Hyperfragments and Slow K-Mesons in Stars Produced by 3-Bev Protons*

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Emission of hyperfragments in 3-Bev proton stars has been investigated. The frequency of hyperfragments per star is 1/1000. Individual events, angular and Z-distribution are discussed. No case of associated production has been found.

Five slow K^+ mesons have been found in the same emulsion volume; in 3 cases the secondary could not be identified, one case is probably a $K_{\mu 2}$ decay and one other a $K_{\mu 3}$ decay. One possible case of a K_{e3} meson is also discussed.

INTRODUCTION

THE first example of a hyperfragment (Λ^0 nucleus) was found by Danysz and Pniewsky.[1] Later on, a great number of cases were found. Most of these cases up to 1954 are compiled in reports from the Padua Conference.[2] An extensive bibliography can be found in a paper by Gatto.[3]

A systematic search for hyperfragments in particle beams of well-defined energy gives information on data related to particle physics (Λ^0-production cross section, particle nature of the Λ^0, associated production, etc.) as well as to physics of the nucleus[4,5] (formation of the hyperfragment, binding energy, etc.).

A systematic investigation of hyperfragments in the 3-Bev proton beam of the Brookhaven Cosmotron has been made by Fry *et al.*[6]

The following investigation is a further contribution to the same problem. Unfortunately, only a few of the disintegrating hypernuclei can be completely analyzed and, therefore, many cases have to be collected before satisfactory information on the process of hyperfragment formation and stability will be available.

EXPERIMENTAL ARRANGEMENT AND SEARCH

A stack of 24 emulsion sheets 2 in.×3 in. and 400 μ thick has been exposed to 3-Bev protons in the "blown-up" beam of the Brookhaven Cosmotron. The stack, provided with adequate shielding, was placed with the 3-in. side parallel to the beam direction and exposed to about 30 000 protons per cm square.

The emulsions were scanned with 300× magnification: (1) All tracks ending in the field of view were inspected for emission of secondaries. (2) All stars with incoming proton tracks were carefully investigated for secondary stars and track endings in the field; special care was given to star centers, so that secondary events with short connecting tracks should not be overlooked. Star tracks, not ending in the field, were followed for $1\frac{1}{2}$ mm length. (3) Furthermore, 2-prong stars and all stars without fast incoming protons, in which one of the prongs seemed heavier than the others, were registered. This heavier track was then followed in adjacent emulsions to trace its origin or ending.

MASS, CHARGE, AND ENERGY DETERMINATION

Range-energy relation.—For protons below 50-Mev kinetic energy, the experimental data of Wilkins[7] were used, and for higher energies the range-energy relation adopted by Fay *et al.*[8] For particles with $Z \geqslant 2$, the range energy relation was corrected for electron pickup with the help of equations given by Barkas.[9]

Ionization.—Grain-count measurements in light tracks were compared with 3-Bev proton tracks crossing the emulsions. This has the advantage that the grain density of each unknown track can be compared with a minimum track at equal depth in the emulsion. The results are given as $g/g_{\min}$.

Gap-count measurements were compared with identified protons, pions, α particles, and occasionally deuterons. Most of the tracks were measured with minimum gap lengths of 1 μ and 0.5 μ (the latter measurement has been made with a Filar Micrometer). In total, 6 protons, 4 π-meson tracks, 2 deuterons, and 3 α-particle tracks, with ranges between 1–3 cm, were measured. Masses of unknown particles are determined by the ratio of residual ranges of track sections with equal gap density. For particles with mass $\geqslant 2\times$ proton mass, the range of comparison becomes small if protons are used as standards. It is advantageous to use long α tracks as standards, if available, because then the range of comparison becomes large and measuring errors consequently smaller. The ratio of ranges corresponding to equal ion density can be calculated by the range-energy relation $E=0.28R^{0.568}M^{0.432}Z^{1.136}$,[8] or from experimental curves.[7,9] δ-ray determinations[10] on unknown tracks

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[1] M. Danysz and T. Pniewsky, Phil. Mag. 44, 348 (1953).
[2] Nuovo cimento 11, Suppl. No. 2 (1954).
[3] R. Gatto, Nuovo cimento 1, 378 (1955).
[4] H. Primakoff and W. Cheston, Phys. Rev. 93, 908 (1954); C. F. Powell, Nature 173, 469 (1954); A. Pais, *Proceedings of the Fifth Rochester Conference on High Energy Physics* (Interscience Publishers, Inc., New York, 1955).
[5] M. Goldhaber, Phys. Rev. 101, 433 (1956). We are indebted to Dr. M. Goldhaber for a preprint of his paper.
[6] Fry, Schneps, and Swami (prepublication data).
[7] T. T. Wilkins, Atomic Energy Report G/R 664, 1951 (unpublished).
[8] Fay, Gottstein, and Hain, Nuovo cimento 11, Suppl. No. 2, 234 (1954).
[9] W. H. Barkas, Phys. Rev. 89, 1019 (1953).
[10] A. D. Dainton and P. H. Fowler, Proc. Roy. Soc. (London) 221, 414 (1954).

