-+p\rightarrow Y^0+\pi^0$
	22				~50,p[g]; 4,p		~74	$K^-+p\rightarrow Y^0+\pi^0$; π^0 scattered
	27				f; f		+	$K^-+p\rightarrow Y^0+\pi^0$
	31F	58 ± 4			11,α; 10,α; 45,p[c]; 5,p		99 ± 14	$K^-+p\rightarrow Y^0+\pi^0$; π^0 scattered
	34F	56 ± 3			14,p		24 ± 5	$K^-+p\rightarrow Y^0+\pi^0$
	36				Blob			$K^-+p\rightarrow Y^0+\pi^0$
	30,32, 37,38, 39							$K^-+p\rightarrow Y^0+\pi^0$
E	33F	58; 76			K			2 elastic scatterings

[a] Termination. [b] $(\bar{\alpha}R)$. [c] Ionization-range. [d] See Sec. E of text. [e] Blob at end, π^- or Σ^-. [f] $(\bar{\alpha}R)$, p or t not excluded. [g] Ionization-range, d not excluded.
[h] $(\bar{\alpha}R)$, d not excluded. [i] Energy balance. [j] Ionization-range, t not excluded.
[k] Kinetic energy determined from $\bar{\alpha}$.
[l] See Sec. C of text for arguments regarding identification.
[m] Prongs listed in parentheses could belong to either K^- star or to hyperfragment.
[n] Kinetic energy determined from ionization.
[p] K^- momentum subtracted.
[q] Visible energies in parentheses include the energies of the prongs listed in parentheses.
[r] For entries in which + is appended, an unknown small amount is to be added for fragment energy.
[s] Evaluated for $Y^\pm=\Sigma^\pm$.

$\sim 1.2\times 10^{-8}$ sec,[11] then the π^- to K^- ratio at the target (for the emission angle and momentum used in these exposures) is 6×10^3. The pion flux, $2.3\times 10^5/\text{cm}^2$, was evaluated by counting the minimum tracks in the beam. That these were practically all pion tracks was verified by counting stars caused by the beam particles; the number of these stars corresponded to that expected from the beam flux and from the pion star cross sections measured by Morrish.[12]

In two additional stars made in flight, the grain count of the incoming track was slightly outside the limits of acceptance set for K mesons, and the same was true for two additional K_ρ tracks. These events were not further considered except in the evaluation of the K-meson mean free path, where they were classified as doubtful and given one-half statistical weight.

From the number of stars made in flight, $8+(2/2)=9$, the total number of K-particles, $39+(4/2)=41$, and from the average track length of 3.7 cm followed for a stopping K particle, a mean free path of $(41/9)\times 3.7$ cm $=17\pm 5$ cm was found.[13] This agrees with the emulsion geometric mean free path of 25 cm. It follows that K^- particles of energies between $\sim$15 Mev and $\sim$80 Mev are strongly interacting.

The stars had from 1 to 6 prongs. Most of the prongs were heavy, but in 14 stars there was a light track, $1.1-1.6\ g_0$ (Table I, Column 4), ascribed to a pion (see Sec. C). Of these pions, 8 had kinetic energies $\geqslant 100$ Mev and 6 had energies between 40 and 80 Mev. Column 4 lists, in addition, 2 (and possibly a third, in *NK* 19) low-energy negative pions that made dark tracks and stopped in the stack.

The most interesting heavy particles emitted in K^- captures were hyperparticles, established in 12 stars. One of these was Σ^+, two were Σ^-, one was a charged Σ of undetermined sign, one was either Σ^- or a hyperfragment, one was ${}_\Lambda H^4$, and one was an unusual hyperon, possibly a $\Sigma^\pm$ decaying into an electron. From one star came a track due either to a π^- or to a Σ^-. From 5 additional K^--capture stars, of which 4 appeared double-centered, a hyperfragment was emitted. It is, of course, possible that in a few cases a Σ^- was captured without emission of a charged particle and so escaped detection. Actual and potential flight times of hyperparticles are given in Table II.

Referring to Table I, each of the 3 events in Group A has a hyperon, a pion, and no other track. In Group B are 9 events with hyperparticles as well as stable heavy prongs and, in 4 cases, with pions. Group C contains 11 stars with pions and no visible hyperparticles, and Group D contains 15 events with neither a hyperparticle track nor a pion track.

It is noteworthy that, while in 4 of the K stars produced in flight a hyperparticle was created, one process permitted by theory, namely, the inelastic scattering of the K^- meson, was not observed[14] and may be said to occur infrequently. Charge exchange scattering ($K^-\rightarrow\bar{\theta}^0$) could possibly have occurred only in the one event (*NK* 34) where the visible star energy is less than the kinetic energy of the K meson. However, K^- mesons, being strongly interacting, could undergo more than one collision in a nucleus. Scattering could, therefore, compete with absorption more strongly in K^--nucleon than in K^--nucleus interactions.

E. SPECIAL EVENTS

(1) Events 1, 8, 14

These three events are quite similar. Each has a fast pion, a charged hyperon, and no other prongs. In each the residual momentum is low, and the visible energy approximately equals the available energy (493 Mev).[15] It follows, then, that, except possibly for an evaporation neutron, no neutral particle could have been emitted. If these three events were due to the capture of the K^- in a light nucleus, an assumption favored by the abscene of stable particles, then the visible energies would be higher by about 5 Mev than the values given in Table I.

Details of events 1 and 8 have been previously reported.[2]

In event No. 14, Fig. 2, star S was produced by a K^- meson in flight (track 1). The light track 5 is so steep that only an approximate grain count could be obtained. The hyperparticle 2, after traveling 9.8 mm in the emulsions, produces a star at P. The star is composed of a 12μ prong 3 and a 1.1-mm prong 4 which, from its multiple scattering, is due probably to an α particle of 60 Mev. Track 2 lacks saturation near S, which indicates that the particle was singly charged. Multiple scattering and gap density measurements give

TABLE II. Proper times of flight of hyperparticles.

Event	Identity	Track length μ	Flight time,[a] 10^{-11} sec	Termination
1	$\Sigma^\pm$	2000	3.2 (6.3)	decay in flight
8	Σ^+	468	1.7	decay at rest
14	Σ^-	9820	15.0	capture at rest
25	Σ^-	70	0.45	capture at rest
4	$Y^\pm$	6900	4.9 (6.0)	decay in flight
5	Σ^-	490	1.8	capture at rest
	${}_\Lambda H^4$		2.5	decay at rest
35	${}_\Lambda H^4$	1460	5.4	decay at rest

[a] Potential proper flight times are given in parentheses.

[11] V. Fitch and R. Motley, Phys. Rev. **101**, 496 (1956); Alvarez, Crawford, Good, and Stevenson, Phys. Rev. **101**, 503 (1956); Iloff, Chupp, Goldhaber, Goldhaber, Lannutti, Pevsner, and Ritson, Phys. Rev. **99**, 1617 (1955).

[12] A. H. Morrish, Phys. Rev. **90**, 674 (1953).

[13] *Note added in proof.*—In subsequent examinations of other stacks, the mean free path has turned out to be appreciably larger, but still not very different from geometric. The smaller value found here is due not to observational error but to chance fluctuation in the number of interactions in flight.

[14] One such event has since been found in a different stack.

