During the coincidence measurements for the cross-section determination, a measured aliquot of the $Mg(OH)_2$ was used to yield the absolute intensity of the gamma rays. This was determined from a measurement of the 1.015-Mev peak area and the ratio of the γ rays previously determined. The disintegration rate of the source was compared to the total gamma ray intensity and found to agree within 5%, thus corroborating the lack of coincidences between the two gamma rays. From this measurement, one can state all β-ray transitions occur to the excited states within this experimental uncertainty.

The decay scheme shown in Fig. 4 may now be constructed. The spin assigned to Mg^{27} is $s_{\frac{1}{2}}$ on the basis of single-particle considerations and the lack of β transitions to the measured 5/2 spin ground state of Al^{27}.[7] The assignments for the excited states of Al^{27} are in agreement with the beta-ray observations, but are based primarily on single particle considerations and the relative intensities of the γ rays. The shell model states predicted, in this region, for the 13th proton are $d_{\frac{5}{2}}$, $d_{\frac{3}{2}}$, and $s_{\frac{1}{2}}$ (not necessarily in this order), and the possible order of the spins of the excited states is still open to question. The probability for the 0.175-Mev transition relative to the cross-over γ ray computed from the indicated spins and the Weisskoff formula is $\sim$1% in agreement with the observed intensity of 2.2%. This transition would be expected to be considerably more intense if the spins were reversed.

[7] J. E. Mack, Revs. Modern Phys. 22, 64 (1950).

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Disintegration of Hyperfragments. II*

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The systematic study ot hyperfragments has been continued. A total of 32 000 cosmic-ray stars, 10 000 6-Bev proton stars, 32 000 3-Bev π^--meson stars and 206 stars produced by stopped negative K mesons were examined. Twenty hyperfragments were found in the cosmic-ray plates, 7 in the proton plates, 30 in the π^--meson plates and 11 in the negative K-meson plates. The average charge of the hyperfragments is between 4 and 5. The average range of the hyperfragments is about 10 microns. Including previous data from this laboratory, only 2 mesonic decays have been found out of 98 events with Z greater than 2. A total of 7 helium hyperfragments have been observed of which 4 decayed mesonically. Of 4 hydrogen hyperfragments, all decayed with the emission of a π^- meson. In the following eight cases, it was possible to measure the total energy release in the hyperfragment disintegration, and hence to find the following values (in Mev) for the binding energy of the Λ^0 particle: ${}_{\Lambda}H^3(B_{\Lambda}=0.6\pm0.6)$; ${}_{\Lambda}H^3(B_{\Lambda}=-0.5\pm0.6)$; ${}_{\Lambda}H^3(B_{\Lambda}=0.4\pm0.7)$; ${}_{\Lambda}H^4(B_{\Lambda}=0.5\pm2.0$ or $1.9\pm2.0)$; ${}_{\Lambda}He^4(B_{\Lambda}=0.0\pm2.0)$; ${}_{\Lambda}He^4(B_{\Lambda}=1.8\pm0.6)$; ${}_{\Lambda}He^5(B_{\Lambda}=2.0\pm0.6)$; ${}_{\Lambda}Be^9(B_{\Lambda}=6.5\pm0.6)$. The binding energies tend to increase with increasing mass number. The fact that ${}_{\Lambda}H^4$ and ${}_{\Lambda}He^5$ hyperfragments exist, plus the fact that the binding energy of the Λ^0 particle in ${}_{\Lambda}Be^9$ is greater than that of the last neutron in Be^9, shows that the Pauli principle need not be considered for a Λ^0 particle bound in a nucleus. If the binding of the Λ^0 particle can be described in terms of a potential well the depth of the well is greater than 6.5 Mev, as indicated by B_{Λ} for ${}_{\Lambda}Be^9$. In light hyperfragments the low binding energies imply that the Λ^0 particle spends much of its time outside the nucleus. The momentum of the Λ^0 particle has been measured in several light hyperfragments where a π^- meson and proton were emitted, by assuming it to be equal to the momentum of the π^- meson and proton. In general the momentum values are quite low, which supports the hypothesis that the bound Λ^0 particle spends considerable time outside the nucleus. No further examples of energetic hyperfragments, as have been previously reported, were found in this work.

INTRODUCTION

FOLLOWING the discovery by Danysz and Pniewski[1] of the decay of a hyperfragment, many cases have been observed where the binding energy of the Λ^0 hyperon could be evaluated.

The program for the systematic study of the production and decay of hyperfragments, some of the results of which have been reported in a previous paper,[2] has been continued. Additional hyperfragments produced by cosmic rays, high-energy protons, π^- mesons, and stopped K^--mesons are reported in this paper.

* Supported in part by the U. S. Atomic Energy Commission and by the Graduate School from funds supplied by the Wisconsin Alumni Research Foundation.
[1] M. Danysz and J. Pniewski, Phil. Mag. 44, 348 (1953).
[2] Fry, Schneps, and Swami, Phys. Rev. 99, 1561 (1955). This paper will be referred to as I.

PROCEDURE

Stacks of 600 micron pellicles were exposed to 6-Bev protons, 3-Bev π^- mesons, and stopped K^--mesons[3] from the Berkeley Bevatron. Additional stacks were exposed to cosmic rays in a skyhook balloon flight. These pellicles were area scanned for stars with a low magnification. The identification and selection criteria for hyperfragments were essentially the same as in the previous work (I).

OBSERVATIONS

A. General Features

The frequencies of hyperfragments from the various exposures are given in Table I. In many of the events

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

which are tabulated as hyperfragments, the connecting track is quite short. Therefore it is not clear that the secondary star was produced by the disintegration of a hyperfragment as opposed to the nuclear capture of a very slow negative π meson. In those events where the range of the connecting track is greater than 15 microns, it is usually possible to distinguish a nuclear fragment track from a slow π-meson track. The number of these events is also tabulated in Table I. Further, in a few cases it is possible to show from the energy release that the secondary disintegration was due to a Λ^0 hyperfragment. Also the absence of Auger electrons from the secondary stars suggests that the bulk of the events with short connecting tracks are not due to slow π^- mesons. Although it is well established that many of the delayed disintegrations of a nuclear fragment are due to the inclusion of a Λ^0 hyperon in the fragment, it must be remembered that is is possible that some of the nonmesonic disintegrations may be due

TABLE I. Frequencies of hyperfragments.

