to radiative pion-nucleon scattering, in which more gentle photons are associated with the interesting phenomena in the resonance region. Although the cross section is typically less than one millibarn, present experimental techniques should suffice to give accurate information about this reaction. Certainly the static theory used in this paper is not adequate for the energies presently under discussion but we should remark that the development of a suitable theory does not appear to be difficult.

As an example, let us discuss the 900-MeV $F_{5/2}$ πN resonance. One might expect photon emission to be especially large at this resonance because of the large cross section for large-angle scattering. [For instance, we might note that the time corresponding to the width (100 MeV) of the resonance is just that required for an F-wave meson to go half a revolution about the nucleon at its classical impact parameter. On the basis of this simple picture, the large accelerations involved should emit substantial high-frequency radiation.] In the "mass spectrum" of the final pion-nucleon system, one expects to see the 600-MeV resonance ($D_{3/2}$), which could be reached by electric dipole emission and the 3-3 resonance, reached by magnetic dipole or electric quadrupole radiation (not to mention the decay $F_{5/2}\rightarrow$ nucleon+photon). Here the relative weight of the lower resonances is of interest. Even more informative (and difficult) would be accurate angular distribution data. This could be expected to tell, for example, something about the intricate mixture of amplitudes near the third resonance. It should be mentioned that Überall has investigated the bremsstrahlung in πN scattering for energies of several BeV and greater.[11] Another relevant proposal has been made by Yennie and Feshbach.[12]

[11] H. Überall, Phys. Rev. 126, 861 (1962).
[12] D. R. Yennie and H. Feshbach, in *Proceedings of the International Conference on High-Energy Physics, Geneva, 1962* (CERN Scientific Information Service, Geneva, Switzerland, 1962), p. 219.

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Production of Hyperfragments by the Interactions of 1.5-GeV/c K^- Mesons in Lithium-Loaded Emulsions*

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Hyperfragment production by some 31 000 interactions of 1.5-GeV/c K^- mesons in Lithium-loaded $K5$ nuclear emulsions has been studied and compared with data from 0.8-GeV/c and existing data from 1.5-GeV/c K^- interactions in normal emulsions. The study of the prong number distributions of the hyperfragment parent stars provides a sensitive method for determining the production rates of hyperfragments by K^- interactions with light ($C,N,0$) and heavy (Ag,Br) emulsion nuclei; these production rates are found to be $(0.66\pm0.11)\%$ and $(5.20\pm0.20)\%$, respectively. An appreciable proportion of mesonic hyperfragments ($Z<6$) and Li^8 fragments have very short ranges ($R_{HF}\leq 10\,\mu$); this fact indicates the possibility of contaminations of "light" hypernuclides among the assumed mesic spallation hyperfragments. The predominant part of the hyperfragment production stars which shows the emission of "short" prongs involves the disintegration of heavy nuclei, thus indicating that Coulomb-barrier criteria cannot be used in discriminating among light or heavy hyperfragment parent stars at high K^- momenta. No double hyperfragment was observed. One K^- interaction emitted two hyperfragments decaying nonmesically. The π^+ decay of a ${}_{\Lambda}He^4$ hyperfragment has been found. An estimate of the branching ratio R of the π^+ decay and π^- decay modes for the ${}_{\Lambda}He^4$ hypernucleus gives $R\leq(2.7\pm1.1)\%$.

I. INTRODUCTION

THE production of hyperfragments by interactions of K^- mesons has been studied in nuclear emulsions at K^- momenta ranging from zero (absorptions at rest) up to 2.5 GeV/c.[1–6]

Characteristic of the experiments at high K^- momenta is the detection of large numbers of short-range hyperfragments attributed to heavy spallation products of silver and bromine nuclei recoiling after having

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[1] N. A. Nickols, S. B. Curtis, and D. J. Prowse, Phys. Letters 1, 327 (1962).
[2] B. D. Jones, B. Sanjeevaiah, J. Zakrzewski, M. Csejthey-Barth, J. B. Lagnaux, J. Sacton, M. J. Beniston, E. H. S. Burhop, and D. H. Davis, Phys. Rev. 127, 236 (1962).
[3] E. R. Fletcher, D. O'Sullivan, T. P. Shah, A. Thompson, J. E. Allen, M. J. Beniston, D. A. Garbutt, J. Lemonne, P. Renard, J. Sacton, P. Allen, Sr., M. Heeran, A. Montwill, R. C. Kumar, P. B. March, T. Pniewski, and J. Zakrezewski, Phys. Letters 3, 280 (1963).
[4] J. P. Lagnaux, J. Lemonne, J. Sacton, B. Bishara, D. H. Davis, and M. A. Hussain, Phys. Letters 4, 341 (1963).
[5] J. Prem and P. H. Steinberg, presented at the International Conference on Hyperfragments, St. Cergue, Switzerland (unpublished).
[6] D. Abeledo, L. Choy, R. G. Ammar, N. Crayton, R. Levi Setti, M. Raymund, and O. Skjeggestad, Nuovo Cimento 22, 1171 (1961).