[15] Webb, Chupp, Goldhaber, and Goldhaber, University of California Radiation Laboratory Report UCRL-3226 (unpublished).

particle 2 a mass of $(1.2\pm0.3)\ m_p$ and $(1.4\pm0.5)\ m_p$, respectively. As this mass is inconsistent with that of a triton, and as a two-pronged star could not result from the decay of an excited deuteron, particle 2 is identified as Σ^-. Even disregarding the mass measurements, the characteristics of star *P* cannot be plausibly reconciled with a $_\Lambda H^3$ or a $_\Lambda H^4$ decay.

Star *S* differs from *NK* 1 and *NK* 8 in that the pion and hyperon tracks depart more from collinearity and in that the pion energy is higher. These differences are caused merely by the appreciable momentum and kinetic energy of the *K* particle, as is shown by the low value of the residual momentum (86 Mev/*c*, which includes the *K* momentum), the near-coplanarity of the tracks (angle between track 1 and plane of tracks 2 and 5 is 6°), and the near equality of available and visible energies [567 ± 6 Mev and $(563-30+60)$ Mev, respectively].

Thus it appears from the kinematics that the hyperon was emitted as a result of a single collision of the fast *K* meson with a nucleon. Hence it is implied that such emission is a fast process, occurring in a time typical of other nuclear processes. This conclusion is consistent with the findings reported in Sec. D, that the K^- mesons interact strongly, and that hyperparticles are frequently formed in these interactions.

(2) Event *K* 25

K^- (track 1, Fig. 3) stops at *S* and causes an all-black star of 4 prongs. Of these, track 2, 70μ long, is due to a particle coming to rest at *P* and producing a star with black prongs 3, 7, and 8. Tracks 7 and 8 are ascribed to protons, of kinetic energies 6 Mev and 13 Mev, respectively. Track 3 is a short but well-defined black stub, 1.5μ in length, that ends at *D* in a third star consisting of track 4 (proton, 40 ± 2 Mev), track 5 (proton, 4.6 Mev), and track 6, a 3μ stub.

There are two possible interpretations, (a) and (b), of this event.

(a) Particle 2 could be a hyperfragment decaying at *P*. In that case, particle 3 is a pion, of kinetic energy $\lesssim 0.1$ Mev, captured at *D*. From the scattering of track 2, the fragment is light. Consider then, as the simplest case, particle 2 to be $_\Lambda H^3$, decaying according to the scheme

$$_\Lambda H^3 \rightarrow p+p+n+\pi^-+Q. \qquad (1)$$

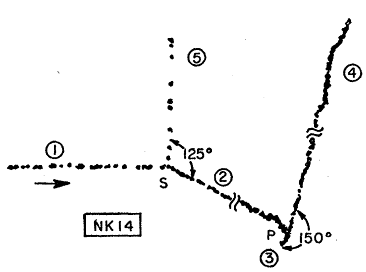

FIG. 2. Drawing of K^- event *NK* 14. K^-, track 1, interacts in flight at *S* and ejects a pion, track 5, and a Σ^-, track 2. Σ^- comes to rest at *P* and produces secondaries 3 and 4. Angles are spatial.

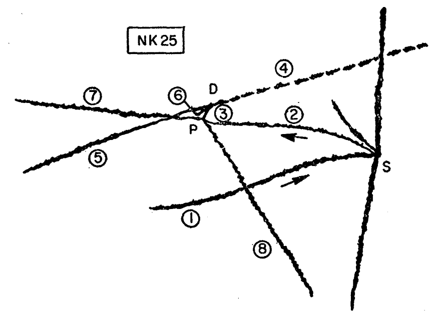

FIG. 3. Drawing of K^- event *NK* 25. K^-, track 1, comes to rest and produces star *S*. From *S* emerges Σ^-, track 2. Σ^- is captured at *P* with emission of protons 7 and 8, and of hyperfragment 3, which decays at *D* with emission of protons 4 and 5 and of unidentified particle 6. See Sec. E2.

For the event at *P* to be so described, the neutron momentum must balance the resultant momentum, 160 Mev/*c*, of the 13 and 6-Mev protons. (The pion kinetic energy and momentum are negligible.) Since the binding energy of Λ^0 in $_\Lambda H^3$ is $\lesssim 1$ Mev,[16] $Q=34$ Mev, and the neutron kinetic energy is $34-13-6$ or 15 Mev. The corresponding neutron momentum is 170 Mev/*c*; consequently the properties of the event are consistent with the decay scheme.

However, this seemingly striking agreement becomes less than convincing when the probability of emission of a 0.1-Mev pion is considered. Since in the loosely bound structure of $_\Lambda H^3$ the Λ^0 decays essentially as if free,[17] the pion should have typically about 30-Mev kinetic energy. If this energy is to be reduced to the observed value because of the motion of the Λ^0, the kinetic energy of the Λ^0 must be some tenfold its average kinetic energy in the nucleus, and its direction of motion must be closely opposite to that of the pion. Each of the two probabilities involved is computed to be less than 10^{-2}, so that the probability for a 0.1-Mev pion to be emitted is less than 10^{-4}. The same figure is obtained if the slowing of the pion is considered as due to its collision with another nucleon in the fragment.

(b) Much more probable appears the interpretation that particle (2) is Σ^-, captured by a nucleus at *P*, and transforming, as required by theory,[6] into Λ^0. The same objection as in (a) applies, then, to interpretation of particle 3 as π^-. Consequently, particle 3 must be a hyperfragment, decaying at *P*. One possible fragment and decay scheme is

$$_\Lambda B^{10} \rightarrow Li^6+2p+2n.$$

Two cases of hyperfragments emitted from Σ^- captures have been previously reported.[18,19]

[16] Bonetti, Levi Setti, Panetti, Scarsi, and Tomasini, Nuovo cimento **11**, 330 (1954).
[17] We are indebted to Dr. Keith A. Brueckner for presenting this argument.
[18] Ceccarelli, Dallaporta, Grilli, Merlin, Salandin, Sechi, and Ladu, Nuovo cimento **2**, 542 (1955).
[19] Schein, Haskin, and Leenov, Phys. Rev. **100**, 1455 (1955).

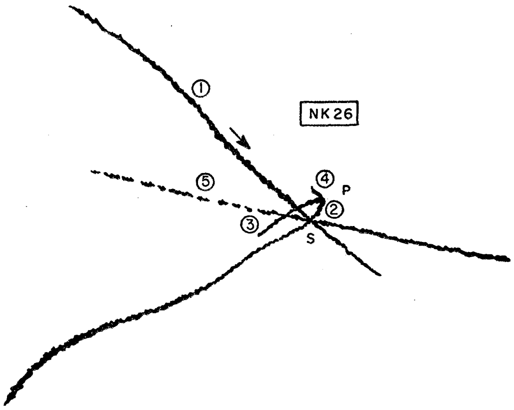

FIG. 4. Drawing of K^- event *NK* 26. K^-, track 1, comes to rest and produces a star at *S*. Star prong 2 is due to a hyperfragment which decays at *P* with emission of particles 3 and 4; less probably, 2 is Σ^-, captured at *P*.

(3) Event 19

Of the prongs associated with this star, one, 750μ long, was observed to end in a large blob, indicating nuclear capture of the particle. Extreme steepness of the track prevents a mass estimate. The particle could be either a 5-Mev π^- or a 13-Mev Σ^-. Both alternatives are listed in Table I.