Nature of exposure	Cosmic rays	6-Bev p	3-Bev π^-	K^--stars
Number of stars observed	32 000	10 000	32 000	206
Total number of hyperfragments	20	7	30	11
Number of hyperfragments with range $R \geqslant 15\mu$	3	3	8	0
Ratio of all hyperfragments to total stars	6.2×10^{-4}	7×10^{-4}	9.5×10^{-4}	$5.3\times10^{-}$
Ratio of hyperfragments ($R \geqslant 15\mu$) to total stars	10^{-4}	3×10^{-4}	2.5×10^{-4}	0

to some other mechanism. The possibility that some result from the absorption of a π^- meson in a mesonic orbit about the fragment, as previously suggested by Danysz and Pniewski,[1] cannot be excluded.

An estimate of the charge of the hyperfragments has been made by assuming that the total visible charge from the fragment disintegration is equal to the charge of the fragment. The charge distribution of the hyperfragments reported here and in I is shown in Fig. 1. The distribution for fragments with $R \geqslant 15$ microns is given in Fig. 2. The assumption that the charge of the fragment is equal to the charge of the disintegration products is undoubtedly justified for nearly all of the events. However, in one case (the mesonic decay of carbon described in detail later), the visible charge is definitely less than the charge of the fragment because the energy of a heavy carbon recoil was probably too low to have produced a visible track. There are other factors which affect the shape of the charge distribution. There is some observational bias which tends to reduce

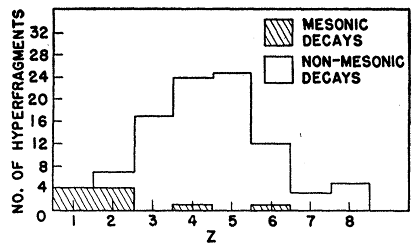

FIG. 1. Charge distribution of hyperfragments. The average Z is between 4 and 5.

the relative probability of finding hydrogen and possibly helium hyperfragments because of their long range in comparison to heavier fragments. The long range increases the probability that the fragment will leave the pellicle and therefore not be observed when the adjacent pellicle is scanned. This bias is reduced by the tendency for the Λ^0 particles to become bound in fragments of low velocity. Also, very heavy hyperfragments may have such a short range ($\sim$1 micron) that they will not be observed.

The mode of decay for hydrogen and helium hyperfragments is predominantly mesonic while the nonmesonic mode of decay predominates for heavier hyperfragments. Nearly all of the π^0-mesonic decays would not be identified as hyperfragments because such events can nearly always be interpreted as scatterings, since only one or possibly two very short recoil tracks would result from this mode of decay. The ratio of π^0 to π^--mesonic decays of the Λ^0 hyperon is not known, so that it is impossible to estimate the number of π^0-mesonic hyperfragment decays that are not recognized. This number may be comparable to the number of charged mesonic decays. All connected stars were carefully studied in an attempt to see if any could be identified as a decay in flight of a hyperfragment.[4] No conclusive decays in flight were found. It is not possible to always determine whether a very short hyperfragment decayed from rest. The stopping

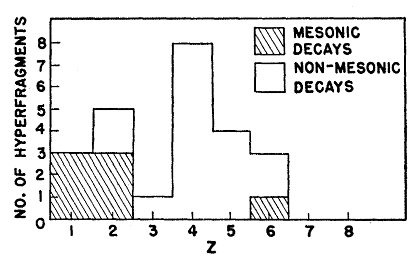

FIG. 2. Charge distribution of those hyperfragments whose range was greater than 15 microns. The average value of Z is between 3 and 4. It would be expected that this average Z would be less than that for all hyperfragments because light fragments in general have a longer range than heavy ones.

[4] A decay in flight in a cloud chamber of a hydrogen hyperfragment was recently reported by Alexander, Ballerio, Bizzarri, Brunelli, De Marco, Micheline, Moneti, Zavattini, Zichishi, and Astbury, Nuovo cimento 2, 365 (1955). See also B. Waldeskog, Arkiv. Fysik. 8, 369 (1954).

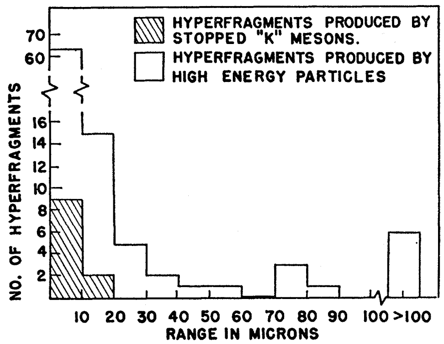

FIG. 3. Range distribution for all hyperfragments reported here and in I. The cross-hatched area represents hyperfragments produced by K^--mesons. These would be expected to have a short range since the energy available for fragments from K^- stars is comparatively small.

time for all hyperfragments reported here and in I of range greater than 15 microns is 1.4×10^{-10} sec. A comparison of this time with the free lifetime would indicate that the lifetime in nuclear matter is not shorter by several orders of magnitude.

The range distribution of the hyperfragments reported here and in I is given in Fig. 3.

B. Measurable Cases

An attempt was made to analyze each disintegration. In most of the cases a complete analysis could not be made for one of two reasons: (1) The visible kinetic energy plus the energy which a single neutron would have, if it were given the residual momentum of the charged particles, was not sufficient to account for the energy release of a bound Λ^0 particle, which indicated that two or more neutrons were probably emitted. (2) One or more of the tracks from the disintegration may have been short so that its identity could not be established by any means.

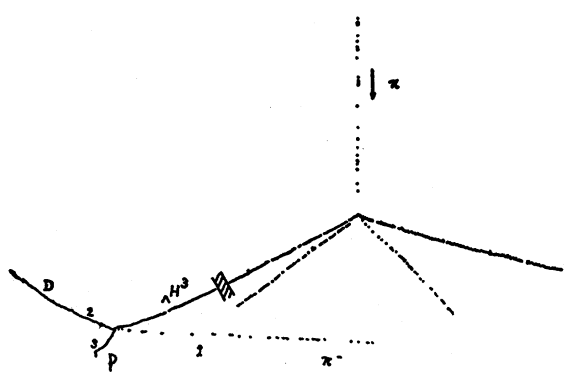

FIG. 4. A drawing of event 87. The three tracks from the hyperfragment are coplanar. Track 1 is 1.71 cm long and due to a π^- meson. Momentun is balanced if tracks 2 and 3 are assigned to a deuteron and a proton, respectively. The binding of the Λ^0 particle in ${}_\Lambda H^3$ is found to be 0.6 ± 0.6 Mev.

The mode of disintegration was such that an analysis of the event could be made in eight cases. A detailed description of these and a few other events of interest follows.