trapped a Λ^0 hyperon (spallation hyperfragments). In particular, Jones *et al.*[2] and Fletcher *et al.*[3] concluded that this process is dominant (accounted for at least 65% of the hyperfragments produced) in the interactions of 0.8, 1.3, and 1.5-GeV/c K^- mesons with emulsion nuclei.

The detection of spallation hyperfragments at lower K^- momenta becomes difficult, since the momentum imparted to the recoiling nucleus is too small to yield a visible track. Thus, while the range of spallation hyperfragments in Refs. 2 and 3 may exceed 5 μ, it is generally less than 2 μ at K^- momenta (50–300) MeV/c, as studied by Lagnaux *et al.*[4] It is conceivable that for K^- absorptions at rest, most of the spallation hyperfragments will escape detection. In fact, Davis *et al.*[7] and Cester *et al.*[8] found that $(30\pm7)\%$ and $\leq 15\%$, respectively, of all K^- absorptions at rest may be ascribed to the formation and decay of such "cryptofragments."

Jones *et al.*[2] also predict the emission of light hyperfragments from K^- interactions with the heavy emulsion nuclei (Ag,Br). For K^- absorptions at rest, Abeledo *et al.*[6] have shown that the fraction of mesic hyperfragments which must have originated in light emulsion nuclei (C,N,O) is large and some indication that at higher K^- momenta (50–300 MeV/c) a fraction of the hyperfragments may also be produced in the light emulsion nuclei was recently obtained by Lagnaux *et al.*[4] The light hypernuclides ($A\leq 16$), therefore, may emerge in the disintegrations of either the heavy or the light emulsion nuclei.

In the present investigation, hyperfragment production at 1.5-GeV/c K^- momentum was studied in a stack loaded with lithium acetate in aqueous solutions. The increased content of light nuclei in these emulsions will enhance hyperfragment production in C, N, O so that a comparison with data in normal emulsion may give additional information on such processes. Furthermore, it was thought that the decreased stopping power of the loaded emulsions would be helpful in the discrimination of the short-range spallation hyperfragments.

A search was also made for the production of "double hyperfragments" following the production of two Λ^0 hyperons in either the high-energy K^- interaction[9] or following the absorption of a Ξ^- hyperon.[10]

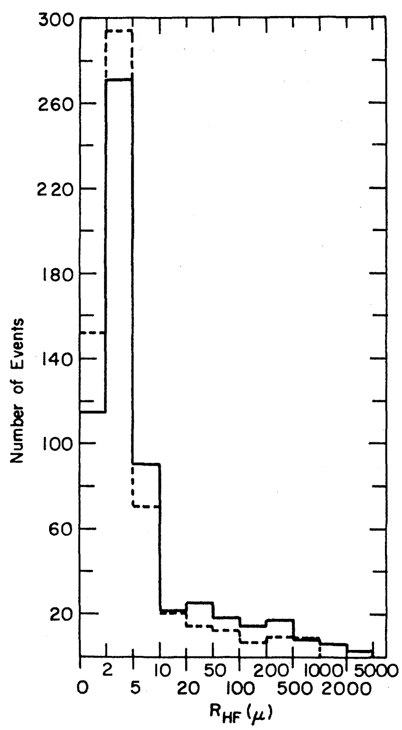

FIG. 1. Range distribution of nonmesic hyperfragments from the interactions of K^- mesons of 1.5-GeV/c momentum in Li-loaded emulsions (590 events). Broken lines indicate the normalized distribution from normal emulsions. Ref. 3.

