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MECHANISM OF HYPERFRAGMENT FORMATION IN K^- CAPTURE

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ABSTRACT

In an attempt to understand the mechanism of hyperfragment production, a sample of 63 parent stars of hyperfragment production has been studied. These were selected to have a fast pion or proton accompanying the HF emission. The pion charges and energy distributions as well as the proton spectrum are used to establish the HF production process. Hyperfragments are emitted preferentially opposite to the direction of emission of associated pions or fast protons. The energy spectrum of the negative pions emitted from the K^-- capture stars in association with hyperfragments can be separated into two groups, the one of lower energy being larger. On the other hand, the fact that all the π^+ mesons have energies typical of the lower-energy group confirms the assumption that the π^+ must originate in association with Σ^- hyperons. We thus deduce that a majority (71%) of the Λ's originate in Σ-conversion processes. We evaluate the frequency of π^0 emission in association with hyperfragment production. The reactions for the production of Λ's by K^- absorption on one or two nucleons are discussed. Attempts to separate K^- captures in C, N, or O from those in Ag or Br are almost completely successful. We estimate that less than 20% of the multinucleon absorption occurred in heavy elements.

I. INTRODUCTION

Lambda hyperons are known to be attracted by nuclear matter to form bound states with all stable nuclei except the nucleon itself. The Λ-nuclei systems are referred to as Λ hypernuclei or hyperfragments (HF).

During the last decade, considerable work has been done on the analysis of hyperfragments, but little has been done on the actual mechanism of hyperfragment formation.[1-9] Although many authors have speculated on different mechanisms of hyperfragment formation, the lack of experimental data precluded the favoring of one model over another.[5,6,10,11] Until now, also, few direct measurements have been made on the interaction between the nucleon and the Λ hyperon.

We attempt here to investigate the mechanism of hyperfragment formation in K^- capture at rest in emulsion nuclei. The hyperfragments are identified with greater certainty by studying the parent star as well as the hyperfragment decay (Sections II and III). This type of study of parent stars also helps greatly in checking the identity of the produced hyperfragments, which are customarily identified from their decay schemes. In Section IV we discuss the analysis of parent stars produced by K^- capture in emulsion nuclei; determination of the relative number of hyperfragments produced in light (C, N, O), and in heavy (Ag, Br) elements of the emulsion is emphasized. Properties of hyperfragments are discussed in Section V. In Section VI, primary reactions involving the production of hyperfragments are considered.

II. EXPERIMENTAL PROCEDURE

A 9-inch-cube stack consisting of 360 pellicles of K.5 emulsion 600-μ thick was exposed to the Bevatron beam of 434-MeV/c K^- mesons by the Barkas research group. The K^- mesons penetrated approximately to the center of the stack before stopping. The flux of the beam was $\approx 10^4\ K^-/cm^2$. The central region of pellicles selected from the middle of the stack was area scanned for K^- stars at rest. All events in which a stopping K^- meson produced a double star of a recognizable hyperfragment were recorded.

From approximately 10 000 K^- stars, we found 63 hyperfragment stars having an associated high-energy pion, or a high-energy proton (kinetic energy > 30 MeV) with or without an accompanying pion, and in each case having a dip angle < 30°. Of the total 63 events selected for analysis, 35 had a pion, 19 had high-energy protons but no pions, and 9 had both a high-energy proton and an accompanying pion. All the prongs of the parent stars of the 63 events were followed until they interacted, came to rest, or left the stack. The dimensions of our stack were large enough that no proton track left the stack. All but 16 pion tracks were followed to their ends. Of these only eight either interacted or left the stack while still possessing a residual range greater than 1 cm, as determined from ionization measurements.

III. ENERGY DETERMINATION

The energies of stopping particles were determined most accurately by measuring their ranges. In the few cases for which there was much scattering at the end of the track, a range microscope was used for the measurement of the last portion of the track.[12]

The residual energy of particles that either left the stack or interacted in flight was estimated by ionization measurements made in pellicles that had been the subject of extensive calibrations. Barkas[13] has derived a rather complete statistical theory of track structure in emulsion; this theory was used for determining the ionization of tracks. For heavy ions we used the range-energy relationship of Heckman et al.[14] These data, determined for a wide variety of ions, are adjusted for the effects of electron pickup and are very useful for the short tracks with which we are here concerned.

IV. PRODUCTION OF HYPERFRAGMENTS FROM LIGHT AND HEAVY ELEMENTS

We have followed the procedures previously used with π^- capture[15-17] and with K^- capture[18] by emulsion nuclei in order to distinguish between a K^- capture in light (C, N, O) and in heavy (Ag, Br) elements of the emulsion. These procedures, which are discussed below, make use of (a) the difference in height of Coulomb potentials for light (C, N, O) and for heavy (Ag, Br) nuclei, and (b) the presence or absence of Auger electrons associated with the capture stars.

1. The minimum values of the effective height of the potential barrier for Ag and Br in emulsion are considered to be about 3.3 MeV for protons and about 6.5 MeV for α particles.[17] In our emulsion this corresponds to a range of 90 μ for protons and of 30 μ for α particles. The emission of protons or α particles with ranges shorter than these values for K^- stars may be interpreted as evidence for capture in a light nucleus of the emulsion. Those stars that have a singly or doubly charged prong of range $< 30\ \mu$ are thus considered as captures of the K^- meson by a light element. This will give a lower limit to the true number of captures in light elements. Figure 1 is a plot of the range distribution of the shortest track connected with a K^--capture star. The ranges of all prongs are greater than 2.5 μ, which is considered the upper limit for the recoil of a nucleus. The fraction of hyperfragment parent stars that probably originated in C, N, or O is large, and it appears to increase with the charge Z of the hypernucleus emitted; with $Z \geq 5$, the distribution is composed entirely of hyperfragments. As shown later in this section, most of these hyperfragments originated in K^- capture by C, N, or O. This is in agreement with the results from studies of the range distribution of Li^8, which show that more than 75% of these fragments originate from light nuclei in K^- capture.[6] There is a possibility that light hypernuclei H_Λ or He_Λ may be produced in K^- capture in heavy nuclei, but