Event 87

A projection drawing of event 87 is shown in Fig. 4. The ${}_\Lambda H^3$ decay was found in a pellicle stack exposed to 3 Bev π^--mesons from the Berkeley Bevatron accelerator. The data relating to this event are given in Table II. The range-energy relationship of Fay *et al.*[5] was used for singly charged particles and the range-energy relationship of Wilkins[6] was used for heavier particles. The stopping powers of the emulsions were determined from the ranges of μ mesons from $\pi-\mu$ decays.

The three tracks from the hyperfragment decay are coplanar within 3 degrees, which suggests that neutral particles were not involved in the decay and also that the hyperfragment decayed from rest. The scattering along the track of the hyperfragment also suggests that the fragment decayed from rest. The δ rays along the track of the hyperfragment suggest that the charge was 1. The identity of tracks 2 and 3 could not be determined from the characteristics of the tracks but was inferred from the momentum balance of the three tracks. Track 1 was followed through 5 pellicles and showed the characteristic multiple scattering and change in grain density of a π-meson track. Low-energy electron tracks are associated with the ending. These facts show that this particle was a negative meson, presumably a π^- meson. If tracks 2 and 3 are assumed to have been produced by a deuteron and a proton, respectively, the momentum unbalance of the three particles is only 5 ± 5 Mev/c. If tracks 2 and 3 are assumed to be protons the momentum unbalance is 34 ± 5 Mev/c; if both are deuterons it is 31 ± 5 Mev/c. Therefore the proton, deuteron assumption seems most reasonable. The disintegration scheme is then

$$ {}_\Lambda H^3 \rightarrow p+d+\pi^-+Q_1, \qquad (1)$$

where Q_1 is 36.3 Mev. Assuming that the decay energy

TABLE II. Details of event 87 (${}_\Lambda H^3$).

Track	Range	Identity	Energy (Mev)	Angle in the decay plane
Hyperfragment	635μ	${}_\Lambda H^3$	17.4	
1	1.71 cm	π^-	31.8	101° (1–2)
2	53.6μ	d	3.1	103° (2–3)
3	22.1μ	p	1.4	

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

[6] J. J. Wilkins, Atomic Energy Research Establishment, Harwell Report G/R664 (unpublished).

of the free Λ^0 particles is 36.9 ± 0.2 Mev,[7] the binding of the Λ^0 particle is found to be 0.6 ± 0.6 Mev.[8]

It might be argued that track 2 could have been due to a proton and that the momentum unbalance of the three tracks was given to a neutron. However the binding energy of the Λ^0 particle is then -6.2 Mev which excludes this interpretation. Likewise, two or more neutrons can be excluded by the same argument.

Event 89

This hyperfragment was also produced by a 3-Bev π^- meson. The track of the hyperfragment is 324 microns long and exhibits the general features of a light nuclear fragment. The small-angle scattering along the fragment track is characteristic of a stopping particle. The disintegration consists of three coplanar tracks (within 2°) which stop in the emulsion stack. A drawing of the event is shown in Fig. 5 and a summary of the measurements is given in Table III.

Track 3 is contained in 15 pellicles and exhibits the characteristics of a light meson. A "blob" accompanies the track ending. Hence the meson was negatively charged and presumably a π^- meson. The dip angle of this meson track is about 45°. Therefore a knowledge of the shrinkage factor is important in determining the true range of the meson. Unfortunately the thickness of the pellicles before processing was not measured, and hence the shrinkage factor could not be determined from a measurement of the thickness after processing. The shrinkage factor was determined by a modification of the regression method suggested by White[9] which consists of a comparison of flat and steeply dipping μ meson tracks from $\pi-\mu$ decays. The thickness of the pellicles was found to be 545 ± 16 microns which gives for the range of the π^- meson a value of 9906 ± 240 microns. Correcting for the stopping power of the particular batch of emulsion, the energy of the π^- meson is found to be 23 ± 0.5 Mev.

Track 2 is 804 microns long and produced by a particle of charge one. The multiple scattering suggests that the particle was a proton. Since the three tracks are coplanar it is reasonable to assume that no neutral particles were involved. Then from momentum balance track 1 is found to be a deuteron and track 2 a proton. The disintegration scheme is then

$$_\Lambda H^3 \rightarrow p+d+\pi^-+Q_2, \qquad (2)$$

where Q_2 is 37.4 ± 0.5 Mev. The binding energy of the Λ^0 particle is found to be -0.5 ± 0.6 Mev.

The possible emission of neutrons can be excluded from momentum and energy considerations as discussed in the description of the previous event.

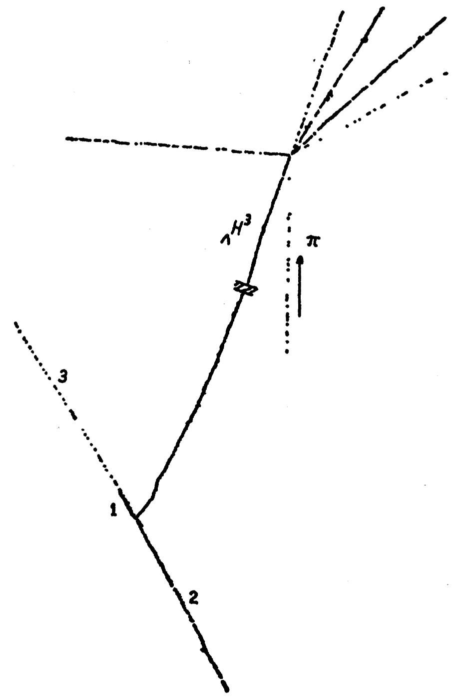

FIG. 5. Event 89 was found in a pellicle exposed to 3-Bev π^- mesons. The hyperfragment, $_\Lambda H^3$, traveled 324 microns and decayed into three coplanar particles; a π^- meson of 23.4 Mev (track 3), a deuteron (track 1), and a proton (track 2).

TABLE III. Measurements on event 89 ($_\Lambda H^3$).

Track	Range in microns	Identity	Energy in Mev	Angles in decay plane
Hyperfragment	324	H^3	11.5	
1	16.2	d	1.3	172° (1–2)
2	804	p	12.7	175° (2–3)
3	9906	π^-	23.4 ± 0.5	

Event 35

The primary, from which the hyperfragment emerged, was found in a pellicle exposed to cosmic rays. The hyperfragment disintegration consists of three non-

TABLE IV. Summary of measurements on event 35 ($_\Lambda H^3$).