TABLE I. Characteristics of hyperfragment stars.

Event	Parent star	Fragment Range in microns	Fragment Time of flight (sec)	Angle of emission	Secondary star Number of prongs	Charge of secondaries	Total visible energy in Mev	Residual momentum
1	11+1p	58	$\sim 2\times 10^{-12}$	89°	2	4	33.4	526
2	9+0p	1134	$\sim 2\times 10^{-11}$	78°	1+1 recoil	2 or 3	24.1	300
3	10+0p	40	$\sim 1\times 10^{-12}$	90°	2	3	47.2	710
4	14+1p	11	$\sim 1\times 10^{-13}$	35°	3	4	68.7	350
5	7+1p	180	$\sim 4\times 10^{-12}$	65°	2	3 or 4	23	390
6	19+1p	825	$\sim 1\times 10^{-11}$	81°	2	3	48	500
7	13+1p	768	$\sim 1\times 10^{-11}$	78°	2	2	18.4	151
8	16+0p	69	$\sim 1\times 10^{-12}$	16°	2+2 recoil	5 or 6	74.2	370
9	15+0p	38	$\sim 1\times 10^{-12}$	79°	3+1 recoil	5 or 6	69	550
10	16+0p	6.5	$\sim 2\times 10^{-13}$	22°	3+1 recoil	$\geqslant 8$	34	392
11	11+1p	52.5	$\sim 1\times 10^{-12}$	68°	2	4	23.6	510
12	10+1p	3400	$\sim 1\times 10^{-10}$	56°	1	1	if triton, 43	492
							if deuteron, 36	370
13	12+1p	81	$\sim 2\times 10^{-12}$	75°	2	3 or 4	both tracks leave stack	
14	7+1p	3	$\leqslant 10^{-13}$	124°	3+2 recoil	$\geqslant 6$	1 track leaves stack	

TABLE II. Event 1: ${}_{\Lambda}Be^8$.[a]

Track	Range μ	Possible identification	Energy Mev	Q-value Mev	$\Sigma m_i - M$ Mev	Δ Mev	B_n Mev	B_Λ Mev
A	93±7	α	13.6±0.8					
B	232.5±24	α	24.7±1					
		He^3	19.8±1	173.4±5	20.6	18.9±5	18.9	0±5
		H^3	9.5±0.7					

[a] *Remarks:* B has probably charge 2, however the possibility of being a triton is not excluded. The residual momentum compensated with a single neutron would give a Q-value, which is too large if B represents He^4 and too small if B is H^3.

were compared with protons, α particles, Li^8, one B^8 track 800 μ long, and one Be^{9*} track (α,α,n,e) 400 μ long.

Scattering.—Scattering measurements were made, whenever dip and distortion conditions made this method meaningful.

EXPERIMENTAL RESULTS ON HYPERFRAGMENTS

The total number of stars investigated was 14 480. Among these stars 14 events were found which are believed to be spontaneous disintegrations of fragments coming to rest in the emulsion, with the possible exception of one event where decay in flight is suspected. In addition, 2 stars with double centers were found which may represent disintegrations of slow and probably heavy hyperfragments. Both cases occurred in large stars (16 and 20 prongs) and it is impossible to disentangle the prongs belonging to each center.

The 14 events are tabulated in Table I. In Tables II–XV, the characteristics of the secondary stars of these events are described in greater detail. A fragment consisting of a hyperon and $x-1$ other nucleons is described by the symbol ${}_{\Lambda}N^x$ as proposed by Goldhaber.[5] The particles emitted in the disintegration of hypernuclei are numbered consecutively by $A, B\cdots$. In cases where the residual momentum of the emitted charged particles could be compensated with the momentum of a single neutron particle, B_Λ and $\Delta = B_n - B_\Lambda$ have been calculated.[2] B_Λ is the binding energy of the hyperon in the fragment and B_n the binding energy of the last neutron in a stable fragment having the same charge and mass number as the hyperfragment. Δ is given by

$$\Delta = Q - (M - \sum m_i) - [Q_\Lambda + m_\pi - (m_n - m_p)],$$

where Q is the sum of kinetic energies freed in the disintegration, M the mass of the stable fragment, $\sum m_i$ the sum of the masses of all decay products, Q_Λ the Q-value of the unbound hyperon, m_π the mass of the meson, and $(m_n - m_p)$ the neutron-proton mass difference. $Q + m_\pi - (m_n - m_p) = 175.1 \pm 0.5$ Mev.