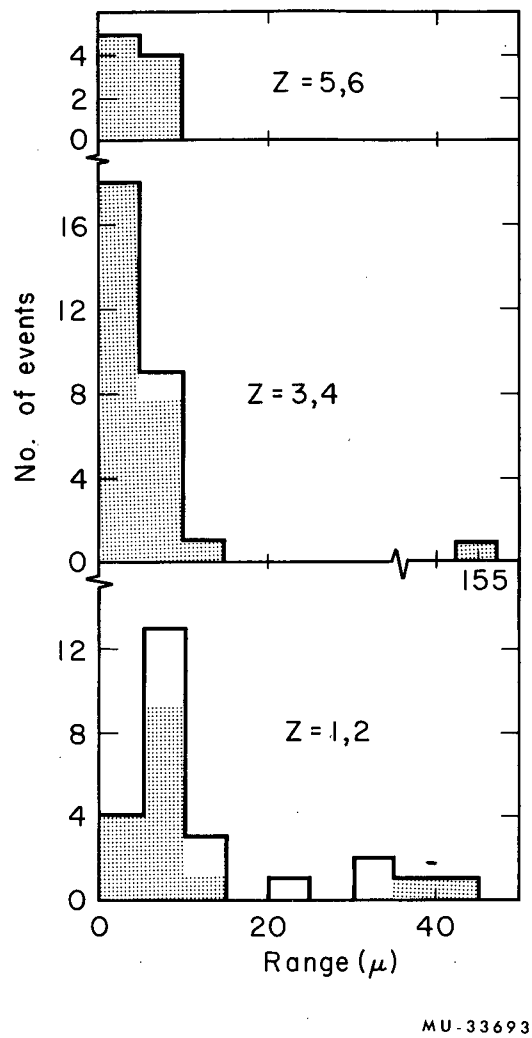

Fig. 1. Range distribution of the shortest prong (> 2μ) from K^- stars at rest, associated with hyperfragments of charge Z. The shaded area indicates events in which the shortest prong is the hyperfragment itself.

heavy hypernuclei with $Z \geq 3$ may be ruled out since the depth of the nuclear potential normally is too great for such hypernuclei to escape. Those that do not escape produce cryptofragments.

2. The absence or presence of Auger electrons accompanying the capture of negatively charged particles in nuclear emulsion has been used as one of the criteria for captures in light or in heavy elements of the emulsion, respectively. Theoretical[19] and experimental[17,20,21] investigations have shown that the mesic Auger effect is much more common in captures on heavy emulsion atoms than in captures on light ones. Indeed, it may be neglected for the light elements C, N, and O.

We checked the center of each of the 63 parent stars, searching for Auger electrons. We noted all blobs having four or more grains, since such a blob may be an electron with energy of about 16 keV, produced by the cascading K^- meson. Out of a total of 63 parent stars having hypernuclei, we found only two events with definite electrons and two events with probable Auger electrons. The background formed by random electron tracks at the star was considered negligible. Since, from this total of four Auger events, we are able to identify none as being definitely an example of K^- capture on a light nucleus, we feel justified in using the presence of an Auger electron as one indicator of K^- absorption on a heavy nucleus; this criterion is in agreement with the works quoted above. Since we found only 12 hyperfragments whose range, charge, and concomitant-prong ranges were of the right magnitude to allow them to be classed as possibly coming from heavy nuclei, we estimate that an upper limit of 19% (12/63) may be placed on the fractions of hyperfragment production taking place in heavy elements. Figure 2 shows the prong-number distribution of parent stars containing hyperfragments of Z = 1, 2, 3, 4, 5, or 6.

V. DETAILS OF HYPERFRAGMENTS

In Fig. 3(a) is shown the histogram of Z values of the hyperfragments whose production was associated with at least one charged, fast particle (π or p). The shaded portion corresponds to mesic hyperfragments. Mesic hyperfragments predominate for Z = 1, and for Z > 1 the nonmesic hyperfragments are more abundant, in agreement with observations by many others. The charge value Z of each hyperfragment was measured from the total visible charge of its disintegration products, obtained either from ionization determinations or track-width measurements. Width measurements on the track of the hyperfragment were also made when possible in order to check the charge estimate. Figure 3(b) gives the range distribution for all hyperfragments that came to rest. Around 90% of the hyperfragments have a range of less than 45μ.