Track	Range in microns	Identity	Energy in Mev
Hyperfragment	100	$_\Lambda H^3$	5.45
1	1.325 cm	π^-	27.04
2	73	p	2.97
3	5	p	0.52

Residual momentum···84.5 Mev/c
Energy of neutron··· 3.8 Mev

[7] Friedlander, Keefe, Menon, and Merlin, Phil. Mag. **45**, 533 (1954).
[8] The errors in energy do not include any systematic error in the range-energy relationship. The largest contribution to the quoted errors arises from the straggling of the π meson.
[9] W. F. Fry and G. R. White, Phys. Rev. **90**, 207 (1953).

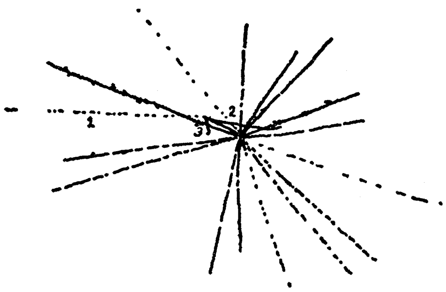

FIG. 6. The hyperfragment was produced by cosmic rays in pellicles aligned for a K^--exposure. Hence none of the tracks could be followed. The three tracks from the hyperfragment decay are not coplanar. The energy of the π^- meson (track 1) is 25.5 Mev from the grain density. If tracks 2 and 3 were due to a proton and deuteron, respectively, the binding of the Λ particle in ${}_\Lambda H^4$ is 1.9±2.0 Mev.

coplanar tracks; one a negative π meson of range 1.325 cm, a nucleonic track 73 microns long, and a short track 5 microns long. The three tracks depart from coplanarity by 11 degrees. The measurements on these tracks are given in Table IV. Since the three tracks are not coplanar, the identity of the short track cannot be inferred from the momentum balance. If this short track was due to a proton, the energy of a single neutron is 3.8 Mev, which gives a total energy release of 34.3 Mev for the decay

$$ {}_\Lambda H^3 \rightarrow p+p+n+\pi^- + Q_3. \tag{3}$$

The binding energy of the Λ^0 particle in ${}_\Lambda H^3$ is found to be 0.4±0.7 Mev from this event.

If two neutrons are assumed to have been emitted, the binding energy of the Λ^0 particle is found to be negative by at least 4 Mev. Any other possible identifications for track 3, aside from a proton, lead to negative binding energies.

Event 70

In the stack carefully exposed to the K^--meson beam, a hyperfragment was produced by cosmic rays. This pellicle stack was assembled and x-ray marked just before the exposure and taken apart shortly after the exposure. None of the tracks from the large primary star could be followed into adjacent pellicles while the tracks from machine produced events were followed with ease. We conclude therefore that this hyperfragment was produced by cosmic rays.

TABLE V. Measurements on event 70 (${}_\Lambda H^4$).

Track	Range in microns	Identity	Energy in Mev
Hyperfragment	13.2	${}_\Lambda H^4$	1.2
1	···	π^-	25.5±2.0
2	9.4	p or d	0.76 0.90
3	32	p or d	1.75 2.19

A tracing of event 70 is shown in Fig. 6. The three tracks from the disintegration depart from coplanarity by 10±3 degrees, indicating that a neutral particle was involved. A decay in flight would not account for the lack of coplanarity because the momentum of these charged particles is in the opposite direction to that of the hyperfragment. Track 1 (Fig. 6) has an ionization of 1.59±0.25 times minimum and therefore we assume that it was produced by a π^- meson of 25.5±2.0 Mev (if a proton, $E_p=180$ Mev). The ranges and energies of the decay tracks are given in Table V. Various assumptions for the identity of tracks 2 and 3 (Fig. 6) have been made and the binding energy calculated under the assumption that one neutron was involved. Two neutrons result in negative binding energies. Only five assignments are consistent with a bound Λ^0 particle. These are given in Table VI.

Assumption 1 (Table VI) does not seem likely because the binding energy is inconsistent with other ${}_\Lambda H^3$ events. Although track 2 is quite short it exhibits a larger amount of multiple scattering than is usually observed along tracks of He nuclei. Therefore, it is likely that the event was ${}_\Lambda H^4$, which decayed by the reaction

$$ {}_\Lambda H^4 \rightarrow p+d+n+\pi^-. \tag{4}$$

Event 90

The hyperfragment originated from a small 5-prong star in a pellicle stack exposed to K^--mesons from the Bevatron accelerator. The nature of the origin of the primary star has not been well established but it seems likely that it was caused by a neutral K-meson. Further work on the analysis of the primary star is being conducted and the results will be described elsewhere. Although the hyperfragment track is not long (171 microns), it appears to have been produced by a particle of charge one or two. There is a small amount of scattering along this track near the secondary star which suggests that the fragment stopped. The secondary star consists of 3 tracks which stop in the pellicle stack. The three tracks are coplanar within the limitations of the measurements (within 10°). The direction of the short track cannot be determined with precision, but it appears to be such as to conserve momentum. The features of this disintegration are given in Table VII.

The vector sum of the momenta of the π^- meson and the proton is 57±1 Mev/c. If the recoil is assumed to

TABLE VI. Interpretations of event 70.

Assumption	Hyperfragment	Track 2	Track 3	B_Λ (Mev)
1	${}_\Lambda H^3$	p	p	6.4±2
2	${}_\Lambda H^4$	p	d	1.9±2
3	${}_\Lambda H^4$	d	p	0.5±2
4	${}_\Lambda He^6$	He^4	p	1.2±2
5	${}_\Lambda He^7$	He^4	d	−0.6±2

be He^3, its momentum lies between 53 and 64 Mev/c as determined from the range. If the track is He^4, its momentum lies between 61 and 73 Mev/c. The momentum balance would imply that the track was due to He^3. The disintegration scheme can be expressed by the equation

$$ {}_{\Lambda}He^4 \rightarrow He^3 + p + \pi^- + Q_5, \qquad (5)$$

where Q_5 is found to be 35.1 ± 0.6 Mev. The energy of the He^3 nucleus was obtained from momentum balance. The binding of the Λ^0 particle in He^4 is found to be 1.8 ± 0.6 Mev.

The characteristics of the fragment track do not exclude a charge of one for the hyperfragment. Hence the possibility that the recoil was a proton, deuteron, or triton must be considered. The expected ranges for these nuclei, as obtained from the momentum unbalance of the π^- meson and the proton, are 32, 8, and 5.4 microns, respectively. These long ranges are inconsistent with the observed range.

Event 95

The hyperfragment was produced by a stopped negative K-meson. The track of the hyperfragment is quite short (2.6 microns) and therefore little information can be obtained from the track alone. The three tracks from the hyperfragment decay are coplanar within 3 degrees. A drawing of this event is shown in Fig. 7. A summary of the data is given in Table VIII.