TABLE III. Event 2: ${}_{\Lambda}He^5$ or ${}_{\Lambda}He^6$.[a] Gap and δ-ray count indicate charge 2 for the fragment.

Track	Range μ	Possible identification	Energy Mev
A	1536±15	deuteron	24.1±0.2
B	2.5	recoil	

[a] *Remarks:* The recoil is emitted at an angle of 110° to the direction of the fragment; therefore, interpretation as scattering event is excluded. Since the charge of the fragment is 2, the charge of the recoil has to be 1 (deuteron or triton).

DISCUSSION

Only a few of the events described can be analyzed; however, in all events, with the possible exception of event 3, the observed disintegrations are compatible with the decay of a Λ^0 bound to the nucleus. All observed hypernuclei, again with the possible exception of event 3, are isotopic spin singlets, $T=0$ for nuclei with odd atomic number, and doublets, $T=\pm\frac{1}{2}$, for even atomic number.[5] Event 3, interpreted as ${}_{\Lambda}Li^9$, would be the first example of a hypernucleus in a $T=1$ state.[5] In this

TABLE IV. Event 3: $_{\Lambda}Li^9$ or decay in flight of $_{\Lambda}Li^8$.[a,b]

Track	Range μ	Possible identification	Energy Mev	Q-value Mev	$\Sigma m_i - M$ Mev	Δ Mev	B_n Mev	B_Λ Mev
A	236.6±25	He^6, electron with 2.9±1.5 Mev is emitted at the end of this track	28.2±1.2					
B	1676±100	proton probable	19.8±0.7	177±14 compensating the residual momentum with 2 neutrons parallel to each other	17.6	19.5±14	5.5	14±14

[a] *Remarks:* The residual momentum is 710±20 Mev/c; only by compensating the momentum with two neutrons emitted parallel to each other results in Q-value compatible with a Λ^0 decay.
[b] *Possible decay in flight of* $_{\Lambda}Li^8$: The dip angle of the fragment is very large, 72° (in undeveloped emulsion), and therefore, it is difficult to decide if the particle has been completely at rest before decaying. The assumption of decay in flight seems acceptable, because both tracks (He^6 and proton) and the fragment have dip angles of equal sign. The residual momentum of the event, projected in the plane of the fragment is considerably decreased, because the Z components of the momenta of both particles become smaller. The angle (space angle) between fragment and He^6 particle is small −12°. Furthermore, the velocity is small ($E = 28.2$ Mev, $\beta = 0.1$), while its momentum and hence contribution to the residual momentum is large. Therefore, in the system of the moving fragment, the momentum of the He^6 particle and consequently the residual momentum decreases rapidly with increasing fragment velocity. Assuming a fragment velocity between $\beta = 0.01$ and $\beta = 0.02$, compensation of the residual momentum with a single neutron is possible.

interpretation, the assumption has been made that 2 neutrons are emitted, moving parallel to each other. Although such angular correlations may occur, this assumption seems somewhat artificial.

It has been shown that the event could be explained as the decay in flight of a $_{\Lambda}Li^8$. However, in this case the lifetime of the hypernucleus would be only $\sim 10^{-12}$ sec, which is rather improbable in view of the long lifetime of Λ^0's.[11]

Since none of the above interpretations is satisfactory, the possibility of the decay of another unstable particle should not be completely rejected. The energy release in the event (if none of the above assumptions are made) is $\geqslant 273 \pm 14$ Mev; the minimum value is very close to the total energy release of charged hyperons.[12] The upper limit of energy release of course is not known, but it may well extend to the rest energy of θ's.

The binding energies of Λ^0 in $_{\Lambda}Be^8$ and $_{\Lambda}Be^9$ (event 1 and 11) are in satisfactory agreement with values found for these nuclei by other authors.[6] In the case of Be^8, B_Λ is definitely smaller than B_n.

A hypernucleus $_{\Lambda}H^4$ (mesonic decay) has been already found,[13] and the binding energy of the Λ^0 has been accurately determined to be $B_\Lambda = 1.2 \pm 0.8$ Mev. Therefore, a decay scheme of $_{\Lambda}H^4$ (event 12)$\rightarrow H^3 + n$, giving a binding energy $B_\Lambda = 10 \pm 4$ Mev, is unlikely and the decay scheme $_{\Lambda}H^4 \rightarrow H^2 + n + n$ is more probable. Since nonmesonic decay of He^4 has been observed,[14] the existence of a $_{\Lambda}H^4$ decaying without meson emission is not astonishing.