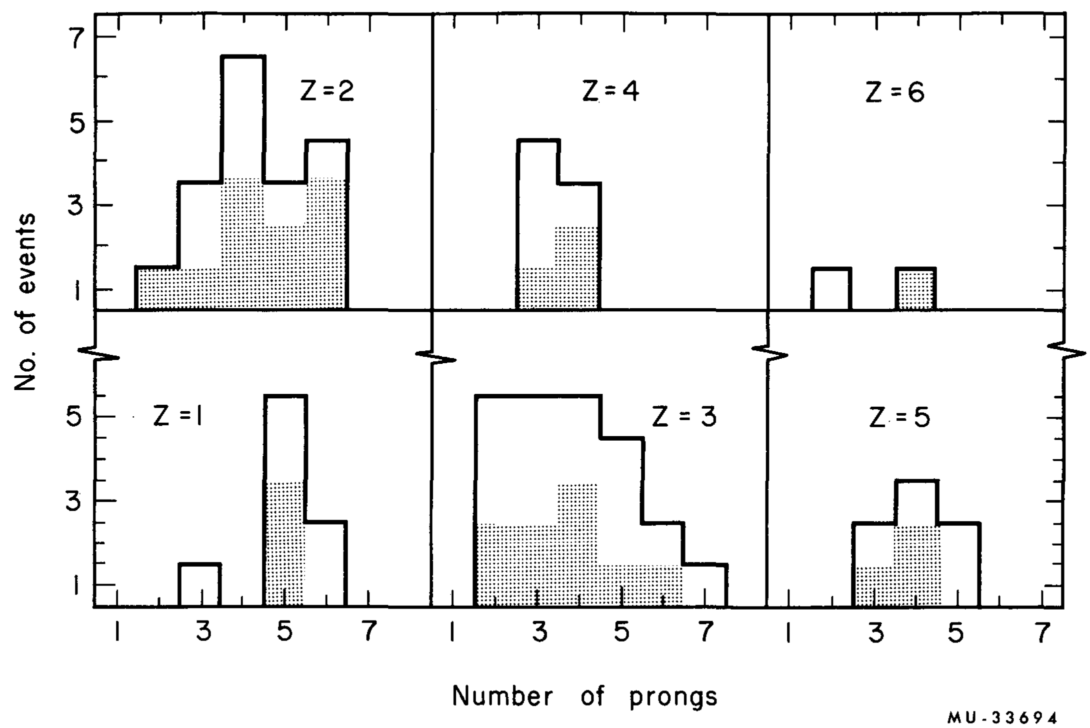

Fig. 2. Prong-number distribution of the parent stars of HF of charge Z = 1, 2, 3, 4, 5, and 6. The shaded squares (mesic HF0 indicate that a π^- was emitted from the K^- star in association with the HF. Use is made of this information in estimating the total charge of the parent star from the prongs making up the star.

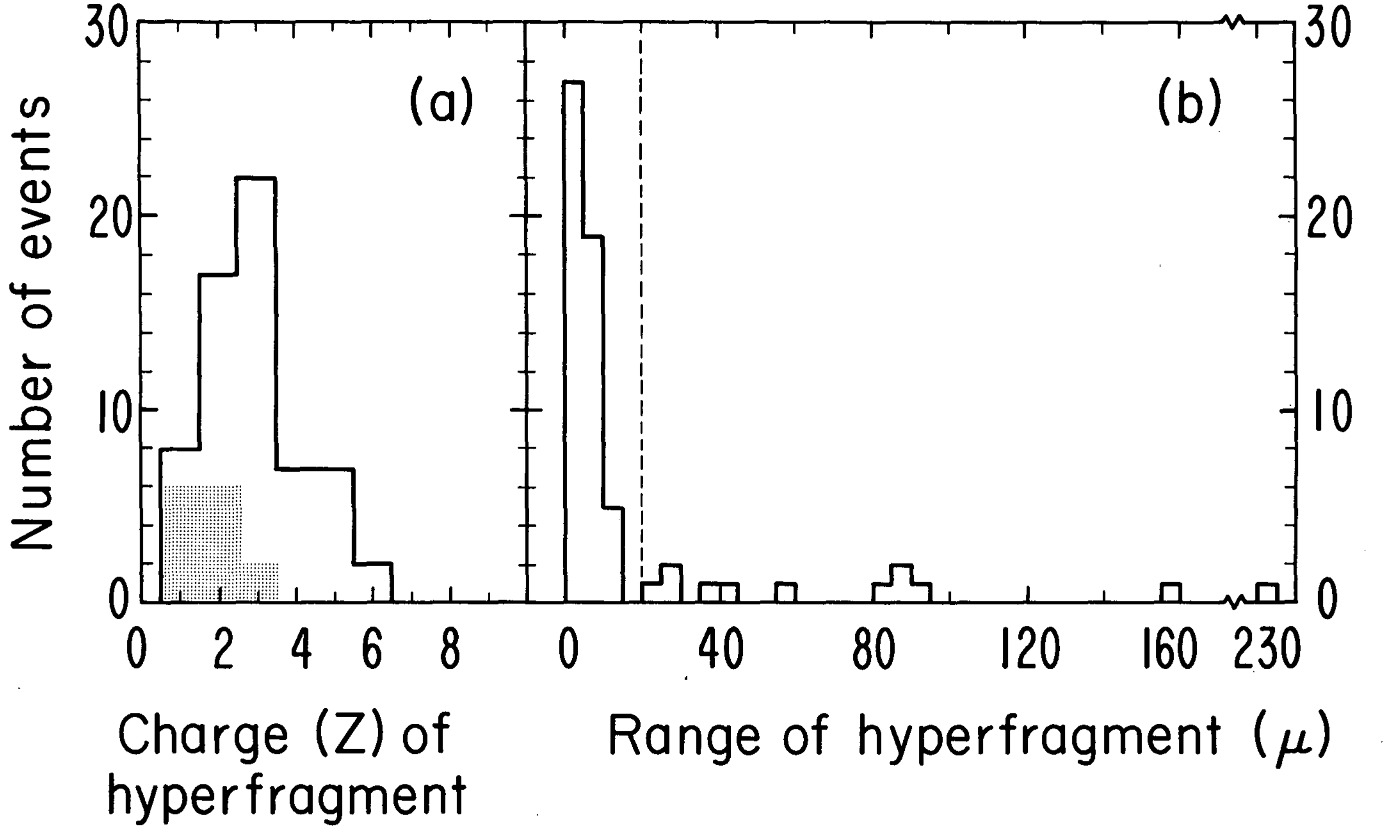

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Fig. 3(a). The charge distribution of hyperfragments. The shaded area (mesic HF) give information on whether the hyperfragment is mesic or nonmesic. (b). Range distribution of the hypernuclei studied in this report. The Coulomb barrier lower limit for emission of a charged particle with $Z > 1$ from a heavy nucleus is indicated by the dashed line.