Track 3 was followed 15 200 microns at which point it produced a one-prong star in flight. The energy of the π^- meson at the point of interaction was obtained from a calibrated grain density *vs* energy curve. Although track 1 is only 18 microns long some scattering is observed which suggests that it was caused by a light nuclear particle. Assuming that it was due to a proton, the component of momentum perpendicular to the π^--meson track is balanced if track 2 is assumed to have been due to He^3. The momentum of the He^3 and proton along the direction of the π^- meson gives 32.9 Mev for the energy of this meson, which is in good agreement with the measured energy. Other assignments for tracks 2 and 3 fail to balance momentum. The disintegration equation is

$$ {}_{\Lambda}He^4 \rightarrow He^3 + p + \pi^- + Q_6, \qquad (6)$$

TABLE VII. ${}_{\Lambda}He^4$ disintegration (event 90).

Track	Range in microns	Identity	Energy in Mev	Angle
Hyperfragment	171	${}_{\Lambda}He^4$	19.7	
1	610	p	10.7 ± 0.1	174° (1–2)
2	$2.0<R<2.6$	He^3	$0.5<E<0.7$	$\sim$0° (2–3)
3	10 600	π^-	23.8 ± 0.5	

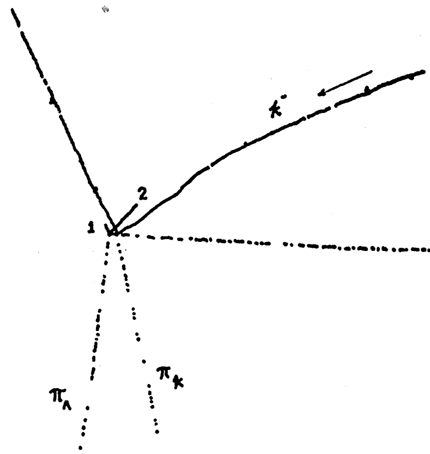

FIG. 7. A drawing of event 95. A ${}_{\Lambda}He^4$ hyperfragment, produced by the absorption of a stopped K^--meson, decayed into a π^- meson (π_{Λ}), a proton (track 2), and a He nucleus (track 1). A π meson (π_K) was also produced by the absorption of the K^--meson.

where Q_6 is found to be 36.9 ± 2 Mev and the binding of the Λ^0 particle is 0.0 ± 2.0 Mev. The measured energy of the π^- meson was used to find Q_6.

Event 36

This hyperfragment came from a star produced in a plate exposed to cosmic rays. The hyperfragment track is 31 microns long and appears to have been caused by a particle of greater than protonic mass. The disintegration star consists of three tracks which are coplanar to within three degrees. A drawing of this event is shown in Fig. 8. A summary of the measurements is given in Table IX.

Track 3 was followed through successive pellicles until it ended. The grain density and scattering along the track indicate that it was caused by a light meson which came to rest. A characteristic σ star at the end of the track shows that it was undoubtedly due to a π^- meson.

Track 2, from its appearance, is consistent with a nuclear particle of $Z=1$.

TABLE VIII. Measurements of tracks from hyperfragment decay ${}_{\Lambda}He^4$ (event 95).

Track	Range in microns	Identity	Energy Mev	Angles
Hyperfragment	2.6	${}_{\Lambda}He^4$	0.7	
1	4.0	He^3	1.2	84° (1–2)
2	18.0	p	1.2	127° (2–3)
3	15 200[a]	π^-	34.5 ± 2.0	

[a] The range quoted in this table is the range from the hyperfragment decay to the point of interaction of the π^- meson. The energy of the meson at the point of interaction was obtained from a grain count.

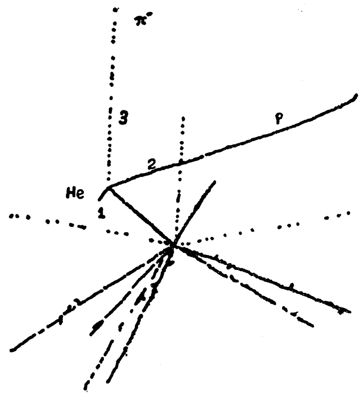

FIG. 8. The $_{\Lambda}He^5$ hyperfragment (event 36) was found in the cosmic-ray stack. The three tracks from the hyperfragment decay are coplanar. Momentum is balanced for the following assignments; track 3 a π^- meson, track 2 a proton, and track 1 an alpha particle. The binding of the Λ^0 particle in $_{\Lambda}He^5$ is found to be 2.0 ± 0.6 Mev.

If one assumes that no neutral particles were emitted in the disintegration, then one can infer the identities of particles 1 and 2 by the requirement of momentum balance. If track 1 is assumed to be He^4 and track 2 a proton the momentum unbalance is 8.5 Mev/c. If tracks 1 and 2 are assumed to be He^3 and a proton, respectively, the momentum unbalance is 27 Mev/c. Any other assignments for tracks 1 and 2 lead to a very large momentum unbalance. The maximum error in momentum balance, due to errors in measurement of angle, is 10 Mev/c. Therefore, the above data strongly indicate that the hyperfragment disintegration was

$$_{\Lambda}He^5 \rightarrow He^4 + p + \pi^- + Q_7, \tag{7}$$

where $Q_7 = 34.9\pm0.5$ Mev. Hence, the binding energy of the Λ^0 particle in $_{\Lambda}He^5$ is 2.0 ± 0.6 Mev.

If one assumes that a neutron was emitted, then no matter what assignments are made for tracks 1 and 2, the binding energy of the Λ^0 particle is found to be negative.

Event 61

The hyperfragment track, from a star produced by a 3-Bev π^- meson, is 79 microns long and does not show any detectable thindown from which we conclude that the charge is less than 4. The multiple scattering along the end of the hyperfragment track is indicative of a stopping particle. Two tracks originate from the hyperfragment decay. Delta rays and grain density show that both tracks were produced by singly charged particles. One track stops in the stack after 2005 microns. Multiple scattering measurements give a deuteron mass for this particle although a proton or triton mass cannot be excluded. The other track from the decay is gray and corresponds to an energy of about 100 Mev if it was caused by a proton. Due to the steepness of this track the energy cannot be evaluated accurately by a measurement of grain density. If the momentum unbalance is given to a single neutron, the total kinetic energy is close to that expected from the nonmesonic decay of a bound Λ^0 particle in $_{\Lambda}He^3$, $_{\Lambda}He^4$, or $_{\Lambda}He^5$. Although the binding energy cannot be evaluated for this event, it is significant to note that this $_{\Lambda}He$ hyperfragment decayed nonmesonically.