[11] B. Waldeskog [Arkiv Fysik 8, 369 (1954)] reports a hyperfragment with charge 9e decaying in flight; the lifetime of the fragment is 2×10^{-11} sec.
[12] A. Pais (reference 4) mentions in his report the possibility of selection rules inhibiting the fast degeneration of charged hyperons to the lowest Λ^0 state.
[13] Report of European G-stack group, Nature **175**, 971 (1955).
[14] An analyzable $_{\Lambda}He^4$ nonmesonic decay has been found recently by Stiller, Seeman, and Shapiro, Bull. Am. Phys. Soc. **30**, No. 5, 13 (1955).

The existence of the doublets $_{\Lambda}H^4$, $_{\Lambda}He^4$ and $_{\Lambda}Li^8$, $_{\Lambda}Be^8$ makes the existence of the doublet $_{\Lambda}He^6$, $_{\Lambda}Li^6$ probable.[5] This doublet has not been observed before. $_{\Lambda}He^6$ (event 3 and possibly event 7) can not be analyzed. The binding energy B_Λ of $_{\Lambda}Li^6$ is small, within the limits of error.

Unfortunately, charge and mass in event 10, $_{\Lambda}O^{16}$, is not unmistakably identified; furthermore, the error in B_Λ is very large, so that the bond strength cannot be estimated. Large and analyzable hyperfragments are very rare and up to now it is not known whether B_Λ stays approximately constant or increases with atomic number.

The great number of nonmesonic decays in the very light elements and the mesonic decay in a carbon or heavier nucleus are unexpected.

In the 14 stars with hyperfragment emission and in the two stars with a double center all tracks have been

TABLE V. Event 4: $_{\Lambda}Be^8$ or $_{\Lambda}Be^9$.[a]

Track	Range μ	Possible identification	Energy Mev
A	4233±57	proton	32±0.2
B	307.8±30	α	28±0.8
C	519±16	proton	8.7±0.2
		deuteron more probable	12.8±0.3

[a] *Remarks:* Two neutrons are necessary for compensation of the residual momentum.

TABLE VI. Event 5: $_{\Lambda}Li^7$ or $_{\Lambda}Li^8$.[a]

Track	Range μ	Possible identification	Energy Mev
A	176±5	α	20.2±0.3
B	49.2±3	proton	2.3±0.2
		deuteron	2.9±0.3

[a] *Remarks:* Two neutrons are necessary for compensation of the residual moment.

TABLE VII. Event 6: $_{\Lambda}Li^6$.[a]

Track	Range μ	Possible identification	Energy Mev	Q-value Mev	$\Sigma m_i - M$ Mev	Δ Mev	B_n Mev	B_Λ Mev
A	822±20	proton	12.6±0.1					
B	452±20	α	35.5±1	171.1±3.5	4	0±3.5	5.5	5.5±3.5

[a] *Remarks:* The probability that A is a deuteron instead of a proton is 1/20.

followed to the end of their range or to their exit from the stack. Measurements of the gradient of grain density and occasionally scattering measurements have been performed, but no case of a charged heavy meson associated with the production of the Λ^0 could be detected with certainty. However, in every one of the investigated stars there is at least one gray track leaving the stack, which is possibly a charged K-meson.

The size of stars with hyperfragments is rather large[6,15] and the fragments originate in heavy elements. This is easy to understand since both, the probability for Λ^0 production and capture is higher for heavy elements. Furthermore, as in the case of stable fragments, high excitation of nuclear matter probably is favorable for the emission of hyperfragments (because of lowering of the Coulomb barrier).

TABLE VIII. Event 7: $_{\Lambda}He^5$ or $_{\Lambda}He^6$.[a]

Track	Range Mev	Possible identification	Energy Mev
A	1448±20	proton	17.4±0.2
B	11.1±0.5	deuteron	1.03±0.02
		triton	1.13±0.03

[a] *Remarks:* Fragment ends in small hook. Gap count and number and distribution of δ rays favor mass 5 instead of 6 in the ratio 0.7:0.3. The residual momentum compensated with a single π^0-meson would lead to a Q-value of 93 Mev. Emission of $n+\pi^0(\Lambda^0\to n+\pi^0)$ is not excluded, however, the energy of the emitted π^0 would be ≤ 22 Mev. (Decay-scheme $_{\Lambda}He^5\to p+t+n+\pi^0$ or $_{\Lambda}He^4\to p+d+n+\pi^0$).