The momentum spectrum of all hyperfragments is shown in Fig. 4. For comparison the normalized momentum distribution of free Λ's from K^- captures in He is also shown.[22] Lower momentum values are assumed to be mostly from the Σ-conversion events, whereas higher momentum values supposedly come from direct Λ events. Although the average momentum expected from a single-nucleon K^- capture is about 250 MeV/c, it is about 580 MeV/c from a two-nucleon capture, with some spread due to the Fermi motion of the nucleons. There are more low-momentum hyperfragment events. Such a difference between the two spectral shapes may be due to Σ conversion. The relation between hyperfragment momentum and the cosine of the space angle ϕ between the hyperfragment and associated pion or proton ($T_p > 30$ MeV, where T_p is the kinetic energy of the proton) is shown in Fig. 5. It indicates that hyperfragments of higher momenta tend to be preferentially emitted at large angles with respect to the pion or fast proton.

Figure 6 is a plot of average fast proton or pion momentum vs associated HF charge. The two distributions are quite similar. The proton distribution stays close to 400 MeV/c and the pion distribution is fairly constant at 160 MeV/c.

VI. PRIMARY REACTIONS INVOLVED IN HF PRODUCTION

The following general reactions produce Λ hyperons when K^- mesons are captured by emulsion nuclei:

Capture by a single nucleon (most of the energy is carried away by the π meson):

$$K^- + N \rightarrow \Lambda + \pi \text{ (direct } \Lambda \text{ production)}, \tag{1a}$$

$$K^- + N \rightarrow \Sigma + \pi \text{ (} \Sigma \text{ conversion, } \Sigma + N \rightarrow \Lambda + N). \tag{1b}$$

Capture by two nucleons:

$$K^- + 2N \rightarrow \Lambda + N \text{ (direct } \Lambda \text{ production)}, \tag{2a}$$

$$K^- + 2N \rightarrow \Sigma + N \text{ (} \Sigma \text{ conversion, } \Sigma + N \rightarrow \Lambda + N). \tag{2b}$$

Another conceivable reaction is $K^- + 2N \rightarrow \Lambda + N + \pi$. If a Σ is produced initially, it may produce a Λ in a secondary reaction with a nucleon. It was mentioned in Sec. II that the total number of selected hyperfragments was 63; of these, 19 events were accompanied only by high-energy protons ($T_p > 30$ MeV), 35 events were accompanied by charged pions, and 9 events by a pion and a high-energy proton. Out of the total of 44 pions, 28

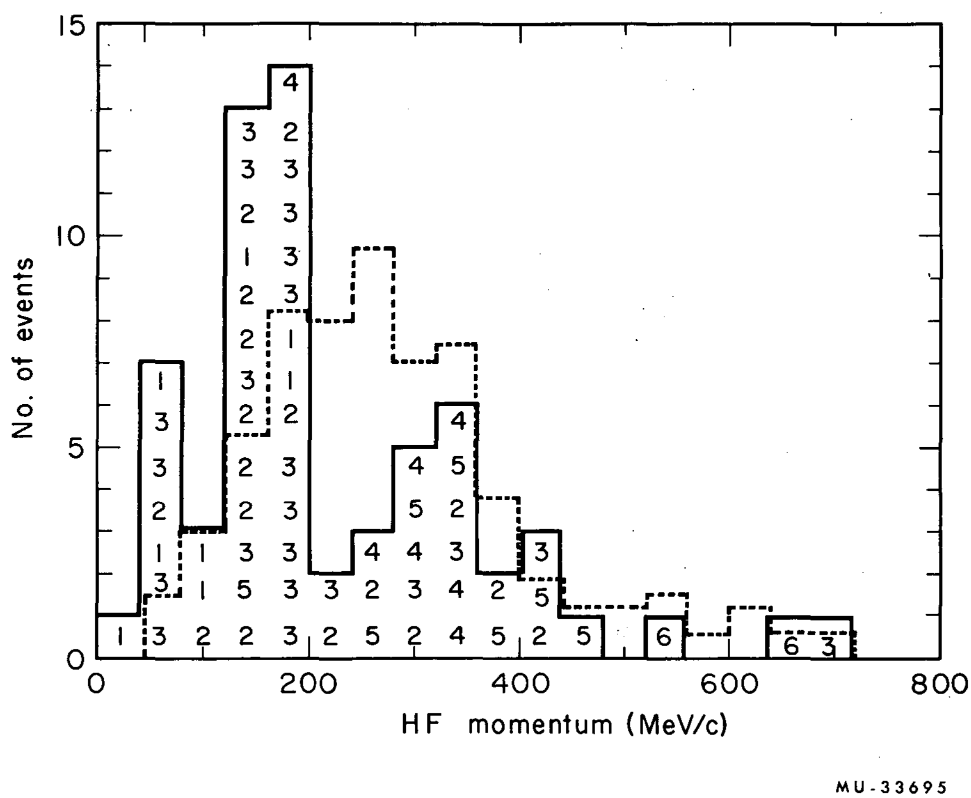

Fig. 4. Momentum spectrum of the emitted hyperfragments (whose charge is indicated by a number in each square of the histogram) from K^- captures at rest in nuclear emulsion, compared with the momentum spectra of free Λ's from K^- capture in He (according to Helium Bubble Chamber Collaboration Group). The spectra are normalized to equal areas: ———, HF; - - -, Λ particles in He bubble chamber.