(4) Events 12, 16, 21, 23, 26

These K^--meson captures have in common the appearance of 2 stars connected by a very short link. In *NK* 26 (Fig. 4) the link 2 is 3.5μ long, and the secondary star consists of 2 short prongs, 3 and 4, of lengths 21μ and 1.5μ. In the other stars, the connecting track is even shorter, about 1μ, and obscured by the blob frequently found at the center of large stars. In events 12, 16, 21, and 23, the double-centered nature is inferred from the failure of all the tracks to meet in the same point.

In *NK* 12, the secondary star has only one track, that of a 42-Mev proton (mass determined from scattering). In *NK* 16, the pion and the ~40-Mev proton belong to the primary star; the origin of a 12-Mev proton (listed in parenthesis in the table) is ambiguous. From the secondary star come two protons of 6 and 8 Mev and a track which, from scattering and range, is due either to a 23-Mev deuteron or a 27-Mev triton. In *NK* 23, the first two tracks listed in Table I belong to the primary star. For the next two tracks, shown in the table in parenthesis, the origin is ambiguous. A 6-Mev proton, a 9-Mev proton, and a 14-Mev α particle belong to the secondary star. If the parenthesized tracks of *NK* 16 and *NK* 23 are assumed to come from the primary star, the visible energies are those given in the table in parenthesis.

In *NK* 21, the connecting link is only 0.5μ long; this short length makes the existence of two centers not quite certain. No assignment of prongs is possible; all the prongs are listed in the table. The energy of the prongs, excluding the two stable fragments, totals 442 Mev, and the momenta add to a resultant of 770 Mev/*c*.

These events can be interpreted in different ways. The secondary stars could result from (a) the collision of a fast particle, (b) capture of a stopping π^-, (c) capture of a Σ^-, or (d) decay of a hyperfragment.

Interpretation (d) is preferred only because tracks of the order of 1μ are to be expected for hyperfragments, but are unlikely in the other three cases. For instance, for (a) the probability is about 10^{-6} that a star-producing collision by a fast proton or pion be observed within 1μ.

With interpretation (b), E_v would be low enough to allow emission of a Λ^0 in events 12 and 23. Events 16, 21, and 26 would have two pions; one of these could result from the decay of a Λ^0 trapped in the capturing nucleus. Thus, (a) can be rejected because of its improbability, (b), though also improbable, is consistent with hyperparticle production from K^- capture, and (c) and (d) definitely involve such production.

(5) Event 35

This disintegration (*S*, Fig. 5), produced in flight, yields track 2 (1.46 mm long) which ends at *P*. From the scattering near the end, particle 2 appears to be stopping. Distortion prevents determination of the mass of particle 2 by scattering measurements, but the energy balance of parent star *S* shows it cannot be a *K* meson. The secondary star at *P* is composed of an 8μ long black prong 3 and a light track 4 of (1.48±0.07) g_0. Within experimental error, these tracks are collinear. Track 4 leaves the stack at *Q*, 29.5 mm from *P* with a grain density of (2.28±0.15) g_0. The grain count-range measurements from *P* to *Q* agree well with our pion calibration curve; hence, particle 4 is a pion. Its residual range at *P* is 38.7±2.0 mm. From the range-energy relation,[20] corrected to correspond to the stopping power of our emulsions, this range corresponds to a pion kinetic energy T_π of 52.8±3.0 Mev at *P*.

The pion is too energetic to result from Σ^- capture (unless Σ^- decayed directly within a nucleus, in violation of theory[6]). The event is interpreted as the decay of $_\Lambda H^4$ according to

$$_\Lambda H^4 \rightarrow He^4 + \pi^- + Q. \quad (2)$$

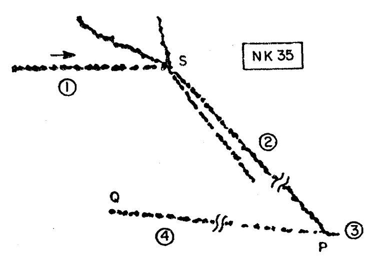

FIG. 5. Drawing of K^- event *NK* 35. K^-, track 1, produces in flight star *S*, from which emerges the hyperfragment $_\Lambda H^4$, track 2. $_\Lambda H^4$ decays at *P* into He^4, track 3, and π^-, track 4. Track 4 leaves the stack at *Q*.

[20] See reference 7; the same results are obtained from W. H. Barkas and D. M. Young, University of California Radiation Laboratory Report UCRL-2579 Rev. (unpublished).

Identifying particle 3 as He^4, its energy from range[21] is 2.2 ± 0.2 Mev. A more accurate value is calculated from momentum balance, namely, $T_{He}=2.3\pm0.1$ Mev, in good agreement with the directly determined value. The Λ^0 binding energy is

$$B_\Lambda=Q_\Lambda+B_p-T_\pi-T_{He}=1.6\pm3.0 \text{ Mev},$$

where $Q_\Lambda=36.9$ Mev is the Q of the free Λ^0 decay, and $B_p=19.8$ Mev is the binding energy of the last proton in He^4. Four decays according to scheme (2), with similar values of B_Λ, have been found by other workers.[19,22]

(6) Event 5

Data for this event have been presented previously,[2] and it was pointed out that the hyperparticle emerging could be either Σ^-, ${}_\Lambda He^4$ or ${}_\Lambda H^4$. If it is the latter, the decay mode that best fits the observations is

$$ {}_\Lambda H^4 \to He^3+\pi^-+n+Q. \quad (3)$$

Kinetic energies of the pion and He^3 are 17.4 ± 0.5 Mev, and 1.2 ± 0.4 Mev, respectively (both values from ranges[7,21]), and the angle included between these two tracks is $33\pm9°$. A neutron balancing the momenta of the two charged particles would have 11.8 Mev. From the total kinetic energy T $(=17.4+1.2+11.8=30.4$ Mev), the binding energy B of the Λ^0 in ${}_\Lambda H^4$ is calculated to be

$$B_\Lambda=Q_\Lambda-T+B_1-B_2=5.8\pm3.3 \text{ Mev},$$

where $B_1=7.6$ Mev and $B_2=8.3$ Mev, the total binding energies of He^3 and H^3, respectively, and $Q_\Lambda=36.9$ Mev.

This value of B_Λ agrees with the one obtained from event NK 35 ($B_\Lambda=2.4\pm3.0$ Mev) and is of the same magnitude as the B_Λ found for other light hyperfragments.

The decay (2) for this event is, thus, acceptable. However, the large error in B_Λ makes the agreement with other B_Λ values unconvincing, and thus the alternative interpretation that Σ^- capture produced the secondary disintegration is not unlikely.[23]

(7) Event 24

In this event a K meson, of $T_K=72\pm6$ Mev, track 1, gives rise in flight to a single light track 2 which forms an angle of 89° with the primary track. No clump or Auger electron is seen at the origin S of track 2.

Track 1, 12.2 mm long, meets all criteria for K-meson tracks. Track 2 is quite flat and goes for 30 mm before leaving the stack.