TABLE IX. Event 8: $_{\Lambda}B^9 - _{\Lambda}B^{10}$ or $_{\Lambda}C^{10} - _{\Lambda}C^{13}$.[a] Charge of fragment $\leqslant 6$.

Track	Range μ	Possible identification	Energy Mev
A	3316±160	proton	27.8±0.8
B	4807±220	proton, more probable	34.5±1
		deuteron	46.4±1
C	4	recoil (light) charge 1 possible	
D	2	recoil (heavy)	

[a] *Remarks:* In either case, B—proton or B—deuteron, 2 neutrons are necessary for the compensation of residual momentum.

TABLE X. Event 9: $_{\Lambda}B^9$ or $_{\Lambda}C^{11} - _{\Lambda}C^{12}$.[a] Charge of fragment >4.

Track	Range μ	Possible identification	Energy Mev
A	169.5±6	proton	5±0.1
B	3428±100	proton	28.5±0.4
C	5045±200	proton	35.3±0.8
D	1.5	recoil	

[a] *Remarks:* Two neutrons are necessary for compensation of the residual momentum.

ANGULAR DISTRIBUTION

Figure 1 gives the angular distribution of hyperfragments with respect to the incoming proton. The shaded boxes correspond to the events in this experiment, while the blank ones are taken from the results of Fry.[6]

Most of the fragments are emitted in the forward hemisphere; however, the preferred direction seems to lie near 90°. The emission angles are distinctly larger than in the case of free Λ^0's in an energy interval, where capture probability is high[16]; in the latter case, the emission angle is centered around 30°. This difference may be due to scattering of hyperfragments and to the fact that the emission angle will also be influenced by the direction of the colliding nucleons. The angular distribution of the hyperfragments is very similar to the distribution of stable fragments.

CHARGE DISTRIBUTION

Figure 2 gives the charge distribution of fragments found in 3-Bev proton experiments here (shaded boxes) and by Fry (blank boxes). In cases where the charge could not be definitely determined, the most probable value has been chosen. Contrary to the case of stable fragments, there seems to be no preference for fragments of charge 4 (interval $Z\geq 3$).[17]

The Z-spectrum for hyperfragments ($Z\geqslant 3$) seems to be displaced toward higher values, in comparison to the spectrum of stable fragments. An obvious explanation would be an increasingly stronger hyperon bond in heavy fragments, but as mentioned before, until now nothing has been known about this interesting fact. Some difference between hyperfragments and stable fragments is expected because in the first case, the formation of certain nuclei is not subjected to Pauli's exclusion principle. (For instance, $_{\Lambda}H^4$ exists but H^4 does not.)

The small number of hyperfragments with charge 1 or 2 in comparison to the stable fragments with the same charge is quite noticeable. A certain percentage of these light fragments may be missed, because these fragments will usually have larger ranges and may, therefore, more often leave the stack. Furthermore, if

[15] In Fry's experiments (reference 6) all hyperfragment stars are also found to be large.

[16] R. Jastrow, Phys. Rev. **97**, 181 (1955).

[17] D. H. Perkins, Proc. Roy. Soc. (London) **203**, 399 (1950).

TABLE XI. Event 10: ${}_{\Lambda}O^{16}$ or higher atomic number. Charge estimated ≥ 8.

Track	Range μ	Possible identification	Energy Mev	Q-value Mev	$\Sigma m_i - M$ Mev	Δ Mev	B_n Mev	B_Λ Mev
A	169±6	proton	5±0.1					
B	420±10	proton	8.5±0.1					
C	49±4	Li^6	14.8±1					
		Li^7	17.5±1.2					
D	3	recoil (heavy)		115±14 assuming {*C*—Li^7, *D*—Li^6}	56	−3.9±14	15.7	19.6±14

TABLE XII. Event 11: ${}_{\Lambda}Be^9$.

Track	Range μ	Possible identification	Energy Mev	Q-value Mev	$\Sigma m_i - M$ Mev	Δ Mev	B_n Mev	B_Λ Mev
A	38±1	Li^6 or Li^7	14.5±0.5					
B	295±4	probably deuteron (heavier than proton)	9.1±0.2	153±5	24	1.9±5	1.7	−0.2±5

TABLE XIII. Event 12: ${}_{\Lambda}H^4$ or ${}_{\Lambda}H^3$.[a] H^4 more probable.