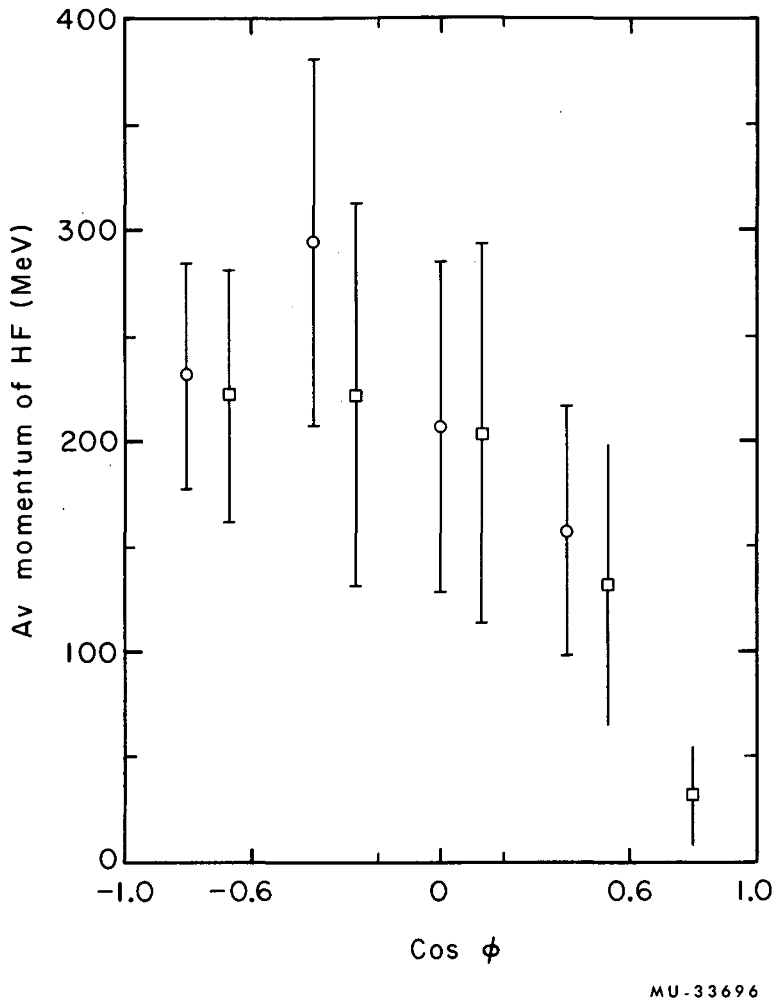

Fig. 5. Plot of cos ϕ (ϕ is the space angle between the hyperfragment and the pion or fast proton) vs the average hyperfragment momentum. The momentum average is taken within a space-angle interval of $\Delta \cos \phi = 0.4$. The error flags on the points indicate only a statistical weight proportional to the number of events in the $\Delta \cos \phi$ interval used to compute the average. O, pion; □, proton.

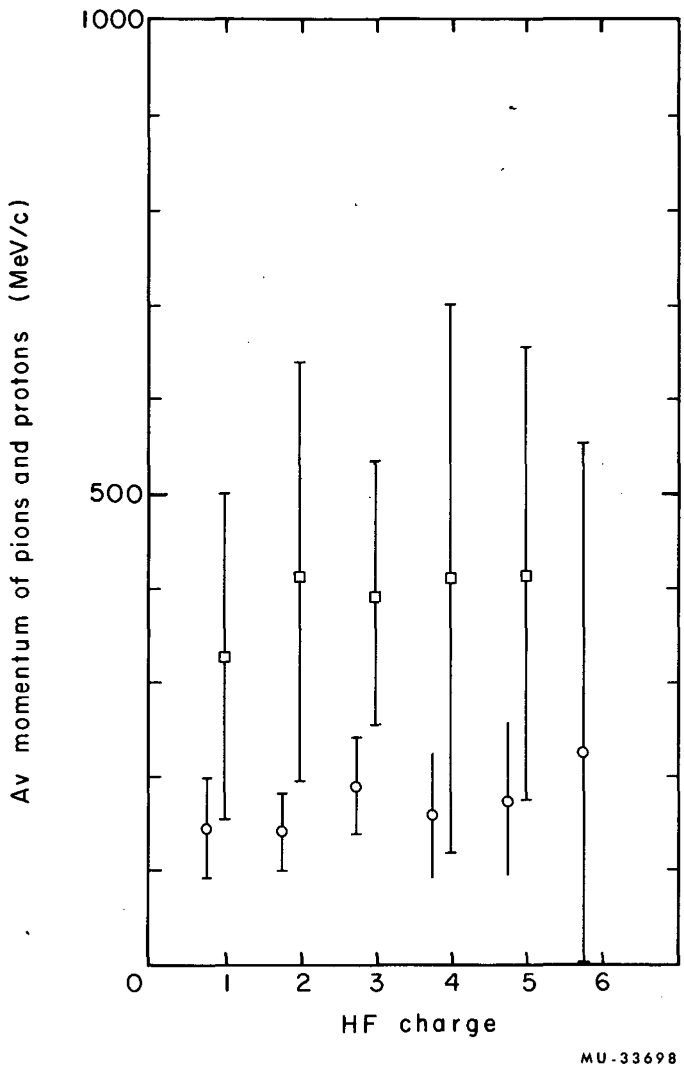

Fig. 6. Plot of average pion or proton momentum versus HF charge. The error flags on the points indicate only a statistical weight proportional to the number of events associated with a particular hyperfragment charge. O, pion; □, proton.

were brought to rest in the stack. The ratio of negatively charged stopping pions (22) to positively charged ones (6) was ≈ 4:1 (π^-/π^+). The energies of the 16 pions not brought to rest were determined by ionization measurements. Eleven pions in this group had energies greater than 95 MeV and were presumably negative. Of the remaining five pions, one scattered inelastically but came to rest and its charge was found to be negative. A second pion was absorbed in flight by a nucleus (DIF) but was so nearly stopped that we presumed it was negative in order for it to have penetrated the Coulomb barrier. This means that a maximum of only three pions could have been positive. If we assign these three pions of undetermined charge to the positive and negative groups in the same ratio (22:6) as the 28 stopping pions, then the π^-/π^+ ratio becomes 37/7 = 5:3. The energy spectra of all the pions is shown in Fig. 7 (a) and (b).

