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Capture of K^- Mesons by Nuclei*

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Seventy events of K^- capture at rest have been analyzed in emulsion stacks exposed to the Berkeley Bevatron. The distribution of prong numbers and energy release of stars is given. The average prong number was 3.3 and the maximum prong number was 10. The small average energy release was found to be consistent with the assumption that in many events a large fraction of the K^- rest energy is carried away by neutral particles. The energy distribution of emitted nucleons was found to include energies up to 200 Mev. The energy distribution of emitted pions falls into two groups, one with a sharp upper limit corresponding to the expected pion energy of Σ-hyperon reactions and the other corresponding to Λ^0-hyperon reactions. The energy release in $\Sigma\pi$ events was found to be consistent with the assumption that the capture process takes place on bound nucleons. A small difference in the energy release of $\Sigma^+\pi^-$ compared with $\Sigma^-\pi^+$ events was found, indicating a possible mass difference $M(\Sigma^-) > M(\Sigma^+)$. An estimate of the ratio of production of Σ to Λ^0 hyperons, based on pion energies, gave Σ/Λ^0 about 2. The ratio Σ^-/Σ^+ was found to be $\geq 7/3$. The emission of pions with energies of more than 100 Mev was found, providing evidence for the direct production of Λ^0 hyperons. Hyperfragments were observed in four events. In one event two fast particles of nucleonic mass were emitted, one of them disappearing in flight, providing evidence for the existence of two-nucleon reactions.

I. INTRODUCTION

THE present interpretation[1–7] of the interactions of strange particles makes it possible to predict in a simple way some of the connected phenomena of K particles and hyperons. These predictions are both an aid in understanding strange-particle phenomena and a test for the correctness of the ideas themselves. In particular, the expected reactions conserving charge, nucleons, and a strangeness in the case of a negative K meson captured at rest by a nucleon are

$$K^- + p \rightarrow \Sigma^+ + \pi^-, \tag{1}$$

$$K^- + p \rightarrow \Sigma^- + \pi^+, \tag{2}$$

$$K^- + p \rightarrow \Sigma^0 + \pi^0, \tag{3}$$

$$K^- + n \rightarrow \Sigma^- + \pi^0, \tag{4}$$

$$K^- + n \rightarrow \Sigma^0 + \pi^-, \tag{5}$$

$$K^- + p \rightarrow \Lambda^0 + \pi^0, \tag{6}$$

$$K^- + n \rightarrow \Lambda^0 + \pi^-. \tag{7}$$

Considerable evidence has been presented[8–18] that pions and hyperons are produced in K^- interactions.

Several of the possible reactions are easily recognized in emulsion events, either because they involve the emission of a charged unstable particle [(1), (2), and (4)] whose decay or interaction can be recognized, or a charged pion [(1), (2), (5), and (7)] with a particular energy. As can be seen in Table I, the energy of an emitted pion can be used to distinguish reactions in which a Σ or Λ^0 hyperon is initially produced, since even for the case of capture on bound nucleons the energy limits for emitted pions are nonoverlapping. This method is limited, of course, to cases where the pion has not lost energy by secondary interaction. On the other hand, in reactions where a neutral hyperon is emitted [(3), (5)–(7)], it is most likely that little energy will be left for excitation of the residual nucleus and only a small star or even a zero-prong ending [(3), (6)] may result.

TABLE I. Table of Q values and particle energies for various capture reactions of K^- mesons. In the case of single nucleon captures by a bound nucleon, the kinetic energy of the nucleon was assumed to be 20 Mev, and 10 Mev was allowed for binding energy. In the case of two nucleon captures, 20 Mev was allowed for binding, and the energy limits were computed by assuming both nucleons were moving in the same direction, each with a momentum of 200 Mev/c.

		Free nucleon		Bound nucleon	
Reaction	Q(Mev)	E_Y	E_π	E_Y	E_π
K^-+nucleon→$\Sigma+\pi$	103	17	86	0– 42	50– 92
K^-+nucleon→$\Lambda^0+\pi$	178	28	150	0– 65	105–170
		E_Y	E_{nucleon}	E_Y	E_{nucleon}
K^-+2 nucleons→Σ+nucleon	224	108	135	27–180	45–200
K^-+2 nucleons→Λ^0+nucleon	297	147	170	50–230	70–250

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[17] MacPherson, Major, Parkash, Rochester, and Short, Nuovo cimento **12**, Suppl. 2, 275 (1954).