Track	Range μ	Possible identification	Energy Mev	Q-value Mev	$\Sigma m_i - M$ Mev	Δ Mev	B_n Mev	B_Λ Mev
A	3072±120	deuteron	36±1					
		triton	43±1	165±4 assuming *A* to be triton	—	9.9±4	—	9.9±4

[a] *Remarks:* If *A* is a deuteron, the decay scheme is ${}_{\Lambda}H^4 \rightarrow H^2 + n + n$. In the first 300$\mu$ of the 3400μ fragment track are 2 δ rays of 3–4 grains; therefore, the velocity of the particle is small. If the particle is H^3, the number of δ rays expected is 7 ± 1; for H^4 the number of expected δ rays is 3 ± 1.

The track passes through 5 pellicles and has a dip angle of 30°. The three center parts of the track have each a projected length of 750μ. The mass calculated from scattering measurements is $(2.8 \pm 1.2) \times$proton mass. Gap count measurements were compared with two identified deuterons, gave a mass $(1.7 \pm 0.6) \times$deuteron mass; comparison with three α particles gave $(0.8 \pm 0.3) \times \alpha$ particle mass. The error in both, scattering and gap density measurements, includes probable errors made in dip angle corrections.

Unfortunately, none of these measurements provides a clear decision between mass 3 and 4. However, the δ-ray count favors mass 4.

The particle comes to an obvious end and emits a particle of range $3072 \pm 120\mu$ (track *A*). Although the dip angle of this track is steeper (40°), there is a distinct increase in the number of gaps in the beginning of this track compared with the ending part of the fragment. In the first 1000μ of track *A* are 6 short δ rays. For a triton 4.5 ± 1 and for a deuteron (11 ± 2) δ rays are expected. The δ-ray count favors the assumption of a triton, but does not exclude a deuteron. Gap count and scattering measurements were not decisive, mostly on account of the large dip angle.

The decay scheme ${}_{\Lambda}H^4 \rightarrow H^3 + n$, leads to a B_Λ, which is not in agreement with a value found by other authors for ${}_{\Lambda}H^4$. [See report of European *G*-stack group, Nature **175**, 971 (1955).]

the decay is nonmesonic, these events may sometimes be mistaken as scattering events, especially if the particle decays in flight. However, even assuming that there are 4 times as many events present as actually observed, the ratio of hyperfragments with $Z=1$ or 2 to those with $Z \geq 3$ remains small, compared with the same ratio for stable fragments. The reason for this is connected with stability problems and probably also production problems. Many of the α particles seen in stars are ejected in elastic collisions with rather fast nucleons, the α-particle subunits acting here as scattering centers; the rest of the α particles are slow, and are probably emitted as evaporation prongs. In the case of stable tritons the pickup process is an important mechanism, which possibly is not effective in the case of Λ^0's.

CROSS SECTION

The number of hyperfragments per star is 14/14 480 $=1 \times 10^{-3}$; this is in good agreement with Fry's results,[6] where 21 hyperfragments are found in 20.000 stars. Since all observed hyperfragments originate in heavy elements—which are responsible for only about 75% of all stars—the frequency is actually somewhat higher, about 1.3×10^{-3}.

Jastrow[16] has calculated the expected number of hyperfragments per star (Ag nucleus) to be 2.5×10^{-3}, about twice the observed number. In his calculations, it is assumed that the mechanism for hyperfragment and stable-fragment emission is the same and that both types of particle are ejected directly in collisions with nucleons. The probability for hyperfragment emission is calculated as the product of the probability for emission of stable fragments times the probability for Λ^0 absorption; the latter depends on the production cross section for Λ^0, which is assumed to be 1 mb for nucleon-nucleon collisions (3-Bev protons), and on the size of the nucleus. For the Ag nucleus Jastrow calculates a Λ^0

TABLE XIV. Event 13: ${}_{\Lambda}Be$ or ${}_{\Lambda}Li$.

Track	Possible identification
A	charge 2 leaves stack
B	charge 1 or 2 leaves stack

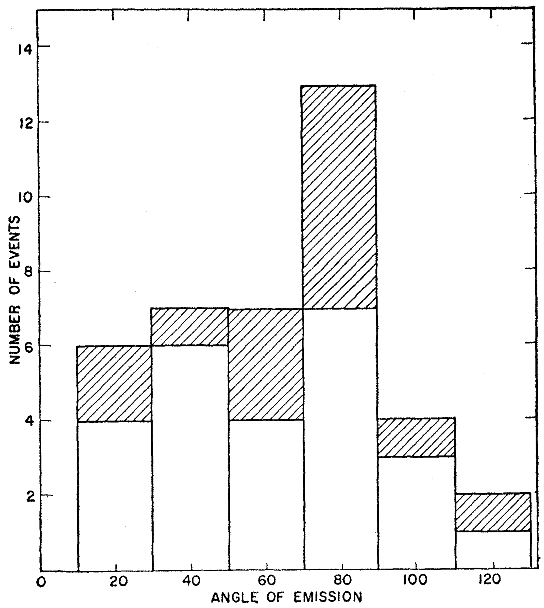

FIG. 1. Angular distribution of hyperfragments. Blank boxes, experiment by Fry *et al.*[6]; shaded boxes, present experiment.

production cross section of 33 mb and the cross section for Λ^0 capture to 15.7 mb.