A. One-Nucleon Capture

We first discuss the one-nucleon interaction. The single-nucleon interactions of K^- mesons result in the production of a hyperon and a π meson. The kinetic energies of all pions emitted from the hyperfragment-parent stars have been plotted in Fig. 7(a) and (b). If charge exchange[23] and charged-pion absorption[24] are neglected, then presumably all single-nucleon capture processes are included in Fig. 7(a) and (b), excepting those events in which neutral π mesons are produced. The latter will be accounted for, however. The energy spectrum of the π^- may consist of two energy groups, the one large group centered around 70 MeV and a second smaller group centered around 125 MeV. Events with energies less than 100 MeV are assumed to consist largely of pions produced in Reactions (1b) (Σ conversion), since severe π^- energy degradation by scattering within the nucleus may be neglected, as shown at the end of this section. All events with energies greater than 100 MeV are presumed to be due to Reaction (1a) (direct Λ production) with Q value ≈ 170 MeV.

For a positive pion, the only production mechanism other than charge exchange (considered negligible) is the reaction yielding (Σ^-, π^+), with a Q value of 95 MeV. Thus normally there should be no pions above 95 MeV from the reaction in which any Σ hyperon is involved. In fact, none of the six positive pions observed had an energy greater than 81 MeV. Figure 7(c) shows the energy distribution of pions produced in the one-nucleon reaction ($\Sigma^{\pm}$, $\pi^{\mp}$).[25] It is in agreement with the above statements.

We can estimate the number of neutral pions emitted on the basis of the branching ratios obtained in the K^- collaboration for K^--meson absorption at rest in nuclear emulsion.[23]

From Fig. 7(b) we obtain the number of positive pions emitted. Pions of energy greater than 30 MeV were restricted by our criterion to those that had relatively flat trajectories (dip angle ≤ 30°). Therefore only half the

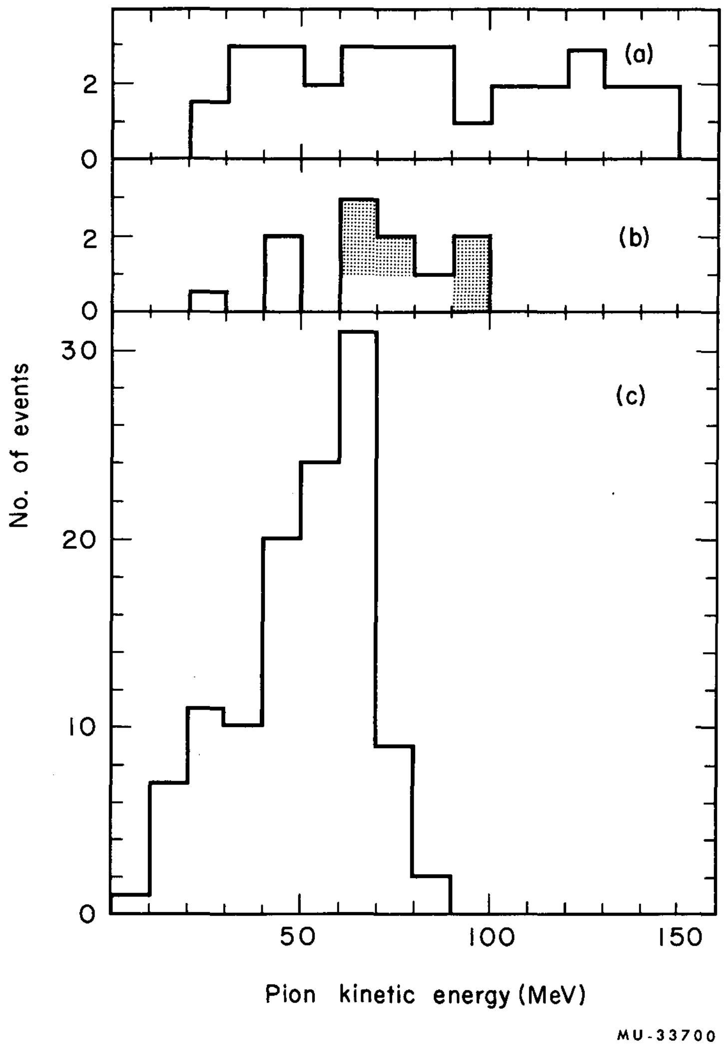

Fig. 7(a). Energy spectrum of negative pions with dip angle < 30° emitted by HF parent stars. Events in the interval 20 to 30 MeV are normalized because here all angles were accepted. This explains the presence of a fraction of an event in the histogram. —, π^-. (b). Same as part (a) except positive pions and those of undetermined charge are represented. ▦, $\pi^{\pm}$; □, π^+. (c). Energy spectrum of pions with dip angle <30° emitted from K^- capture stars and associated with $\Sigma^{\pm}$ (according to Dyer).[24] The data are not normalized. —, $\pi(+, -, \pm)$.

pion spectrum could be obtained and a correction factor of 2 must be introduced. Also, the number of pions of undetermined charge with energy less than 100 MeV were divided into positive and negative groups according to the procedure outlined in the preceding subsection. This added one pion to the π^+ group.