At a point 1.0 mm from S, its grain count is $(1.27\pm0.04)g_0$; 11.5 mm from S, it is $(1.40\pm0.05)g_0$; 18.0 mm from S, it is $(1.42\pm0.05)g_0$; 25.2 mm from S, it is $(1.53\pm0.05)g_0$. From grain count and multiple scattering, the mass of particle 2 is (370 ± 50) m_e. Thus the particle cannot be a muon but is identified as a pion. Pion energies T at S derived from each of the four grain counts are 68.9 ± 5.7 Mev, 63.7 ± 3.6 Mev, 67.3 ± 3.6 Mev, and 66.3 ± 1.9 Mev, respectively; the weighted average is 66.3 ± 1.5 Mev.

To determine whether the event can be interpreted as a decay, T must be transformed into its corresponding value T' in the K-meson rest system. From the average of T, $T'=95\pm4$ Mev is obtained. Because track 2 is almost normal to track 1, this number is insensitive to the value of T_K. If the K^- meson has the τ mass, then for the decay $K^-\to\pi^-+\pi^0$, one expects $T'=108$ Mev, more than 3 standard deviations above the observed value. Conversely, T' of 108 Mev corresponds to $T=77$ Mev, which is larger than each of the above-listed experimental energy values. It is, therefore, probable that the event represents a star and not a decay. (Sufficient reduction of pion energy by radiation loss, though possible, cannot justify classifying this event as a decay.) It is to be remembered (see Table I) that light tracks similar to track 2 of this event are not infrequently observed in stars.

(8) Event 4

Because of the unusual nature of its hyperparticle, event 4, already reported,[2] is here described in greater detail. The star S, produced by the capture of the K^- at rest (see Fig. 1 of reference 2), consists of track (6) due to an 11-Mev proton, and a moderately steep 6.9 mm long gray track (2), extending to P. The passage of track (2) through 7 emulsions to P has been checked and rechecked, and each of the several observers was certain that the track was correctly followed.

Within the errors of measurement, the grain density, $(2.83\pm0.06)g_0$ at S and $(2.85\pm0.05)g_0$ at P, does not vary along the track. These measurements show that the particle is singly charged and has a kinetic energy (0.105 ± 0.005) times its rest energy. The lack of variation of density (within ±0.10 g_0) over an interval of 6.9 mm determines a lower limit for the particle mass, namely, the mass of a Σ hyperon. Unfortunately, distortion in the emulsion frustrated attempts to obtain a better mass value from scattering measurements.

At P appears track (3) which has a grain density of $(1.08\pm0.06)g_0$; this light particle moves backwards at an angle of 73° (erroneously labeled 68° in the figure) with respect to the motion of particle (2). Because track (3) is short and steep, only a lower limit of $p\beta\geqslant100$ Mev/c could be determined; if the particle were a pion, its kinetic energy, from its grain count, would be (123_{-25}^{+70}) Mev. If the particle were an electron, its energy, equal to $cp\beta$, would be $\geqslant100$ Mev.

[21] J. J. Wilkins, Atomic Energy Research Establishment, Harwell Report AERE-G/R 664, 1951 (unpublished).

[22] Crussard, Fouché, Kayas, Leprince-Ringuet, Morellet, Renard, and Trembley, Preliminary Report of the Pisa Conference, 1955 (to be published), p. 481; Ö. Haugerud and S. O. Sörensen, Phys. Rev. **99**, 1046 (1955); Friedlander, Keefe, and Menon, Nuovo cimento **2**, 663 (1955).

[23] A similar star, that was ascribed to Σ^- capture and consisted of a short prong and a 29-Mev π^-, has been reported by Friedlander, Keefe, and Menon, Nuovo cimento **1**, 482 (1955).

The event at P resembles in appearance the decay in flight of a charged hyperon according to the scheme

$$Y^{\pm}\rightarrow\pi^{\pm}+n+Q. \qquad (4)$$

The following analysis shows, however, that the data do not fit this process for $Y^{\pm}=\Sigma^{\pm}$, for which $Q_{\Sigma^{\pm}}=110$ Mev.[22] Assuming that particle 3 is a pion, its kinetic energy in the rest system of particle 2 is $T'=(181_{-29}^{+78})$ Mev, giving for decay (4) $Q=(225_{-38}^{+103})$ Mev. Conversely, a $\Sigma^{\pm}$ decaying according to scheme (4), with the pion emitted at the angle observed, would require a pion energy of 52 Mev in the laboratory system, corresponding to $g/g_0=1.40$, larger than the observed grain count by 5 standard deviations (probability 6×10^{-7}).

It could be assumed that the hyperon is not free but is Σ^- bound to a neutron. This assumption does not violate theory, but is made unlikely by the argument given further on. Then, for the complex decaying according to

$$(\Sigma^- n)\rightarrow\pi^-+2n+Q, \qquad (4a)$$

the value of Q, (203_{-38}^{+94}) Mev, as calculated from the data, is still too large. It follows that if the event is a decay according to reaction (4) or (4a), then either the hyperon must be heavier than a Σ particle or, if particle (2) is Σ^-, then a different decay scheme must be assumed.

Some of the possibilities so far considered can be eliminated or made unlikely by an analysis of the energy and momentum balance of star S. If particle 2 is $\Sigma^{\pm}$, then the residual momentum $p_v=410$ Mev/c and the visible energy $E_v=406\pm12$ Mev, leaving $(493-406)$ Mev$=87$ Mev for emission of a neturon of 10-Mev binding energy, 77-Mev kinetic energy, and 380-Mev/c momentum. Then, the residual momentum of the 3 star particles could be as low as $(410-380)$ Mev/c $=30$ Mev/c, an unbalance readily compensated by nuclear recoil. Emission of a π^0 instead of a neutron in the K^--meson capture process is energetically not possible unless the error in E_v is stretched unreasonably and unless it is assumed that the π^0 is created with but little kinetic energy and then reabsorbed in the nucleus with ejection of the 11-Mev proton. Even then it would be difficult to achieve momentum balance to which the π^0 would not contribute significantly.

If particle 2 were a Σ^- bound to a neutron, then $E_v=505\pm15$ Mev, a barely acceptable value, and $p_v=840$ Mev/c, much too large for balance by Fermi momentum. Identification as Σ^- bound to 2 neutrons is energetically impossible.

If particle 2 were a heavier hyperon, decaying according to process (4), its rest energy would be at least (taking the lowest Q-value allowed by the error) 85 Mev higher than that of Σ^+. In that case, $E_v\geqslant500\pm12$ Mev and $p_v\geqslant450$ Mev/c, and there would be energy for emission of a neutron of at most $\sim$100 Mev/c. This could reduce the residual momentum to $\sim$350 Mev/c, an unbalance that could possibly, but improbably, be taken up by Fermi momentum.

To summarize: the energy-momentum balance of star S readily admits the emission of $\Sigma^{\pm}$, barely of $Y^{\pm}$ with rest energy $\sim$1270 Mev, and not of a heavier particle.

Alternatively, we consider the decay schemes:

$$\Sigma^{\pm}\rightarrow\mu^{\pm}+\nu+n+145\text{ Mev}, \qquad (5)$$

and

$$\Sigma^{\pm}\rightarrow e^{\pm}+\nu+n+250\text{ Mev}. \qquad (6)$$

For decay (5), the kinetic energy T' of the muon in the rest system, as calculated from the experimental data, is (137_{-29}^{+59}) Mev, corresponding to $p'=207$ Mev/c. Then p' could be balanced by a neutron of 23 Mev, so that but little energy would be left for the neutrino. Process (5), therefore, is possible but improbable from phase space consideration.