[18] S. von Friesen, Nuovo cimento **12**, Suppl. 2, 273 (1954); Arkiv Fysik **8**, 305 (1954).

A K^- meson may also interact with two nucleons,[14] in which case the expected reactions conserving charge, nucleons, and strangeness are

$$K^-+p+p\rightarrow\Sigma^++n, \tag{8}$$

$$K^-+p+p\rightarrow\Sigma^0+p, \tag{9}$$

$$K^-+p+n\rightarrow\Sigma^-+p, \tag{10}$$

$$K^-+p+n\rightarrow\Sigma^0+n, \tag{11}$$

$$K^-+n+n\rightarrow\Sigma^-+n, \tag{12}$$

$$K^-+p+p\rightarrow\Lambda^0+p, \tag{13}$$

$$K^-+p+n\rightarrow\Lambda^0+n. \tag{14}$$

The expected kinetic energies of the nucleon and hyperon in these reactions are also shown in Table I. Among these reactions, only (10) can be recognized unambiguously by its two charged secondaries, but other reactions [(8), (10), and (12)] can be identified from hyperon decay or interaction, and in some cases (13) may be distinguished from (9) by the energy of the emitted nucleon.

Since the first observation of artificially produced K^- mesons from the Cosmotron,[11] it has become increasingly feasible to select beams of K^- mesons from high-energy accelerators now in operation suitable for observations in emulsion stacks. The analysis of exposures similar to the present work has been reported by a number of groups.[19–24]

II. EXPERIMENT

Sixty-seven events[25] discussed here were found in part (30 sheets) of a stack of 2 in.×3 in. 600-μ Ilford G-5 emulsion[26] exposed to a magnetically analyzed channel of the University of California Bevatron. The energy of incoming K^- mesons varied from 80 to 100 Mev across the stack and the range before coming to rest varied from 3.2 to 4.9 cm.

Events were located by area-scanning, with a magnification of 200×, a strip 2 cm wide, centered on the range at which K^- mesons were expected to stop. Stopping tracks that produced stars at their end were traced back toward the incident edge of the stack and verified to have K-meson mass by comparing ionization and range. A few starless endings due to stopping K^- mesons were observed, in agreement with other workers,[18,22] but are not included in this analysis because of the low detection efficiency for such events with the scanning method used. For K^- stars with at least one black prong, the detection efficiency was about 90%.

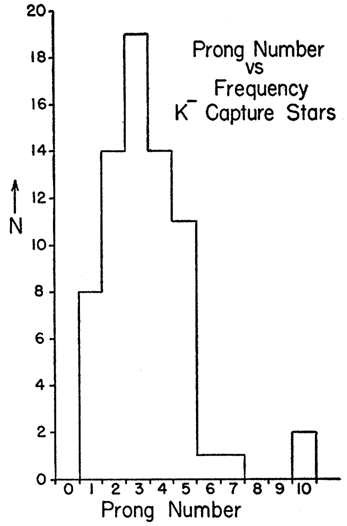

FIG. 1. Distribution of prong numbers for K^--capture stars with one or more prongs. All charged particles emitted are included in the prong number. N gives the number of events for each prong number.

All of the tracks originating in the K^- stars were traced out until they ended or left the stack. Out of the total of 237 tracks, 35 tracks left the stack. Of these 19 were fast pions, 10 were gray tracks ($2\times$minimum ionization$<I<6\times$minimum ionization), and 6 were black tracks ($I>6\times$minimum ionization).

The energy of emitted particles was obtained from measurement of range in the case of stopped particles. Of the fast tracks, all favorably located tracks were identified by a comparison of ionization and scattering and frequently results obtained in successive plates were combined to improve statistical accuracy. For each fast track, a calibration of grain density was obtained in the same region of the emulsion using the fast pions that accompany the K^- mesons in the momentum analyzed beam. The energy of these pions was calculated from the observed ranges of the K^- mesons, assuming them to have τ-meson mass, and correcting for energy loss of the pions in the emulsion.