The cross section for star production in heavy emulsion nuclei is about 80% geometric for 3-Bev protons and therefore ($r_0=1.3\times10^{-13}$ cm) about 900 mb. Hence in 17 out of 1000 stars one Λ^0 should be captured by the heavy nucleus. This may be compared with the experimental result that 1.3 out of 1000 large stars (therefore produced in heavy emulsion nuclei) emit a hyperfragment. Therefore, about every tenth captured hyperon is emitted as a hyperfragment. Actually the ratio will be

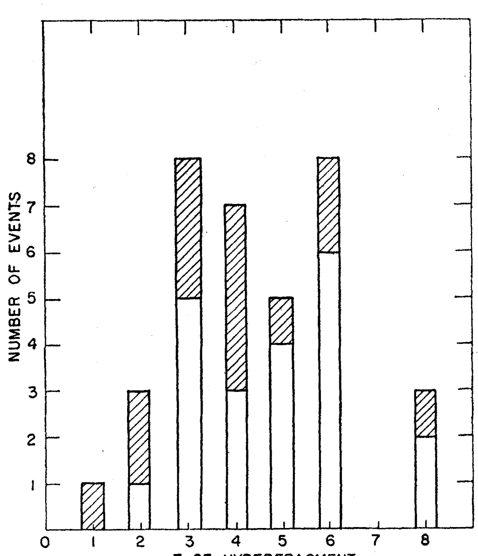

FIG. 2. *Z*-distribution of hyperfragments. Blank boxes, experiment by Fry *et al.*[6]; shaded boxes, present experiment.

somewhat larger than 1.3/17 because the cross section 900 mb is calculated for a nucleus $A=100$ (mixture of heavy emulsion nuclei), while 15.7 mb refers to the Ag nucleus; furthermore the cross section 1 mb for hyperon production may be an over estimate.

K-MESON EMISSION FROM STARS

Four examples of K^+-mesons emitted from stars have been observed. The events are described in Table XVI.

All four *K*-mesons are of low energy; this is understandable, since the probability of finding particles with range $\geqslant 2.5$ cm is small in a stack of the size used in this experiment.

All tracks of the parent stars have been followed, but no other unstable particle has been found.

K-1.—The *K*-meson has a dip angle of 47° and traverses 2 plates; scattering measurements therefore could not be made and gap measurements gave only an approximate value. The δ-ray count in this track is 9, in good agreement with a value expected for a *K*-meson.

TABLE XV. Event 14: C or higher mass and charge.[a]

Track	Range μ	Possible identification	Energy Mev
A	leaving stack after 1130 μ	proton	
B		meson negative making 1 prong star	1.8
C	12	Li or heavier	
D	3	recoil	

[a] *Remarks:* The energy release in this disintegration cannot be calculated; however, the residual momentum is probably small. Proton track and 12μ track have opposite sign of dip and the latter and the recoil are opposite to each other.
Mesonic decay of a fragment of such a high atomic number and emission of such a slow meson is quite unusual.

The secondary particle could be observed in two adjacent plates, the observed length is 4 mm. The minimum track in the parent star is a π meson of 130 Mev.

K-2.—The secondary particle into which the *K*-meson decays is steep—52°—and therefore only grain count measurements could be made. The track could be followed through 14 emulsions. The two light tracks in the parent star have ionization corresponding to $E/mc^2=0.7$ and 0.8. The first track makes a secondary star and is probably a π meson.

K-3.—The observed length of the secondary track is 8.2 mm (2 consecutive emulsions). The minimum track of the parent star is a π meson of $\sim$150 Mev.

K-4.—The secondary track has a dip angle of 27°. It has been observed in 5 consecutive plates (4 mm).

The light track in the parent star is a π meson of $\sim$90 Mev. The identity of the secondary particles in *K*-1, *K*-2, and *K*-3 is unknown; *K*-4 is probably a $K_{\mu 2}$-decay.

The small size of these stars in comparison to stars

TABLE XVI. Range and energy of primary and secondary particles in K-meson events.