For decay (6), the kinetic energy of the electron $T'>124$ Mev. Thus, roughly half of the available energy could be taken by the neutrino, a division favored by phase space arguments. It is seen that of the processes considered for the event at P, decay (6) is least objectionable.[24]

Because a decay of type (6) has not previously been observed, it is necessary to discuss other explanations.

Particle 2 cannot be a stable hydrogen isotope, because its kinetic energy, 300 Mev if it were a triton, is too low for production of particle 3 interpreted as a 120-Mev pion. Production of high-energy electrons in nuclear interactions is not known.

Suppose, next, that the event at P represents the nuclear capture in flight and subsequent decay at rest of a charged hyperon. From the track length ($\sim$0.02 mean free path), and from the observation that roughly 0.04 of the stars caused by protons of about the same kinetic energy are zero-pronged,[25] it is estimated that the probability for the observed event to result from such a capture is $\lesssim10^{-3}$. Furthermore, a pion of the observed energy could result only from the direct decay within the capturing nucleus of a $\Sigma^{\pm}$, not of a Λ^0. This process would violate theoretical predictions which demand that a Σ particle within a nucleus transform into a Λ^0. Therefore, nuclear capture appears very improbable, leaving decay (6) as the preferred interpretation.

(9) Event 33

In this event a track is deflected by 8° at a point B, 16.3 mm from the point A where it was found, and again by 47° at a point C, 12.4 mm from B. There is no change in grain count at either point. The track leaves the stack at D, 8.7 mm from C with a grain count roughly 3.7 g_0, hence the residual range is small. It

[24] This decay mode has been considered (for Λ^0) by G. Costa and N. Dallaporta, Nuovo cimento 2, 519 (1955).

[25] Lees, Morrison, Muirhead, and Rosser, Phil. Mag. 44, 304 (1953).

meets all criteria of a K-meson track in the interval between A and B, and if it is considered to be made by a particle scattered elastically at B and C, then the grain count variation between A and D is at all points in agreement with that typical of a K-meson track. These statements also imply that the residual range of a K meson of the track density estimated at D, namely 6 mm, added to the 37.4 mm distance from A through B and C to D, for a total of 43.4 mm, is within the limits of residual range at A observed for K particles. This reinforces the identification of the particle mass from grain-count variation. Thus both deflections are interpreted as elastic scatterings of a K meson. From the grain counts, the K-meson energy at B is 77 Mev, and at C, 58 Mev. At B the deflection could be due either to Coulomb or to nuclear scattering. At C Coulomb scattering can be shown to be excluded by the combination of large deflection and high energy, and the scattering must be nuclear.

F. K-MESON CAPTURE REACTIONS

The following question will now be examined: does capture of negative K mesons always result in production of hyperparticles? Expressed otherwise, this is a question of the ubiquity in K^--meson captures of reactions such as (I) and (II):

$$K^- + N \to Y + \pi, \tag{I}$$

$$K^- + 2N \to Y + N, \tag{II}$$

where N stands for a nucleon, and the pions π and hyperons Y may be either charged or neutral.

In the course of analyzing the observed captures, it was often found possible to specialize reaction I further, so as to distinguish the character of the hyperon, Λ^0 or Σ, according to reactions (Ia) and (Ib):

$$K^- + N \to \Sigma + \pi, \tag{Ia}$$

$$K^- + N \to \Lambda^0 + \pi. \tag{Ib}$$

Reaction Ia definitely occurred in events 8, 1, and 14. This follows from the observation, stated in the preceding section, that those stars consisted of a Σ particle and a pion, with at most a very small amount of energy left over for neutral particles; the appropriate reactions are special cases of (Ia):

$$K^- + p \to \Sigma^+ + \pi^-,$$
$$K^- + p \to \Sigma^- + \pi^+.$$

Furthermore, hyperparticles are observed directly in the 9 stars of Group B. Of these, event 25 shows a Σ^- particle and can be described by (Ia):

$$K^- + n \to \Sigma^- + \pi^0,$$

where the pion can have a kinetic energy up to about 40 Mev. With the exception of event 4, the other stars of Group B have been assigned to (I) rather than to (II), for reasons that will appear later; their complexity prevents good analysis. The discussion in Sec. E of the kinematics of event 4 (which has a fast hyperon) leads to its assignment to reaction (II).

While a third of the stars show charged hyperparticles, two-thirds (Groups C and D) do not. The ensuing discussion is concerned primarily with showing that the events of Groups C and D are consistent with reaction (I). While, accordingly, this reaction is at first taken for granted, at the end of this section it will be considered whether reaction (II) is important, and whether at least some of the captures without visible hyperparticles might, indeed, have produced no neutral hyperon.

From a study of the visible star energies E_v of Groups C and D (set Column 7 of Table I) emerges the striking fact that in all these events E_v is much smaller than the available energy. This situation would be expected if the missing energy were consumed in the production of a Y^0 which escaped from the nucleus. It may also be noted that in stars without a charged pion (with the exception of NK 4), π^0 emission is energetically possible, and that in stars showing neither a hyperparticle nor a pion (Group D) visible energies are so small that both a π^0 and a Y^0 could have been emitted.

A kinematic analysis of the reactions (Ia) and (Ib), the results of which are summarized in Table III, leads to more detailed conclusions. In stars made by a K^- meson at rest and containing a pion track, the emission of a neutral hyperon can be assumed only if

$$E_v \leqslant m_K c^2 - (m_Y c^2 - m_p c^2) - B_N, \tag{7}$$

where $m_K c^2$ is taken equal to the τ-meson rest energy (493 Mev[14]), $m_Y c^2$ is the rest energy of hyperons (1115 Mev for Λ^0 and 1189 Mev for Σ), $m_p c^2$ is the rest energy of protons, and B_N ($\simeq$10 Mev) is the binding energy of a nucleon. (Energy losses from x-ray emission during K^- capture should in principle also be subtracted from $m_K c^2$, but can be shown to be negligibly small even in heavy nuclei.) The upper limits of E_v given by relation (7) are 233 Mev for Σ^0 emission (assumed to have the same mass as Σ^+) and 307 Mev for Λ^0 emission (Column 8). If both a π^0 and a Y^0 are made, the pion rest energy must be subtracted from the foregoing expression, and the limits of E_v become 98 Mev and 172 Mev, respectively (Column 10).

Were the capturing nucleon at rest (but bound with $B_N = 10$ Mev), then the kinetic energies T_π and T_Y of the pion and hyperon would be as given in Columns 2 and 3. For nucleons moving with Fermi momenta p_F up to 200 Mev/c, pion kinetic energies are calculated to lie between the limits given in Columns 4 and 6, hyperon energies T_Y to lie between the values in Columns 5 and 7; and the numbers in Columns 2 and 3 become median kinetic energies. The median visible energies for the reaction $K^- + n \to Y^0 + \pi^-$, given in Column 9, are computed with the median energies in Column 3.

TABLE III. Analysis of K^--meson capture reactions.[a] Energies are in Mev.