III. RESULTS

A. Prong Distribution

The prong distribution for K^- stars with one or more prongs is shown in Fig. 1. The average prong number computed from the distribution shown in the figure is 3.3. The average prong number for stars that include a pion is the same within statistics. However, for stars that include a hyperon, the prong number is 2.1.

The frequency of emission of various types of par-

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[19] J. Hornbostel and E. O. Salant, Phys. Rev. **98**, 218 (1955); **102**, 502 (1956).

[20] S. C. Freden and H. K. Ticho, Phys. Rev. **99**, 1057 (1955).

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[23] George, Herz, Noon, and Solntseff, Nuovo cimento **10**, 95 (1956).

[24] Fournet, Pevsner, Ritson, and Widgoff, Bull. Am. Phys. Soc. Ser. II, **1**, 64 (1956).

[25] Three additional events located in a stack exposed to 3.0-Bev π^- mesons from the Bevatron are also included in this analysis.

[26] We are indebted to Professor W. F. Fry for sharing with us part of his stack. The exposure is described in his paper, Phys. Rev. **100**, 939 (1955).

TABLE II. Table of frequency of emission of various particles from K^- stars. Protons with energies of more than 35 Mev are listed as fast protons. The last column refers to events with only black prongs, with energies of less than 35 Mev, if protons. Note that the categories are not mutually exclusive.

Emitted particles	Pion	Charged hyperon	Hyper-fragment	Fast proton	Evaporation prongs only
Number of events	20	10	4	18	22
Percentage	29±6	14±5	6±3	26±6	31±7

ticles is shown in Table II. Events in these categories will be discussed in greater detail separately.

B. Energy Distributions

The total kinetic energy release in the form of charged particles from K^- stars is shown in Fig. 2. Singly charged nuclear particles were assumed to be protons. This assumption leads to an underestimation of the energy release, since deuterons and tritons are also emitted in stars, but the error is small. In every event the kinetic energy release was sufficiently small to be consistent with the assumption that a hyperon was produced.

The energy distribution of emitted pions is shown in Fig. 3. The shaded part of the histogram represents the pions in events from which a definitely identified Σ hyperon has been emitted. In three additional cases a pion in the same energy interval is emitted in association with a black prong. Whether these can be regarded as additional cases of Σ^- emission where the Σ^- forms a starless ending, will be considered later.

The spectrum strongly suggests two distinct energy groups corresponding to the pion energies appropriate to the different hyperon reactions [(1)–(5) and (6), (7)]. The sharp upper limit to the first energy interval is made up almost entirely by events where a Σ hyperon and a pion have escaped with little interaction in the capturing nucleus. The average energy in the lower interval of about 40 Mev is consistent with the pion energies expected from Σ reactions, if allowance is made for inelastic scattering in the capturing nucleus. Inelastic scattering can obviously reduce the energy of a pion originally in the high energy group to the lower energy group. However, this effect is difficult to estimate. Pion energies in the upper energy group are consistent only with reactions in which Λ^0 hyperons were produced. No pions have been found in the energy range between 90 and 120 Mev.

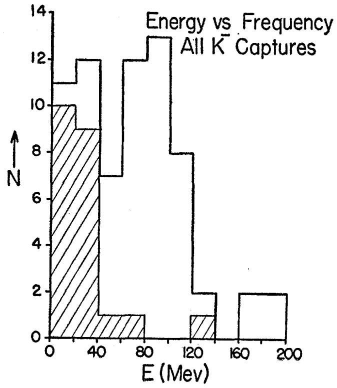

FIG. 2. Kinetic energy release in the form of charged particles from K^--capture stars. Shaded portion of histogram represents 22 events from which only black prongs were emitted.

The energy distribution of particles of nucleonic mass from K^- stars is shown in Fig. 4. It is seen that most of the nuclear particles emitted are of low energy, but that some energetic nucleons occur. Except for the higher energies these particles can be consistent with stars formed by the reabsorption of pions. The higher energies, however, are consistent only with interactions of the K^- meson with two nucleons.