Particle	Parent star	Angle of emission with respect incoming proton	Range in microns	Energy in Mev	Mass determination: Scattering *vs* range: in m_e	Mass determination: Gap density *vs* range: in m_e	Secondary particle: $p\beta$ in Mev/c	Secondary particle: g/g_0 Grain density/minimum grain density	Identity
K-1	$5+1p$	1300	1460±60	13.3±0.3		2	144±43	0.96±0.05	?
K-2	$3+2p$	490	1970±25	15.46±0.2	870±300	1050±280		1.09±0.06	?
K-3	$7+1p$	610	1343±10	12.6±0.2	864±220	750±220	158±30	1.00±0.03	?
K-4	$3+1p$	1550	14.178±100	48.1±0.2	1020±180	1040±100	165±48	1.01±0.03	probably μ
K-5	from outside	89° to beam direction	7500±200	33.7±0.5		Range in microns	E in Mev		
($K_{\mu 3}$)						2910±50	10.1±0.2		$\mu-e$ decay

with hyperfragments is noticeable. With exception of case K-3, the K-mesons may have been produced in light elements.

In addition to the four K-mesons, one K-meson (K-5) has been found entering the stack from the outside at an angle of 89° to the beam direction. The dip angle of the track is 72° and no measurements on this track can be made. The particle decays into a μ meson of 10±0.2 Mev which, at the end of its range, decays into an electron.

In a track of this steepness it is difficult to judge whether the particle actually reaches the end of its range; therefore, it may seem possible to explain the event as a $\pi-\mu-e$ decay in flight. However, the angle between the incoming meson and the μ meson is 116° and therefore this explanation is excluded. Furthermore, the particle has six δ rays in the last 1000 μ of its range—a value expected for heavy mesons. The event is a $K_{\mu 3}$-decay.

EVENTS NOT DEFINITELY ESTABLISHED

(a) From a star of type $21+0p$, a short steep track, probably of charge 1, is emitted at an angle of 71° to the direction of the incoming. The track comes to the end of its range after 89 μ. The mass of the particle is certainly larger than the mass of a π meson. From the end of the track a proton of 1522±80 μ is emitted. If this event can be assumed to be $\Sigma^+ \rightarrow p+\pi^0$, then the Q-value is calculated to $Q=110\pm3.5$ Mev. The Q-value is low compared to the Q-value 116±4 Mev established for Σ^+ decay, but is still acceptable. However, the fact that the primary particle can not be analyzed makes this event doubtful.

(b) From a parent star $5+1p$, a track of length 45 μ is emitted at an angle of 78° to the track of the incoming particle. The track ends with a small hook and probably has charge 1. Charge 2 is not completely excluded but higher charge is extremely unlikely. The particle decays into a light track. The track can be followed through 11 plates and the length in each plate is about 1.2 mm. In the first plates the track is very near the edge of the emulsion and visibly distorted. Therefore, scattering measurements can not be applied. The mean grain density in 5 plates is 1.03±0.03. After 4.2 mm the track has a $p\beta=16\pm3$ Mev/c and after 1 cm, $p\beta=8\pm2$ Mev/c. Therefore, the light track is an electron. It is believed that this event represents a K_{e3} decay, since a radioactive element of charge 1 or 2 emitting such a high-energy electron is not known. Even if one would assume charge 3, the event could not be explained as the radioactive decay of Li^8, since the characteristic hammer track is not present.

(c) From a star $13+1p$ a track of charge 1 and range 2520±200 μ is emitted at an angle 76°. The dip angle of this track, which travels through 5 plates, is 47°. Scattering measurements give a mass $\geqslant 350$ m_e; gap count gives a mass value $m_1=1270\pm560$ m_e.

The track comes to the end of its range (typical hook) and makes a secondary star consisting of 3 tracks (not coplanar):

(1) 83±5 μ if proton 3.2 Mev if α, more probable—12.6 Mev.

(2) 32±3 μ proton 1.75 Mev.

(3) proton: scattering: $p\beta=233\pm32$ Mev/c,
grain count $E/mc^2=0.15\pm0.01$,
gap count $E/Mc^2=0.14\pm0.02$.

Therefore, the kinetic energy of this track is between 110 and 150 Mev.

Assuming the lowest value, the total visible energy of this star plus binding energy is 139 Mev. Since at least 1 neutron will have been emitted, the energy is greater than the rest energy of a π meson; the interpretation of the event as a σ star seems also excluded by the measurements of the connecting track. However, it can not be decided if the connecting track is a negative K-meson or a negative hyperon.

In the same emulsion volume in which the described hyperon and heavy meson events were found, 800 negative and 730 positive π mesons come to rest.

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