1	2	3	4	5	6	7	8	9	10
	$p_F=0$		$p_F=+200$ Mev/c		$p_F=-200$ Mev/c				
Reaction	T_π	T_Y	$T_{\pi\ max}$	$T_{Y\ min}$	$T_{\pi\ min}$	$T_{Y\ max}$	E_{v1}	$\bar{E}_v$	E_{v2}
(Ia) $K^-+N\rightarrow\Sigma+\pi$	82	12	94	0	49	45	233	221	98
(Ib) $K^-+N\rightarrow\Lambda^0+\pi$	142	26	166	2	99	69	307	281	172

[a] Kinetic energies T_π of the pion and T_Y of the hyperon are calculated with $m_\pi c^2=139$ Mev. Columns 2 and 3 are for the capturing nucleon at rest. Columns 4 and 5 are for the nucleon moving with Fermi momentum $p_F=200$ Mev/c in the same direction as the pion, and Columns 6 and 7 are for the nucleon moving with 200 Mev/c in the same direction as the hyperon. E_{v1} is the maximum, and $\bar{E}_v$ is the median visible star energy for the reaction $K^-+n\rightarrow Y^0+\pi^-$, with Y^0 escaping. E_{v2} is the maximum visible star energy for the reaction $K^-+p\rightarrow Y^0+\pi^0$, with both Y^0 and π^0 escaping.

So far it has been assumed that in freeing the capturing nucleon from the nucleus, only the binding energy B_N is expended. This assumption is valid for the removal of nucleons having high Fermi energies, and is, therefore, appropriate for calculation of the maximal energies in Columns 8 and 10. (For consistency, the values in the other columns were computed on the same basis.) In general, however, the adiabatic removal of a nucleon will cause a nuclear excitation U of roughly 15–20 Mev on the average and up to 50 Mev for the most tightly bound nucleons[26]; correspondingly, pion and hyperon kinetic energies will be reduced below the values listed in Table III. Such nuclear excitation is sufficient for the emission of one, two, or three evaporation nucleons. In stars having either more dark prongs or else nuclear particles too energetic to result from evaporation, other processes must have contributed to the production of the heavy prongs.

The following four conclusions may be drawn from the data of Table III:

(1) The median kinetic energy of the hyperons is low, roughly 20 Mev. This favors the formation of hyperfragments, which were observed in about 15 percent of the K-meson captures.[27]

(2) Scrutiny of the visible energies in column 7 of Table I shows that, in all events of Group C, emission of neutral hyperons is possible, as is shown by the observation that E_v is less than the upper limits of visible star energy, given in column 8 of Table III. (For events 9 and 24, the K-meson kinetic energy T_K has to be added to the values in Table III.) Specifically, in stars 2, 6, 11, 13, and 10 (and probably 3 and 9, even after allowing for T_K in the latter event), E_v exceeds the limit for reaction Ia (Σ^0 emission); accordingly, these events were assigned to reaction (Ib) (Λ^0 emission). The values of E_v are near the expected median values $\bar{E}_v$ of column 9.

In the events of Group D (except NK 29), E_v is below the limits of column 10, so that both a neutral hyperon and a neutral pion could have been emitted. In no case of Group D is reaction (Ia) excluded; therefore, the nature of the hyperon was left unspecified in Column 8, Table I. (In NK 15, process (Ib) is more probable, but the error in E_v leaves (Ia) as a possibility.)

[26] Keith A. Brueckner (private communication).

[27] The percentage is lower in emulsion subsequently examined.

These conclusions are not altered if allowance is made for the energy carried away by neutrons; the *average* neutron energy per star (including binding) taken as equal to the average proton energy, is 33 Mev in Group C, 42 Mev in Group D.

(3) The maximum energy of pions coming from reactions (Ia) (with the K^- meson captured at rest) is about 100 Mev. Events with $T_\pi \gtrsim 100$ Mev (NK 2, 3, 6, 11, 13) are, therefore, more likely to have involved reaction (Ib) which confirms the classification already given.[28] On the other hand, in events 17 and 28, and in event 24 (which, being caused by a K^- meson in flight, requires special analysis) both T_π and E_v have values consistent with reaction (Ia). These events have been so classified, though it is possible to assume that a Λ^0 instead of a Σ^0 was emitted, and that the pion energy was reduced below the limit for reaction (Ib) by a collision with a nucleon. Such a pion interaction should generally result in the formation of additional star prongs. However, event 24 has no dark prongs, and each of stars 17 and 28 shows only one low-energy proton that could easily have resulted from the nuclear excitation U accompanying the primary capture. This observation makes assignment to reaction (Ia) more plausible than to (Ib).

(4) Table III shows that, for reaction (Ib), in one-half of the cases the pion kinetic energy is between $\sim$140 Mev and 166 Mev. For pions of such energies the cross section for collisions with nucleons (approximately $\frac{2}{3}$ the π^+-p cross section) is about 3 times geometric[29]; therefore, it is to be expected that these pions will frequently interact and lose energy before emerging from the nucleus. Events 21, 10, and possibly 26 and 19, having pions of kinetic energy below the lower limit $\sim$50 Mev (reaction (Ia), Column 6 of Table III), can be so explained. This interpretation is supported by the observation of high-energy nuclear particles in these stars. Pion interactions are likely to have occurred also in those events, so noted in Column 8 of Table I, where the energy of the heavy prongs exceeds the excitation energy U. Probably pions interacted in still other events, and neutrons carried away appreciable energy.

[28] In NK 9 and NK 16, both due to K mesons in flight, the numbers of Table III do not apply. In these events, the pion energies are consistent with either reaction (Ia) or (Ib).

[29] S. J. Lindenbaum and Luke C. L. Yuan, Phys. Rev. **100**, 306 (1955).

For reaction (Ia), on the other hand, half of the pions have energies less than $\sim$80 Mev. At such energies, the cross section is roughly one-half geometric,[30] so that these pions are less likely to interact than the pions of (Ib). Thus, the energies of stars assignable to reaction (Ia) should often be low. The low (or vanishing) stable-prong energy of stars 8, 1, 14, 25, and possibly 17, 28, and 24 is consistent with this argument.

The average share of the heavy-prong energy contributed by pion collisions (irrespective of the capture reaction involved) may be estimated as follows. The average visible energy in Group D is 49 Mev; and the average energy of the heavy prongs in Group C is also 49 Mev. By allowing for the energy of neutrons, star energies of 92 Mev and 82 Mev are obtained for the two groups. It has been stated that about 20 Mev is contributed by the nuclear excitation attending K^--meson capture; this leaves about 70 Mev per star. Most of the 70 Mev must come from pion and not hyperon collisions, since the hyperon kinetic energies are low. Hyperon decay within the capturing nucleus could increase the size of a star appreciably, but appears to be infrequent (see below).

In events showing hyperfragments (in Group B) the average energy given the stars by stable particles, including neutrons, is much higher, namely 187 Mev. Possibly this difference can be explained by the consideration that fragment emission from a nucleus requires high local excitation, so that fragments are more likely to be observed in larger stars.[31]

In the preceding discussion, some of the reasons for selecting the reactions entered in Column 8 of Table I were given; further considerations follow.

(1) The reactions were chosen to interpret the observations most directly. Unless there was experimental evidence for subsequent interactions, it was assumed that the reaction products observed were the same as the products directly emitted in the K^--meson capture. Formation of a hyperfragment implies the secondary interaction of a hyperon with nucleons. The hyperon originally formed could have been, then, either a Λ^0, or a Σ (charged or neutral) later transforming into a Λ^0; accordingly, the nature of the hyperon was left unspecified in events with hyperfragments.