C. Emission of Σ Hyperons

In ten events, the stopping of a K^- meson resulted in the emission of a charged hyperon. Three of these cases are identified as positive, since the hyperon stops and gives rise to a single proton track with the characteristic 1.65-mm range. Five cases in which the hyperon stops are identified as negative. Three of these five cases give rise to a star, and the other two end with associated Auger electrons. One event is interpreted as the decay in flight of a negative hyperon and another as the charge exchange of a negative hyperon in flight.

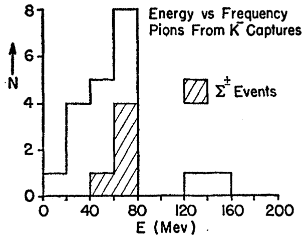

FIG. 3. Energy distribution for pions emitted from K^--capture stars. Shaded area represents pion energy in two-prong $\Sigma\pi$ events.

In six of the above-mentioned K^- stars, the hyperon is produced in association with a pion. A typical event of this kind is shown in Fig. 5. Four of these events consist of the hyperon and pion tracks alone and are well situated for accurate measurement.[27] In one of the additional cases the star contains two other prongs and in the other the pion track is too steep for accurate energy determination.

From the general appearance of these events, it could be assumed that they were due to one nucleon capture. However, since none are collinear, they cannot be captures by hydrogen, but must be captures by heavier elements in the emulsion. That the captures are by only one nucleon is strongly supported by the fact that the distribution of residual momenta for these events is consistent with the distribution of Fermi momenta of bound nucleons, which has a broad maximum near 200 Mev/c. The residual momentum dis-

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[27] Short recoil tracks (less than 2 μ) are visible in two of these events, but are disregarded in the energy and momentum balance.

tribution for the six $\Sigma\pi$ events, the three doubtful events, in which a pion is emitted along with an ending black prong, is shown in Fig. 6. These black prongs could be interpreted as stopping Σ^- hyperons, which in turn undergo the fast capture process,

$$\Sigma^- + p \rightarrow \Lambda^0 + n + Q (Q = 78 \text{ Mev}),$$

without secondary interaction of the products. Since Σ^- stars have frequently a very small visible prong number (1 or 2 prongs), it is quite probable that Σ^- endings with no visible prong do occur.

It is interesting to compare the energy release in the reactions:

$$K^- + p \rightarrow \Sigma^- + \pi^+ + Q(-),$$

and

$$K^- + p \rightarrow \Sigma^+ + \pi^- + Q(+).$$

A difference in the Q values of these reactions would be expected if the masses of the Σ^+ and Σ^- hyperon were not the same. The data for four $\Sigma\pi$ events, selected only by the requirements of measurability, are summarized in Table III. It can be seen that the average of $Q(-)$ is smaller by 22 Mev than the average of $Q(+)$. The contribution of Fermi momentum to this difference can be almost neglected, since for these cases the residual momentum varies less than ±35 Mev/c. In spite of the relatively large error in the determination of the Q (because of the pion energy) (±10 Mev), it should be noted that the discrepancy in Σ mass is in the same direction as reported in the emulsion work of Goldhaber[22] and the recent bubble chamber results of Steinberger.[28]

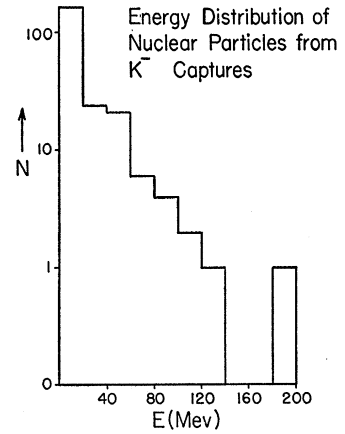

FIG. 4. Energy distribution of nuclear particles emitted from K^--capture stars. Singly charged particles were assumed to be protons.

D. Σ^--Capture Stars

Most Σ^--capture stars observed to date have been characterized by a small energy release in the form of charged particles, as would be expected, if the Σ^- capture occurs according to the reaction $\Sigma^- + p \rightarrow \Lambda^0 + n + Q$, since Q is somewhat small, only 78 Mev. The usual small energy release has been observed in this experiment. Of the Σ^- stopping regarded as certainly identified, two have associated Auger electrons, and one each has one prong, two prongs, and four prongs. If the doubtful cases, inferred from the presence of a pion near the correct energy and a residual momentum compatible with the Fermi momentum are included, three zero-prong endings were observed.