We obtained 13 as the total corrected number of positive pions that were presumably from the reaction $K^- + p \rightarrow \Sigma^- + \pi^+$. This number then allows the calculation, on the basis of charge independence,[24] of the number of pions to be expected from each of the other single-nucleon reactions in which a Λ might finally be produced, either directly or by Σ conversion. These reactions are:

$K^- + p \rightarrow \Sigma^+ + \pi^-$ (experiment 28), (3)

$K^- + p \rightarrow \Sigma^0 + \pi^0$ (calculated as 15), (4)

$K^- + p \rightarrow \Lambda + \pi^0$ (calculated as 10), (5)

$K^- + n \rightarrow \Sigma^- + \pi^0$ (calculated as 10), (6)

$K^- + n \rightarrow \Sigma^0 + \pi^-$ (calculated as 10), (7)

$K^- + n \rightarrow \Lambda + \pi^-$ (calculated as 23, experiment 24). (8)

For Reaction (8) the calculated number (23) may be compared with the number found experimentally. We had 11 pions with energy greater than 100 MeV; we attribute these to Reaction (8). The dip correction increases this number to 22, and the correction for absorption brings the number up to 24 (we assumed 10% absorption as previously stated). Therefore to Reaction (8) we assign the corrected experimental value of 24 pions. The calculated value was 23, in good agreement. This would indicate that the number of π^- mesons from direct Λ production, which scatter inelastically into the region of $T_\pi < 100$ MeV, is quite small. Hence π^-'s below 100 MeV were regarded as indicators of Σ conversion.

1. <u>Direct Λ Production</u>

Charged pions above 100-MeV energy comprise about $22/109 \approx 20\%$ of the total number of pions, and are produced in about $11/63 \approx 18\%$ of the hyperfragment-forming events. We attribute these to the direct (Λ, π) Reaction (1a). This is a lower limit. The total number of hyperfragments produced directly by Λ's could be somewhat larger owing to the greater inelastic-scattering cross section for pions in this energy interval. As a result, there would be pions which, although they were produced by (Λ, π) reactions, would scatter inelastically in the nucleus and thus be observed in the interval of energy range $T_\pi < 100$ MeV. As shown previously, we believe that this number is small. There is also some loss of π^- mesons, which are absorbed while coming out of the nuclei in which they are produced. We consider the π^-

absorption loss to be 10%.[9,26] Therefore we estimate the total fraction of hyperfragments formed by the capture of directly produced Λ hyperons in Reaction (1a) as 29%. Inelastic scattering may, however, contribute to a degradation in energy of pions that were directly produced in association with Λ's. Their T_π remains above 100 MeV, however.

2. Indirect Λ Production through Σ Conversion

In Sec. VI.A.1 it was estimated that in 29% of the cases of hyperfragment production from K^- one-nucleon interactions, the Λ is produced directly. Thus in the remaining 71% of the cases of one-nucleon capture, the Λ forming the hyperfragment is presumably produced through the Σ-conversion Reaction (1b), where an energetic nucleon is produced along with the π^- meson. Thus, Σ conversion in the capturing nucleus plays a major role in producing hyperfragments.

By comparing our results with data gathered by the Bologna group[27] on inelastic scattering of π mesons, we see that high-energy protons are not produced from the inelastic scattering of π mesons of average energy 50 MeV coming from the (Σ, π) reaction. The conversion processes involving Σ hyperons are:

$$\Sigma^- + p \to \Lambda + n, \qquad (9)$$

$$\Sigma^+ + p \to \Lambda + p, \qquad (10)$$

$$\Sigma^0 + p \to \Lambda + p, \qquad (11)$$

$$\Sigma^0 + n \to \Lambda + n. \qquad (12)$$

From the above interactions one may deduce that a fast proton can be produced only through the absorption of a Σ^+ or Σ^0. However, the production of Σ^+ and Σ^0 must take place in association with a π^- or π^0 meson. Therefore the interaction of the Σ hyperon would be expected to have a strong correlation with negative π mesons. If a hyperfragment-parent star emits both a high-energy proton and a charged pion, then the pion should generally be negative, and the concomitant fast proton may be regarded as an indicator of indirect Λ production by Σ^+ or Σ^0 absorption; Σ^- absorption does not usually yield fast protons.[23]

Of the eight pions of identified sign associated with high-energy protons, only one was positive, thus indicating that most such protons originate from Σ^+ or Σ^0.

We may further compare our pion-energy spectrum in Fig. 7(a) with results of deuterium[28] experiments for which two distinct peaks correspond to direct Λ production and to indirect Λ(Σ-conversion) processes.

The two peaks of this distribution are shifted towards values higher than those of our pion-energy spectrum. One could explain this difference by considering the deuteron structure to be so loose that the absorption of a K^- meson takes place on a more-or-less free nucleon, whereas in a complex nucleus this available energy is reduced by the higher binding energy of the nucleons. Furthermore we may compare the higher energy distribution of charged mesons emitted in direct Λ production.[29] The two energy spectra are in agreement.

From the one-nucleon reaction followed by Σ conversion, one expects in general that the energy of fast protons will be less than 60 MeV. The Fermi motion of the nucleons, however, complicates the picture. It has been calculated that in about 25% of the absorption cases the energy of fast protons may be greater than 60 MeV.[30] This calculation is based on the assumption that the yield of fast protons in Σ^0 capture is half that of Σ^+ absorption. From our experimental data we get about $2/9 \approx 22\%$ protons with $T_p > 60$ MeV from one-nucleon reactions (as identified by pion production). This is not in disagreement with the calculated value.

We may compare our minimum value of the ratio

$$\frac{\pi^- \text{ from direct } \Lambda^0}{\text{all pions}} = \frac{21}{84} = 0.25$$

with the corresponding ratio 0.31 deduced from the results of the deuterium experiment.[28] As a check we compare the ratio given by Cester <u>et al.</u>, which also is 0.31.[29]

B. Discussion of Two-Nucleon Capture

The simple two-nucleon reactions are given in the first part of Sec. VI. The energy distribution of fast protons produced with hyperfragments in both the one-nucleon and two-nucleon reactions of K^- mesons in emulsion nuclei are shown in Fig. 8. The cutoff for proton-evaporation prongs ($T_p < 30$ MeV) is also shown in this histogram. The interpretation of the histogram involves those processes in nuclear matter that contribute protons of energy >30 MeV, e. g., (a) π-meson scattering or absorption, (b) $\Sigma^{+,0}$ absorption, and (c) two nucleon interactions.