(2) Interactions of pions from reaction (Ib) were considered to be scatterings, because absorption is improbable at the high energies at which these pions were emitted. Because most of the events in which the choice between (Ia) and (Ib) was not made were assumed to involve Λ^0 creation (see Sec. G), the same consideration was used in their classification. (If in NK 5 the hyperparticle is Σ^-, pion absorption, rather than scattering, must be assumed, as the energy in the visible prongs alone, 131 Mev, exceeds the maximum kinetic energy 100 Mev of a pion from reaction (Ia).) As charge-exchange scattering occurs in only $\frac{1}{6}$ of the π^--nucleon interactions[32] and, as can be easily shown, in $\frac{1}{3}$ of the π^0-nucleon interactions, the more probable process of ordinary scattering was assumed in specifying the reactions.

(3) It needs hardly be emphasized that some of the reactions listed are still ambiguous. In particular cases, reactions may have been assigned erroneously for any of the following reasons: (a) where charge exchange scattering of pions actually occurred, the wrong nucleon appears on the left side of the listed reaction; (b) as already mentioned, pion interactions may also have taken place in events not so classified; (c) in some events in Groups B and D a fast nucleon could have resulted from a $\Sigma\rightarrow\Lambda^0$ transformation, rather than from a pion collision; (d) in Groups C and D, the size of a star (for example of NK 11 and NK 15) could have been increased by the decay of a Λ^0 trapped in the capturing nucleus, rather than by a pion collision; (e) except in event 26, a low-energy pion could have resulted from the decay of a trapped Λ^0 rather than from degradation of a fast pion; (f) it cannot be excluded that a few of the events in Group D are due to reaction (II), $K^-+p+n\rightarrow Y^0+n$. However, this reaction cannot be frequent for the reason that the hyperon produced would be fast. Only one event with a fast hyperon, NK 4, was found and accordingly assigned to (II). The other charged hyperons had low energy. It is likely that hyperons bound in hyperfragments were also created slow, because capture of a fast hyperon seems improbable. Reaction (II) is also possible for event 29; reasons are given in the Appendix.

The effects of the ambiguities (a)–(f) will now be discussed. Ambiguity (a) could shift the ratio of protons to neutrons involved in K^--meson capture, but there is partial compensation, since charge-exchange scattering of π^- increases that ratio, whereas such scattering of π^0 decreases it. The same comment applies to (b), if the interaction there referred to is charge-exchange scattering. Otherwise, (b) affects merely the previously given amount of star energy contributed by pion collisions. No conclusions are affected by (c). Effect (d) is probably infrequent, as will be discussed in the following section. Ambiguity (e) is related to (d), and the same remark applies. Furthermore, this ambiguity can exist only if the hypernucleus, from which the π^- is assumed to come, either remained stationary or made only a very short track. This is not probable for light hyperfragments. For heavier hypernuclei, mesonic decay is rare.[33] The alternative process referred to in (f) is infrequent, as has already been stated. Thus, it appears that these ambiguities do not seriously affect the distribution of reactions assigned.

[30] Anderson, Fermi, Martin, and Nagle, Phys. Rev. **91**, 155 (1953).

[31] Even larger parent stars than observed here in K^--meson captures are typical for fragments, both stable and unstable, ejected by interactions of fast cosmic-ray particles; see D. H. Perkins, Proc. Roy. Soc. (London) **A203**, 399 (1950); Friedlander, Keefe, Menon, Johnston, O'Ceallaigh, and Kernan, Phil. Mag. **46**, 144 (1955). However, the features of the two classes of events need not be the same in all respects, as the K^- stars differ from the cosmic ray stars in that the energy available for star formation is smaller and in that most of the fragments have very low kinetic energy.

[32] H. A. Bethe and F. de Hoffmann, *Mesons and Fields* (Row, Peterson, and Company, Evanston, 1955), Vol. 2, pp. 47 and 62.

[33] M. Danysz, Preliminary Report of the Pisa Conference, 1955 (to be published), p. 457. The first such case was found by M. E. Blau, Phys. Rev. (to be published).

The ambiguities do not affect at all the general conclusion that K^- capture could have been associated with hyperon formation even in the events where no hyperparticle was observed. As hyperparticles were seen in one-third of all cases, it must be expected, irrespective of other arguments, that at least in some of the other events (Groups *C* and *D*) neutral hyperons escaped.[34,35] However, it cannot be disproved from our observations that in some events K^--meson capture occurred without hyperon emission, for instance according to the scheme

$$K^- + N \rightarrow N' + \pi, \tag{III}$$

although there is no evidence for this reaction. Kinematic analysis shows that in reaction (III) the median kinetic energies of the pion and nucleon should be 276 Mev and 78 Mev, respectively. No pion of such high energy was observed, although it is, of course, possible that in one or two cases the energy of a pion was underestimated because the error in grain count was larger than believed. It would also be possible that a pion from reaction (III) lost a large part of its energy before emerging from the capturing nucleus. However, there is no star in which the visible prong energy indicated so large an energy transfer from a pion. Protons of high energy have been seen in 6 of the events in Groups *C* and *D* (*NK* 13, 10, 29, 7, 22, 31) but it was pointed out before that they could result from interactions of pions from reaction (Ib). In fact, as pions of energies corresponding to large interaction cross sections were seen, observation of fast protons must be expected.

G. CONCLUSIONS

(1) All experimental data are consistent with the theoretical prediction that K^--meson capture always leads to hyperon formation. Of the 39 *K*-meson capture stars reported, 12 showed a charged hyperparticle. Not one of the remaining 27 stars showed either pion energy or star energy sufficient to reject the possibility that a neutral hyperon was emitted.

(2) If it is believed that *K*-meson capture does indeed always lead to hyperon formation, then it must be concluded that these hyperons escape from the capturing nucleus in most cases. For charged hyperons, such escape was seen in 4 or 5 stars. Trapping with subsequent hyperfragment emission was observed in 6 or 7 cases; this is probably in excess of the average abundance.[27] From the remaining events, 11 in Group *C* and 15 in Group *D*, a neutral hyperon must have escaped in a large majority of the cases. That the hyperon remained in the capturing nucleus in many of the events in Groups *C* and *D* is unlikely, because the resulting star should be large, possibly of nearly the size that the events with hyperfragments would have had if the prongs of both the primary and the secondary star had come from one point. Such compound stars would have an average of 6 prongs. In Groups *C* and *D* there are only 2 stars with 5 or 6 prongs and 2 with 4 prongs. Thus, in no more than about a fourth of all stars, and probably in even fewer, is the hyperon trapped in the nucleus.

If the K^- mesons were captured in the body of the nucleus, then the hyperons must have a long mean free path in nuclear matter to escape frequently. If the *K* meson were captured near the surface of the nucleus (as their strong interaction would indicate), then about half of the hyperons would move outward and could easily escape. For the fraction escaping to be appreciably larger, one must again conclude that the hyperons have a long mean free path in nuclear matter, or, on colliding with a nucleon, are predominantly scattered backward.