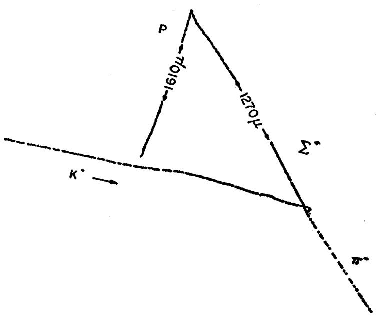

FIG. 5. Projection drawing of a typical $\Sigma\pi$ event. The Σ^+ has an energy of 18 Mev, the pion 78 Mev. The angle between them is 140°. p is the decay proton of 1.61 mm range.

The four-prong Σ^--capture star, however, is of more than usual interest. A drawing of the event is shown in Fig. 7. Prongs a and b are singly charged tracks and, if protons, have energies of 6.8 and 26.5 Mev, respectively. Track c is 1.5 μ recoil, and track d is a fast particle, steeply inclined to the plane of the emulsion. From measurement of the grain density, this track is found to have an ionization of 2.7×minimum, corresponding either to a pion of 21 Mev or a proton of 140 Mev.

Because of the small Q value of the capture reaction, the emission of such a high-energy nucleon is excluded, unless the Λ^0 decayed within the capturing nucleus, and the pion was reabsorbed. The most likely interpretation of the event is that track d is a pion due to a Λ^0 which remained bound to the residual nucleus and decayed. The observed pion energy of 21 Mev is in agreement with such an interpretation. The event could not be explained as a $Z=1$ hyperfragment, since in this case charge could not be conserved.

E. Evidence for Λ^0 Reactions

The only proof of the direct production of Λ^0's by K^- mesons captured at rest is the observation of pions with

TABLE III. Data for four $\Sigma\pi$ events. For these events the capturing nucleus is bound, as can be seen from the residual momenta and angles of emission of the products. The average energy release $Q(+)$ for $\Sigma^+\pi^-$ events is 22±10 Mev greater than the average energy release $Q(-)$ for $\Sigma^-\pi^+$ events.

Event	E_π	E_Σ	$E_\pi+E_\Sigma$	Residual momentum (Mev/c)	Angle between Σ and π
$\Sigma^+ + \pi^-$	78±14	18	96	135	140°
$\Sigma^+ + \pi^-$	76±11	16.5	92.5	197	115°
$\Sigma^- + \pi^+$	62± 9	17	79	162	116°
$\Sigma^- + \pi^+$	42± 7	23.5	65.5	153	119°

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[28] J. Steinberger, Sixth Annual Rochester Conference on High-Energy Physics, 1956, (unpublished).

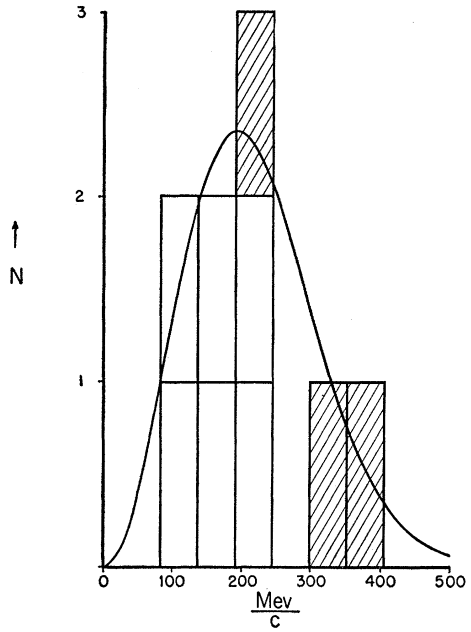

FIG. 6. Residual momentum distribution for K^--capture stars consisting of pion and hyperon only. The shaded portion represents doubtful events in which the possible hyperon ends giving a zero-prong star. The smooth curve shows the theoretical distribution of Fermi momentum within a nucleus, assuming Gaussian distribution of momentum density normalized to the area of the histogram.