TABLE IX. Measurements on event 36 ($_{\Lambda}He^5$).

Track	Range in microns	Identity	Energy in Mev	Angles
Hyperfragment	31	$_{\Lambda}He^5$	7.1	
1	6.7	He^4	2.0	133°
2	92	p	3.4	84°
3	15 470	π^-	29.5	

Event 74

Another example of the nonmesonic decay of a helium fragment was also found in a stack exposed to 3-Bev π^- mesons. This fragment had a range of 129 microns. The small amount of scattering along its track indicates that the mass was greater than protonic. Since it disintegrated into two charged particles its charge must have been at least two, whereas from comparison with the tracks of lithium fragments in the same emulsion, the charge appears to be less than three. Thus we conclude that this was a helium hyperfragment. One of the two particles into which the hyperfragment disintegrated had a range of 3051 microns and is shown by multiple scattering to have been a proton. The second particle had a range of 62 microns. Some scattering along its track indicates that it was singly charged, which is consistent with the conclusion that this hyperfragment was helium. If one assumes that one neutron was emitted in the decay the event cannot be made consistent with a Λ^0 particle bound in helium. Therefore it is probable that it was a nonmesonic decay of $_{\Lambda}He^4$ or $_{\Lambda}He^5$ with the emission of two or more neutrons.

Event 38

A third example of the nonmesonic decay of a probable $_{\Lambda}He$ hyperfragment was found in the cosmic ray stack. Two tracks emerge from the 4 micron long hyperfragment track. Both outgoing particles had a charge of one. They could have been protons, deuterons, or tritons. If only one neutron were emitted, the total kinetic energy is considerably less than the available energy from a nonmesonic Λ^0 decay, so that two or more neutrons were probably emitted.

Event 100

This hyperfragment emerged from a star produced by a stopped K^--meson. Its track is only 13 microns long and therefore little information regarding the charge of the hyperfragment can be obtained from it. However, the track is thick and straight and appears to have been produced by a nuclear fragment of charge greater than 2.

The secondary star produced by the disintegration of the hyperfragment consists of three tracks. A projection drawing of the event is shown in Fig. 9 and the detailed measurements on the secondary star are given in Table X. Track 3 was followed in the pellicle stack to its end, where it produced a characteristic two prong σ star. In addition the grain density and scattering shows that track 3 was produced by a π^- meson. The energy, as deduced from the range, was 26.6±0.5 Mev. Track 1 is 51.6 microns long. The scattering along it strongly suggests that it was caused by a singly charged particle. Track 2 has a range of 2.8±0.4 microns. Upon close observation it is seen to consist of two individual tracks. This is highly suggestive that track 2 was the result of the decay in flight of a Be^8 nucleus into two alpha particles.

TABLE X. Detailed measurements on event 100 ($_{\Lambda}Be^9$).

Track	Range in microns	Identity	Energy in Mev	Angle in the decay plane
Hyperfragment	13.2	$_{\Lambda}Be^9$	13	
1	51.6	p	2.38	162° (1–2)
2	2.8±0.4	He^4+He^4	1.56	152° (2–3)
3	12840	π^-	26.6	

From the angular measurements the three tracks are 5° off coplanarity. In these measurements the dip of track 2 was taken to be zero, because of the fact that it is so small as to be immeasurable. In order to make the three tracks coplanar, the dip of track 2 need only be 0.1 micron in the processed emulsion. Therefore it is reasonable to assume that the three tracks are coplanar and that no neutral particles were involved in the disintegration of the hyperfragment.

If it is assumed that track 1 was due to a proton, the residual momentum of the π^- meson and proton is 144.5 Mev/c. Then each alpha particle should have a momentum of 72.3 Mev/c, and hence a range of 3.16 microns. This compares very well with the measured range of 2.8±0.4 microns. In addition, the direction of the residual momentum is within 10 degrees of the direction of track 2, which is within the error in angular measurements. On the other hand, if one assumes that track 2 was caused by a deuteron, then the alpha particles should have a range of 4.76 microns. This is inconsistent with the observed range.

The disintegration scheme of this hyperfragment can then be written

$$_{\Lambda}Be^9 \rightarrow Be^8+p+\pi^-+Q_8 \ (Be^8 \rightarrow He^4+He^4), \qquad (8)$$

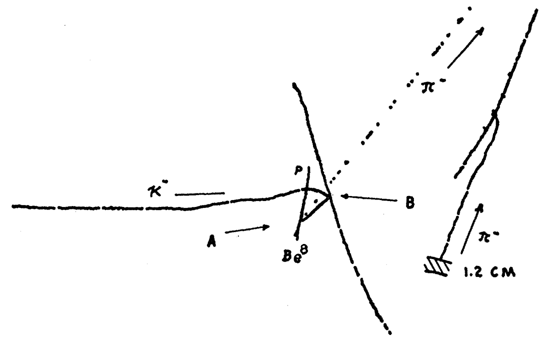

FIG. 9. A $_{\Lambda}Be^9$ hyperfragment was produced by the nuclear absorption of a negative K-meson from rest (event 100). The star produced by the K^--meson absorption is indicated by arrow B. The hyperfragment (F) decayed (at the point indicated by arrow A) into a π^- meson of 26.6±0.6 Mev, a proton and Be^8. The two alpha tracks begin to separate near their end.

where $Q_8=30.5\pm0.5$ Mev. The binding of the Λ^0 particle in $_{\Lambda}Be^9$ is then 6.5±0.6 Mev.

Event 34

This example of a mesonic decay of a heavy hyperfragment was found in a cosmic-ray stack. The track of the hyperfragment is 87 microns long and has a measurable thindown. A drawing of the event is shown in Fig. 10. The thindown and the residual range from the beginning of δ rays give a charge of 6 or 7. There are only two tracks from the disintegration of the fragment; a track due to a π^- meson of range 2100 microns (9.5 Mev), and the track of a nuclear particle of range 326 microns. The multiple scattering suggests a deuteron mass, but a proton or a triton is consistent with the data. The residual momentum of the π^-