(3) For several stars, two reactions are listed. If each is given one-half weight, then it is found that 8 events were ascribed to reaction (Ia) (Σ and π emission), $7\frac{1}{2}$ to (Ib) (Λ^0 and π emission), 21 to either (Ia) or (Ib), and $1\frac{1}{2}$ to reaction (II) (hyperon and nucleon emission). If the 21 ambiguous reactions are divided in the same proportion between (Ia) and (Ib) as was found for Group *C*, namely in the ratio of 1:2, then 15 events would be classified under reaction (Ia), and $21\frac{1}{2}$ under reaction (Ib). However, this distribution is quite uncertain for several reasons: (a) the 1:2 ratio is statistically unreliable; (b) Σ^- particles, captured without star formation, may have escaped detection; (c) the argument for assigning events in Group *C* to reaction (Ia) was merely plausible, not compelling; (d) the frequency of Σ creation in Group *B* may be different from that in Group *C*, because the probability of fragment formation may differ for Λ^0 and Σ hyperons; (e) the fraction of Σ hyperons formed is not necessarily the same in Groups *C* and *D*, because of difference in isotopic spin, as, according to the theoretical schemes,[6] the isotopic spin of Σ is 1 and that of Λ^0 is 0, and the system K^-+n, Group *C*, has isotopic spin 1, whereas the system K^-+p, Group *D*, can have isotopic spin 1 or 0. Thus, it can only be concluded that in *K*-meson captures the creation of Σ hyperons, neutral or charged, is somewhat less frequent than, or about as frequent as, the creation of Λ^0 particles. This is consistent with the results of the Wisconsin group,[36] who found a $\Sigma:\Lambda^0$ ratio of 1:2.

(4) For most of the events in Group *B*, the natures of the nucleons and hyperons involved in the K^--meson capture reactions were left unspecified. If the fraction of the hyperons that are neutral is assumed to be the same in the stars with and without pions, then it is found independent of the value of that fraction, that about half of those nucleons are protons, and half neutrons. One then arrives at the result that of all the

---

[34] Λ^0 emission from K^- capture was observed by H. De Staebler, Jr., Phys. Rev. **95**, 1110 (1954).

[35] M. Teucher, Preliminary Report of the Pisa Conference 1955 (to be published), p. 327.

[36] Fry, Schneps, Snow, and Swami, Phys. Rev. **100**, 950, 1448 (1955).

K^- mesons about 21 were captured by a single proton and 15 by a single neutron. Within the statistical uncertainty the relative frequency 1.4 of captures by protons and by neutrons does not differ from the ratio 0.9 of protons to neutrons in the average emulsion nucleus. However, because of the asymmetry in the isotopic spin states of the (K^-+n) and (K^-+p) systems, such equal probability of capture by proton and neutron need not be expected.

(5) In general, the basic features of the K^- interactions here reported, such as the short mean free path, the frequencies of emission of charged hyperons and of pions and the small average size of the stars formed, are similar to the features of the K^- stars reported by us[1–5] and by other workers.[35–39] Attention is called to one difference: whereas pions of energy $\geqslant 100$ Mev come from $\frac{1}{6}$ of our stars (a similar proportion was found in plates exposed at the Bevatron[35,37]), only 1 in about 50 stars produced by cosmic rays shows so energetic a pion.[37,39] Possibly, this difference results from a bias in the scanning of the cosmic-ray plates. The further possibility cannot at present be rejected that shorter-lived K^- particles, with different interaction, predominate in the cosmic-ray emulsions.

ACKNOWLEDGMENTS

We take great pleasure in acknowledging our indebtedness to our colleagues: to G. T. Zorn for invaluable suggestions and criticisms; to R. Serber and K. A. Brueckner for discussions of relevant theoretical topics; to the Cosmotron staff for making the bombardments possible; to J. W. Quinn, for his help both in preparing the experimental arrangements and in carrying out the exposures; to M. D. Carter and P. A. Simack for processing of emulsions; to M. C. Hall, B. M. Cozine, A. Lea, J. D. Leek, E. R. Medd, and R. Wagner for microscopy; and to J. E. Smith for help in scattering measurements and other phases of this work.

APPENDIX

Event 29

In this star, produced by a K^- meson at rest, a 180-Mev proton was observed to emerge. This is the highest energy of a nuclear particle found in the present series of K-meson capture stars, and it is for this reason that assignment to reaction (II), $K^-+2p\rightarrow\Lambda^0+p$, was considered.

Ignoring Fermi motion, a proton kinetic energy of 170 Mev is calculated for this reaction, an energy in agreement with the observed value. Furthermore, if the difference between the available and the visible energy were all taken up by the Λ^0, its kinetic energy would be 74 ± 23 Mev, and its momentum of 414 ± 65 Mev/c could balance the observed residual momentum of 376 ∓ 42 Mev/c. (Note that the errors in the two momentum values are completely dependent and of opposite sign.) It is seen that the observations are consistent with the kinematics of reaction (II), which justifies the tabulation of this reaction for event 29. However, if Fermi motion is considered, reaction (II) could yield proton energies widely differing from 170 Mev, and the momenta of charged and neutral reaction products could be unbalanced by as much as 200 Mev/c. Therefore, the consistency of the observational data with the values calculated from the kinematics of reaction (II) in the absence of Fermi motion must be regarded as fortuitous and does not strongly support the choice of this reaction.

Alternatively, it is possible to choose reaction (Ib), $K^-+N\rightarrow\Lambda^0+\pi$. In that case, it must be assumed further that the high-energy proton was produced by reabsorption of the pion in the capturing nucleus. The interpretation is, then, similar to that of the other two events with protons of more than 100-Mev kinetic energy (NK 10 and NK 21). If the visible energy of star 29 ($E_v=233$ Mev) is compared with the energy typical of reaction (Ib) (281 Mev, see Table III, column 9), it is seen that about 60 Mev is left for the emission of neutrons, which, together with the Λ^0 (and possibly with Fermi momentum), could easily balance the residual momentum of 376 Mev/c.

---

[37] D. Keefe, Preliminary Report of the Pisa Conference 1955 (to be published), p. 307. A spectrum of pions emitted from K^- stars is given in this paper.

[38] Chupp, Goldhaber, Goldhaber, and Webb, University of California Radiation Laboratory Report UCRL-3044 (unpublished).

[39] Lal, Pal, and Peters, Phys. Rev. **92**, 438 (1953); Lal, Pal, and Peters, Proc. Indian Acad. Sci. **38**, 398 (1953); D. Hirschberg and L. Hirschberg, Nuovo cimento **12**, 296 (1954); Y. Eisenberg, Phys. Rev. **96**, 541 (1954); Naugle, Ney, Freier, and Cheston, Phys. Rev. **96**, 1383 (1954); di Corato, Locatelli, Mignone, and Tomasini, Nuovo cimento Suppl. **12**, 270 (1954); Macpherson, Major, Parkash, Rochester, and Short, Suppl. Nuovo cimento **12**, 275 (1954); Ceccarelli, Grilli, Merlin, Salandin, and Sechi, Nuovo cimento **2**, 828 (1955); Baldo, Belliboni, Ceccarelli, Grilli, Sechi, Vitale, and Zorn, Nuovo cimento **1**, 1180 (1955); Friedlander, Keefe, Menon, Johnston, O'Ceallaigh, and Kernan, Phil. Mag. **46**, 144 (1955); Tsai-Chü, Preliminary Report of the Pisa Conference 1955 (to be published), p. 323; Bacchella, di Corato, Ladu, Levi Setti, and Scarsi, Preliminary Report of the Pisa Conference, 1955 (to be published), p. 299. References to earlier work are given by B. Rossi, Nuovo cimento Suppl. **2**, 163 (1955).