too great an energy to have been produced in association with a Σ. (See Table I.) Two events provide good evidence for such direct production, because of the observed pion energy. One of these events is a 4-prong star (1,2,3,4) shown in Fig. 8. Track 1 scatters strongly and appears to stop after 7 μ, forming a four prong secondary star (a,b,c,d). Tracks 2 and 4 are singly charged black prongs, and if protons, have energies of 4.3 and 11.8 Mev, respectively. Track 3 is nearly parallel with the plane of the emulsion, and travels 1210μ before interacting to form a two prong star. From the interaction, and from measurements of grain density and scattering, track 3 is identified as a pion of 148±35 Mev. Since this pion energy is outside the energy limits for Σ reactions, it can be concluded that track 1 is not a Σ^- hyperon. It does not seem likely that track 1 is a $Z=4$ hyperfragment undergoing nonmesonic decay, since the energy release in the secondary event is small, about 15 Mev. However, if this were the case, the capture reaction is still (7). The considerable scattering along track 1 makes it seem most probable that it is a negative pion and (a,b,c,d) is a capture star. Again, it could be assumed that the pion resulted from a Λ^0 which became bound to the residual nucleus and decayed mesonically.

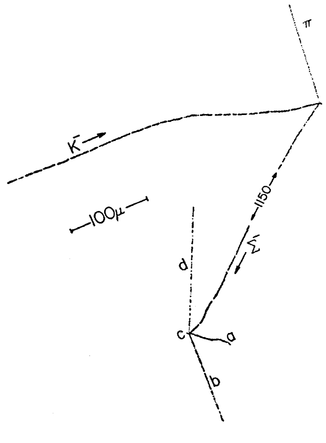

FIG. 7. Projection drawing of K^--capture star leading to an unusual Σ^- interaction. The Σ^- has an energy of 17 Mev, the pion 62 Mev, and the angle between them is 116°. In the Σ^- star, track a is a proton of 6.8-Mev energy, track b is a proton of 26.5 Mev, and c is a 1.5μ recoil track. Track d has an ionization of 2.7 ×minimum and is most probably a pion of 21-Mev energy.

In a second event, a high-energy pion is the only visible prong.[29] The secondary is favorably located, with more than 15 mm of track length available in one emulsion. The energy of the pion, obtained from combining grain density and scattering measurements, is 125±10 Mev, which is again outside the limits for Σ reactions.

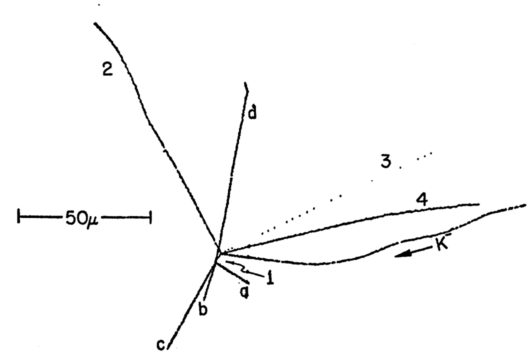

FIG. 8. Projection drawing of K^--capture star emitting energetic pion. Track 1 has a range of 7 μ, and scatters strongly, terminating in the secondary star (a,b,c,d). The total visible energy release in the secondary star, assuming a, b, c, and d to be protons is less than 15 Mev. Tracks 2 and 4 are protons of 4.3 and 8.8 Mev, respectively. Track 3 is a pion of 148±35 Mev which interacts, forming a 2 prong star after traversing 1210 μ of emulsion.

F. Hyperfragments form K^- Captures

Hyperfragments were observed in four cases of K^- capture. Of these, one has been identified as mesonic decay of $_1H^{3*}$ and has already been reported.[30] The other three cases are all nonmesonic decays and are not definitely identified. Two are most probable $Z=2$ hyperfragments, and the last is $Z=3$, or $Z=4$. The ranges of the nonmesonic decays are 3, 22, and 19 μ.

G. Two Nucleon Captures

Several events have been observed that can most readily be explained as captures by two nucleons. Of

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[29] In a previous publication from this laboratory [Williams, Haskin, Koshiba, and Schein, Phys. Rev. **100**, 1547 (1955)], this event was reported as the emission of a high-energy electron from a K^--meson capture. Re-examination of the data has shown the track in question to be a pion.