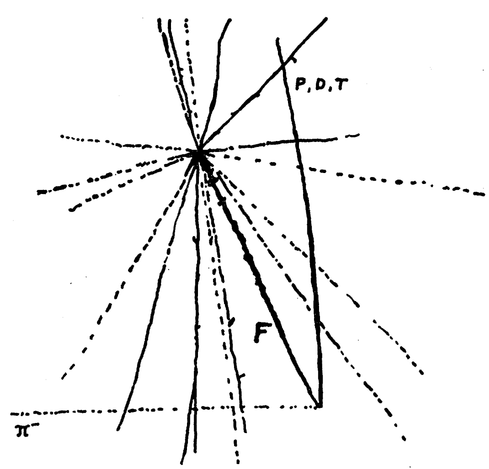

FIG. 10. The moderately heavy hyperfragment (probably C or N) came from a cosmic-ray star (event 34). The hyperfragment track F shows an appreciable thin-down. Delta rays can be observed near the primary star. A π^- meson of 9.5 Mev and a p, d, or t originate from the disintegration of the fragment. It is probable that the remaining heavy nucleus received such a small energy from the decay that it did not produce a visible track.

meson and the deuteron is 125 Mev/c. A carbon or a nitrogen recoil of this momentum would not be visible. If a neutron was not involved, the binding energy for the Λ^0 particle is of the order of 10 to 17 Mev. But it is quite possible that a neutron was emitted, in which case it is impossible to obtain the binding energy from the disintegration. Furthermore, it must be remembered that the residual carbon or nitrogen nucleus may have been left in an excited state,[10] in which case the total energy release from the decay would be greater than the measured energy.

The main interest in this event is that the Λ^0 particle bound in this heavy nucleus decayed mesonically.

SUMMARY AND DISCUSSION

Many of the delayed disintegrations of nuclear fragments can be shown to be due to the decay of a bound Λ^0 particle. Aside from the two energetic fragments reported in I, which are clearly not bound Λ^0 particles, there is no clear experimental evidence for some other process which could produce delayed disintegrations. For this reason, the delayed fragment disintegrations where the energy release cannot be determined are also interpreted as Λ^0 hyperfragments.

The ratios of hyperfragments to stars produced by 3-Bev protons, 6-Bev protons, 3-Bev π^- mesons, and cosmic rays are 10^{-3}, 7×10^{-4}, 9.5×10^{-4}, and 6.2×10^{-4}, respectively.[11] All stars were counted in the tabulation of the cosmic-ray events. If low-energy stars are not counted, the ratio of hyperfragments to stars is nearly doubled. It is interesting to note that the above ratios are not significantly different. They may be somewhat high because of inclusion of events due to the nuclear capture of very slow π^- mesons. A lower limit to the ratio of hyperfragments to stars can be obtained by considering only the hyperfragments with ranges greater than 15 microns (see Table I). It is possible to rule out slow negative π mesons as the cause of these connected stars.

TABLE XI. Summary of binding energies.

Event	Hyperfragment	Decay scheme	B_Λ (Mev)
87	$_\Lambda H^3$	$d+p+\pi^-$	0.6 ± 0.6
89	$_\Lambda H^3$	$d+p+\pi^-$	-0.5 ± 0.6
35	$_\Lambda H^3$	$p+p+n+\pi^-$	0.4 ± 0.7
70	$_\Lambda H^4$	$d+p+n+\pi^-$	1.9 ± 2.0
			or 0.5 ± 2.0
4	$_\Lambda He^3$	$d+p+\pi^0$	5.9 ± 1.0
	or $_\Lambda He^4$	$t+p+\pi^0$	3.9 ± 1.0
95	$_\Lambda He^4$	$He^3+p+\pi^-$	0.0 ± 2.0
90	$_\Lambda He^4$	$He^3+p+\pi^-$	1.8 ± 0.6
36	$_\Lambda He^5$	$He^4+p+\pi^-$	2.0 ± 0.6
3	$_\Lambda Be^7$	$He^4+p+p+n$	5.9 ± 8.0
1	$_\Lambda Be^8$	He^3+He^4+n	3.7 ± 3.0
	or $_\Lambda Be^9$	He^4+He^4+n	-0.7 ± 3.0
100	$_\Lambda Be^9$	$Be^8+p+\pi^-$	6.5 ± 0.6
2	$_\Lambda C^{11}$	Li^7+He^3+p	13 ± 6

[10] This point was suggested by Professor V. Telegdi.

[11] Castagnoli, Cortini, and Franzinetti, Nuovo cimento 2, 550 (1955). These authors find 2.5×10^{-4} for the frequency of hyperfragments in cosmic rays.

The fraction of stars produced by stopped K^--mesons which have hyperfragments is about 1/20.[3] Although this fraction is high, the rate of finding hyperfragments in the present pellicles is considerably lower than for the other exposures that were used in this study. (On the average, 2 K^--meson stars were found in each plate in an area of 5 cm^2.) The rates of finding hyperfragments in the cosmic-ray plates, the proton plates, and the high-energy π^--meson plates are comparable.

One of the striking features of the observations is the ratio of mesonic to nonmesonic decays for various nuclei. Including the data from I, 3 hyperhydrogen nuclei were observed, all of which decayed mesonically. Seven hyperhelium nuclei were found of which 4 decayed mesonically and 3 decayed without π-meson emission. Of the remaining 88 hyperfragments with charge greater than two, only two decayed with the emission of a π^- meson (events 34 and 100). These data show that the nonmesonic mode of decay is important in helium and predominates for heavier elements.

No decay in flight of a hyperfragment has been identified. Although it is not always possible to detect a nonmesonic decay in flight, a mesonic decay should be quite distinctive. The absence of decays in flight suggests that the lifetime of the Λ^0 particle is not greatly reduced in nuclear matter.

Definitely one example of the mesonic decay of a $_\Lambda He^5$ fragment has been found (event 36). In addition, one $_\Lambda H^4$ has been observed (event 70). Since the exclusion principle is inoperative for the Λ^0 particle in a nucleus, it might be expected that a Λ^0 particle could become attached to a stable nucleus with the resulting hypernucleus being stable. It is not surprising, therefore, that $_\Lambda H^4$ and $_\Lambda He^5$ fragments are observed.[12]

A summary of the data reported in this paper and in I on the binding energy of the Λ^0 particle in various nuclei is given in Table XI.

Dalitz[13] and Jones and Knipp[14] have shown, assuming charge independence, that the binding energy of $_\Lambda He^3$ should be less than that of $_\Lambda H^3$. The small value for the binding of the Λ^0 particle in $_\Lambda H^3$ strongly suggests that $_\Lambda He^3$ may not exist, and that event 4 should be interpreted as $_\Lambda He^4$. Also the value of the binding energy for $_\Lambda Be^9$ from event 100 would imply that event 1 was $_\Lambda Be^8$ rather than $_\Lambda Be^9$.