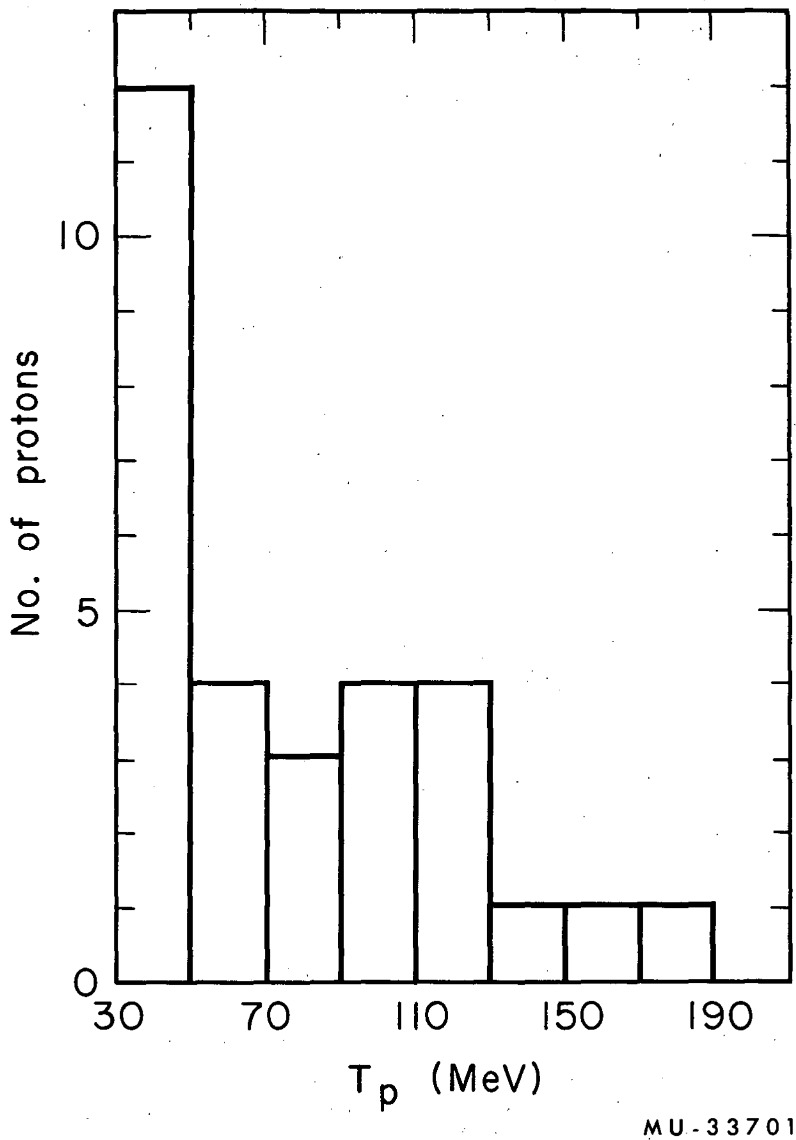

Fig. 8. Energy spectrum of fast protons with dip angle < 30° emitted by HF parent stars. The evaporation cutoff for protons is at 30 MeV.

Events with only charged pions and no high-energy proton ($T_p > 30$ MeV) are probably produced in one-nucleon reactions. However, the stars having both a pion and a proton ($T_p > 30$ MeV) also may be produced through one-nucleon reactions according to Eqs. (1a) and (1b). The events without pions are not all due to the two-nucleon capture process, however. Such events may be from one-nucleon captures for which there was subsequent absorption of the pion or the emission of a π^0 meson. In Sec. VI. A. 1 it was mentioned that for most one-nucleon reactions the energy of the proton is < 60 MeV. Thus we may certainly say that events with $T_p \geq 80$ MeV are due to two-nucleon capture processes. Most of the protons from the two-nucleon interaction should have energy in this region. Some 12 out of 19 events with protons alone have energies > 80 MeV. We may assume that these were produced in two-nucleon interactions. This means that at least 19% of the hyperfragments were produced in two-nucleon reactions.

These two-nucleon events could have been produced either through direct Λ production or through the Σ-conversion process [Eq. (2b)]. There was one star in which two fast protons were produced. Both protons had energy $T_p > 80$ MeV. We may possibly explain their production through the Σ-conversion process, i.e., $K^- + p + p \rightarrow \Sigma^0 + p$ and $\Sigma^0 + p \rightarrow \Lambda + p$. In the final state we have $\Lambda + p + p$. Another possible explanation for (Λ, 2p) production is through a one-nucleon interaction in which (Λ, 2p) are produced in the final state through both pion absorption and Σ-Λ conversion.

Of the events having a π^+ meson, only one had a > 75-MeV pion; its energy was 81 MeV. This is in agreement with previous results; the frequency of the two-nucleon reaction producing an energetic π^+ meson (i.e., $K^- + 2p \rightarrow \Lambda^0 + n + \pi^+$) is small compared with the π^+-producing-nucleon reaction given by Eq. (1a).

As mentioned in the Sec. IV discussion of K^- capture by light and by heavy nuclei, in some of the hyperfragment events K^- absorption apparently took place in heavy elements (Ag, Br). Two of these 12 events belonged to the two-nucleon absorption reaction leading to hyperfragment production, as identified by fast protons ($T_p > 80$ MeV). This result is an agreement with the work of Condo and Hill,[21] which indicates that a relatively small percentage of the two-nucleon absorption takes place in heavy elements. It is consistent with the recent experimental results of a two-nucleon yield of only 1% in deuterium[27] but 17% in He.[22]

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FOOTNOTES AND REFERENCES

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