[30] Haskin, Bowen, Glasser, and Schein, Phys. Rev. **102**, 244 (1956).

particular interest is a K^- star which consists of two fast visible prongs, both of nucleonic mass. A drawing of the event is shown in Fig. 9. Track 1 has an ionization corresponding to a proton of 80±5 Mev, and leaves the stack after traversing 6.8 mm. Track 2 is emitted almost oppositely, 168° with respect to track 1, and has an ionization of 4×minimum. After traversing 10.8 mm the track disappears in the sensitive region of the emulsion at an ionization of 6×minimum. This sudden disappearance could possibly be attributed to the charge exchange of a Σ^- hyperon, according to the reaction $\Sigma^- + p \rightarrow \Lambda^0 + n$. With this interpretation, the event corresponds to reaction (10). It might be pointed out that reaction (10) is the only two-nucleon reaction with entirely charged secondaries, and the certain identification of the other two-nucleon reactions is more difficult. The possibility that the disappearance is due to the charge exchange of a proton with a neutron cannot be excluded.

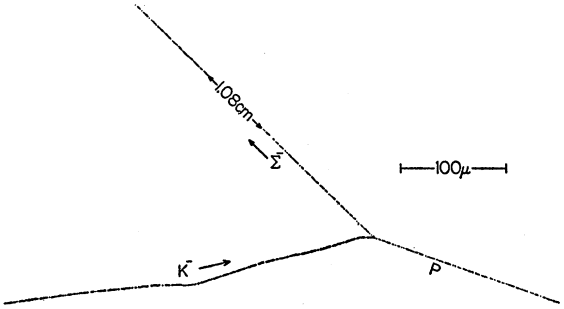

FIG. 9. Projection of K^--capture star assumed to be the result of the 2-nucleon reaction $K^- + p + n \rightarrow p + \Sigma^-$. The proton ($p$) has an energy of 80±5 Mev. The Σ^- is emitted with an energy of 95 Mev and disappears in the sensitive region of the emulsion at 6×minimum ionization, corresponding to an energy of about 60 Mev.

Protons with energies of 100 Mev or more were emitted from four K^- captures. The energies found were 100±4, 105±5, 130±12, and 185±5 Mev. Except in the last case, the stars included a few evaporation prongs as well. The last case is of particular interest as the star contains only the energetic proton and an Auger electron. It is possible that this event is an example of reaction (13), since no star is observed and the proton is near the expected upper limit given in Table I. It cannot be shown conclusively that the other events are due to two nucleon captures, but the large residual momentum in each case makes it reasonable to suppose that energetic neutral particles were also emitted, and the reactions took place according to (9), (10), or (13), and that the interaction of one of the secondaries accounts for the star.

IV. FREQUENCY OF PRODUCTION OF Σ AND Λ^0 HYPERONS

It is of interest to estimate the frequency of Σ to Λ^0 hyperon production in K^- captures. It is necessary to distinguish here between the emission of a Λ^0 and its production in the primary capture process, since Λ^0 hyperons should also be emitted in some cases where a Σ is initially produced, but undergoes either a secondary collision, a charge exchange or spontaneous decay.

To avoid the necessity of particular assumptions about the mechanism of K^- capture, our estimate is based on the relative frequency of emission of pions with energies characteristic of the two hyperon reactions. (See Table I.) In this case we assume that the pion is emitted without secondary interaction in the nucleus. In the energy interval 60–80 Mev, eight pions were observed, and in the interval 120–160 Mev,[31] two pions were observed. Since the total pion-nucleon cross section increases by about a factor of two between the median energies of these two intervals, the number of pions originally in the high-energy interval is estimated to be doubled. This would imply that the production ratio Σ/Λ^0 is roughly 8/4.

It should be pointed out that this estimate gives only the order of magnitude of the production ratio Σ/Λ^0. The estimate assumes an inverse dependence on the total cross section for the probability of pions escaping the capturing nucleus, and does not take into account the possible contribution to the 60–80 Mev interval from inelastic scatters of pions originally in the higher energy interval.

V. CONCLUSIONS

Several of the expected reactions corresponding to one nucleon capture of K^- mesons at rest have been verified. Captures of K^- mesons by two nucleons appear to occur, but with comparatively small probability, about 5%. The prong distribution and kinetic energy release of K^--capture stars indicates that in general a large fraction of the K^--meson rest mass is accounted for by the emission of neutral particles. Charged hyperons were observed in about 15% of the captures. All remaining cases are consistent with the assumption that a neutral hyperon was emitted.