Three examples of the mesonic decay of $_\Lambda H^3$ yield an average binding energy for the Λ^0 particle of 0.2 ± 0.4

[12] $_\Lambda H^4$ events have been reported by O. Haugerud and S. O. Sorensen, Phys. Rev. 99, 1046 (1955). Friedlander, Keefe, and Menon, Nuovo cimento 2, 663 (1955). Schein, Haskin, and Leenov, Phys. Rev. 100, 1455 (1955). A $_\Lambda He^5$ event has been reported by Hill, Salant, Widgoff, Osborne, Pevsner, Ritson, Crussard, and Walker, Phys. Rev. 94, 797 (1954). $_\Lambda H^4$ and $_\Lambda He^5$ events were reported at the Pisa conference by the Bristol, Genoa-Milan, Paris, Dublin, and Rome groups.

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

[14] J. T. Jones and J. K. Knipp, Nuovo cimento 2, 857 (1955).

Mev. The average Λ^0 particle binding energy for the three ${}_{\Lambda}He^4$ events (4, 95, and 90) is 2.2 ± 0.6 Mev, where the individual values were given a weight inversely proportional to their errors. These values are in agreement with those reported by other laboratories.[15]

Event 100 is quite singular in that it is the only event known to the authors where the binding energy can be accurately determined for a nucleus heavier than ${}_{\Lambda}He^5$. The binding in ${}_{\Lambda}Be^9$ (6.5 ± 0.6 Mev) is considerably higher than in ${}_{\Lambda}He^5$ (2.0 ± 0.6 Mev). A comparison of the Λ^0 particle binding energies in ${}_{\Lambda}H^3$, ${}_{\Lambda}He^4$, ${}_{\Lambda}He^5$, ${}_{\Lambda}Be^9$, and ${}_{\Lambda}C^{11}$ shows that the binding energy tends to increase with increasing mass number, for A as high as 11. The variation of the binding energy with A is illustrated in Fig. 11. It is interesting to note that a Λ^0 particle is more tightly bound in ${}_{\Lambda}Be^9$ than the last neutron in Be^9 (1.7 Mev). This can be considered as further evidence, in addition to the ${}_{\Lambda}H^4$ and ${}_{\Lambda}He^5$ events, that the Pauli principle need not be applied to a Λ^0 particle in a nucleus. The observed variation of the Λ^0 particle binding energy with mass number suggests that the study of hyperfragments heavier than Be may yield further interesting results regarding the interaction of the Λ^0 particle with nuclear matter. However, the study of heavy hyperfragments is not easy because the decay mode for elements heavier than helium is predominantly nonmesonic, which leads to a high nuclear excitation. The emission of more than one neutron from such a disintegration is quite probable and therefore most of the events are not analyzable. Nevertheless, since a majority of the hyperfragments are heavier than helium, it should be possible occasionally to find a disintegration where a neutron is not involved. In such a case, the error in the measurement of the binding energy should not be much larger than for the light elements. Also, it is possible that further examples of mesonic decays in heavy elements will be found.

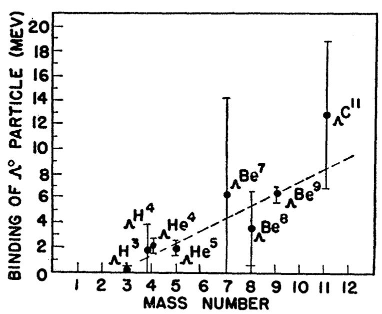

FIG. 11. The variation of the binding energy of the Λ^0 particle with mass number.

[15] ${}_{\Lambda}H^3$ hyperfragments have been reported by Bonetti, Levi Setti, Panetti, Scarsi, and Tomasini, Nuovo cimento **11**, 210 and 330 (1954); Debenedetti, Garelli, Tallone, and Vigone, Nuovo cimento **1**, 1180 (1955); H. Yagoda, Phys. Rev. **98**, 153 (1955). ${}_{\Lambda}H^3$ events were also described at the Pisa conference by the Dublin, Paris, and Bristol groups. Examples of ${}_{\Lambda}He^4$ fragments have been observed by Naugle, Ney, Freier, and Cheston, Phys. Rev. **94**, 677 (1954); Balbo *et al.*, loc. cit; Seeman, Shapiro, and Stiller, Phys. Rev. **100**, 1480 (1955). A ${}_{\Lambda}He^4$ event was reported at the Pisa conference by the Bristol group.

TABLE XII. Momenta of Λ^0 particles in hyperfragments.

Event	Hyper-fragment	p in Mev/c	Kinetic energy in Mev
87	${}_{\Lambda}H^3$	105	5.0
89	${}_{\Lambda}H^3$	70	2.19
35	${}_{\Lambda}H^3$	81	3.0
70	${}_{\Lambda}H^4$	34 or 76	0.5 or 2.6
95	${}_{\Lambda}He^4$	82	3.0
90	${}_{\Lambda}He^4$	57	1.46
36	${}_{\Lambda}He^5$	122	6.7
100	${}_{\Lambda}Be^9$	144.5	9.5

A comparatively large number of hyperhydrogen nuclei have been found in this study (4 events). In view of the fact that more protons are emitted from stars than deuterons, if ${}_{\Lambda}H^2$ exists, one might expect it to be more abundant than ${}_{\Lambda}H^3$. It therefore seems significant that no ${}_{\Lambda}H^2$ fragments were found. The decreasing Λ^0 binding energy with decreasing A, along with the low binding in the hypertriton (0.2 ± 0.4 Mev), strongly suggests that a proton and a Λ^0 particle do not form a bound system.

In seven examples of hyperhydrogen and hyperhelium disintegrations (events 87, 89, 35, 70, 95, 90, and 36), the proton and π^- meson were emitted in nearly opposite directions. This observation implies that perhaps the momentum of the Λ^0 particle in the nucleus was small, and that it can be found from the vector sum of the momenta of the proton and π^- meson. This assumes that neither the proton nor the π^- meson interacted with the residual nucleus after the decay. In view of the very low binding energy of the Λ^0 particle, this assumption would seem reasonable. The momentum and kinetic energy of the Λ^0 particle in the hyperfragment as obtained by this method are shown in Table XII.

If the binding of the Λ^0 particle can be described in terms of a potential well, the depth of such a well is not very shallow ($\sim$20 Mev), as indicated by the binding energy in ${}_{\Lambda}Be^9$. For the light hyperfragments, the low binding energy suggests that the Λ^0 particle spends an appreciable fraction of its time outside the nucleus. This suggestion may explain the low kinetic energy of the Λ^0 particle in the light hyperfragments.

No additional energetic hyperfragments, such as events 27 and 28 in I, were found.

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