K^- captures from which both charged hyperons and charged pions were emitted, were consistent with the assumption that captures occurred on a bound nucleon. The average energy release of events involving $\Sigma^-\pi^+$ was found to be less than that of the corresponding events, $\Sigma^+\pi^-$. It is possible to interpret this result as a small difference in mass of the Σ^- and Σ^+ hyperon, $M_{\Sigma^-} > M_{\Sigma^+}$.

From the pion energies observed, it is concluded that direct production of Λ^0 hyperons occur in captures of K^- mesons. An estimate of the production ratio Σ/Λ^0, based on the number of pions observed

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[31] These intervals are chosen as the most probable intervals for pions from the different hyperon reactions.

within the energy intervals appropriate to Σ and Λ^0 hyperon reactions, yields Σ/Λ^0 about 2.

VI. ACKNOWLDEGMENTS

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Modulation of Primary Cosmic-Ray Intensity*

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It is assumed that the cosmic-ray particles observed at the earth are of galactic origin, except for the occasional bursts from solar flares. With this interpretation the 11-year variation of the cosmic-ray intensity and the Forbush decreases represent depressions of the steady galactic intensity. The observed rigidity dependence of the depression indicates that magnetic fields are responsible. A quantitative investigation of the possible motion and configuration of magnetic fields capable of producing the observed effects is carried out. It is shown that, within the limitations imposed by what we think we know today of the galactic magnetic field, of solar activity, and of interplanetary fields, serious difficulties are encountered by any mechanism, such as Morrison's interplanetary cloud model, modulating the galactic cosmic-ray intensity throughout the solar system.

It is proposed that the modulation of the intensity is produced locally, within a few earth's radii, by interplanetary magnetic gas clouds captured by the terrestrial gravitational field. Such a model seems to produce the observed effects on the basis of the known facts about solar activity. The most straightforward test of this geocentric model, independent of inferences from cosmic-ray effects, is the question of whether the absorption of the captured magnetic hydrogen gas can be detected as a narrow line in the center of the broad solar L_α emission line.

I. INTRODUCTION

FOR some years it has been known that the cosmic-ray intensity in the atmosphere of the earth changes with time, but it has been only the last few years that it could be shown that the changes were due to variations in the primary cosmic-ray intensity and therefore not meteorological in origin or induced by changes in the geomagnetic field. At the same time it has become clear that the variations in the primary spectrum are related somehow to solar activity, though apparently many effects occur simultaneously and the solar relation is not a simple one: low-energy studies show that the variations are a function only of the particle rigidity, the variations being larger for smaller rigidities.

It is indeed fortunate that the theoretical study of the dynamical properties of ionized gases, plasma dynamics, has been pushed ahead in the last decade, because the electromagnetic fields associated with plasma motions afford the only known coupling between cosmic-ray particles and the matter throughout space, except, of course, for short-range nuclear forces that come into play in nuclear collisions. Naturally the attempts to account for the observed variations in the cosmic-ray intensity have appealed to plasma motions; observations would seem to indicate that the most of space is occupied by streaming gases carrying magnetic fields. The high electrical conductivity and relatively slow variations in the gas suggest that the displacement current and the inertial separation of electrons and protons may be neglected, leading to the hydromagnetic approximation of the electromagnetic field equations[1] wherein the gas is treated as a classical conducting fluid.

In this paper we shall concern ourselves with the hydromagnetic processes which might be expected to produce a modulation effect in a pre-existing steady primary cosmic-ray spectrum. In particular, we shall be interested in schemes by which the sun could modulate the galactic cosmic-ray spectrum within the confines of the solar system.

Several interesting hydromagnetic modulating devices are already well known and may be found in the literature. Alfvén has made use of the fact that the magnetic field carried in a rapidly moving beam or jet of ionized gas in interplanetary space will give rise to an electric field for an observer in a fixed frame of reference; he suggests[2] that the resulting electrostatic accelaration of

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[1] W. M. Elsasser, Phys. Rev. **95**, 1 (1954).

[2] H. Alfvén, *Cosmical Electrodynamics* (Clarendon Press, Oxford, 1950).