II. EXPERIMENTAL MATERIAL

A stack consisting of sixty 1200-μ Ilford $K5$ pellicles, 20×20 cm^2 in size, was loaded with a lithium acetate solution, as described by Davis *et al.*[11] and exposed to the separated 1.5-GeV/c K^- beam at the CERN PS. The pellicles had, at exposure, a thickness of $\sim$2.1 mm and, as a result of the increased light-nuclei content, the stopping power was reduced in the loaded emulsion to yield, at least for low-Z ions, ranges $\sim$20% greater than in normal emulsion. The plates were area scanned for nuclear interactions produced by beam particles. Every star was examined to detect the presence of more than one center and every prong from each star was followed within the emulsion sheet containing the event and any secondary interaction or decay recorded. 31 635 beam stars were detected, yielding 116 mesic hyperfragments of which one decayed with the emission of a π^+. No decay of a double hyperfragment was observed. A subsample of 21 038 beam stars yielded 640 events which were classified as due to the production and subsequent decay of a hyperfragment. Of the latter, 60 decayed mesically; 74 hammer tracks (mostly Li^8 fragments) out of this subsample were also recorded.

In addition, a stack consisting of 117 1200-μ Ilford K5 pellicles, 15×20 cm^2 in size, which was exposed to a separated 0.8-GeV/c K^- beam at the Berkeley Bevatron, was also available. Details of this stack have

[7] D. H. Davis, M. Csejthey-Barth, J. Sacton, B. D. Jones, B. Sanjeevaiah, and J. Zakrzewski, Nuovo Cimento **22**, 275 (1962).

[8] R. Cester, G. Ciocchetti, A. Debenedetti, A. Marzari Chiesa, G. Rinaudo, C. Deney, K. Gottstein, and W. Püschel, Nuovo Cimento **22**, 1069 (1962).

[9] W. H. Barkas, N. N. Biswas, D. A. De Lise, J. N. Dyer, H. H. Heckman, and F. M. Smith, Phys. Rev. Letters **2**, 466 (1959).

[10] M. Danysz, K. Garbowska, J. Pniewski, T. Pniewski, J. Zakrzewski, E. R. Fletcher, J. Lemonne, P. Renard, J. Sacton, W. T. Toner, D. O'Sullivan, T. P. Shah, A. Thompson, P. Allen, Sr., M. Heeran, A. Montwill, J. E. Allen, M. J. Beniston, D. H. Davis, D. A. Garbutt, V. A. Bull, R. C. Kumar, and P. V. March, Phys. Rev. Letters **11**, 29 (1963).

[11] D. H. Davis, R. Levi Setti, M. Raymund, and G. Tomasini, Nuovo Cimento Suppl. **26**, 345 (1962).

already been described by Levi Setti and Skjeggestad.[12] For the present purpose 139 mesic hyperfragments and 77 hammer tracks were used.

III. ANALYSIS OF THE DATA AND RESULTS

A. Hyperfragment Range Distributions

The distribution of the ranges (R_{HF}) of the hyperfragments decaying nonmesically is given in Fig. 1, where our data for the Li-loaded emulsions are compared with analogous ones[3] obtained at 1.5-GeV/c K^- momentum in normal emulsion. Since the prongs were followed only within the original pellicles (of different thicknesses in the two experiments) a "flat chamber correction"[13] is applied to both distributions. The agreement suggests that the effects on these range

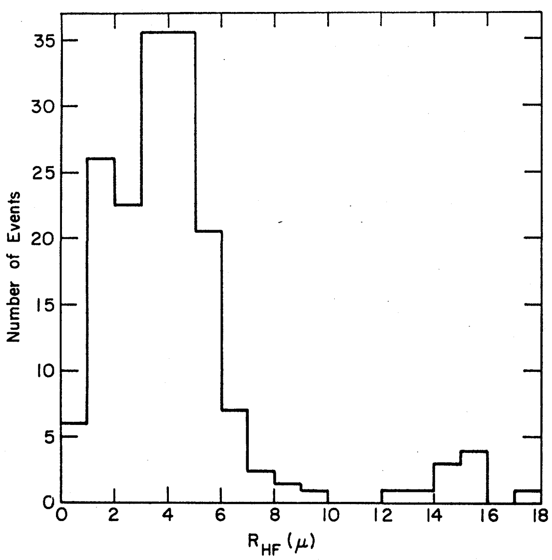

FIG. 2. Range distribution of hyperfragments of range less than 18 μ (equal range intervals!) for 1.5-GeV/c K^- momentum in Li-loaded emulsions (168 events).

distributions, due to loading, namely the decrease in stopping power and the increase of interactions with light nuclei are small.

The range distribution of a sample of nonmesic hyperfragments of $R_{\mathrm{HF}} \leq 18\,\mu$ is shown in Fig. 2. This distribution indicates that the hyperfragments of "short" range ($R_{\mathrm{HF}} \leq 10\,\mu$) form quite a distinct group (with a mean of 3.7 μ and a standard deviation of 1.7 μ).

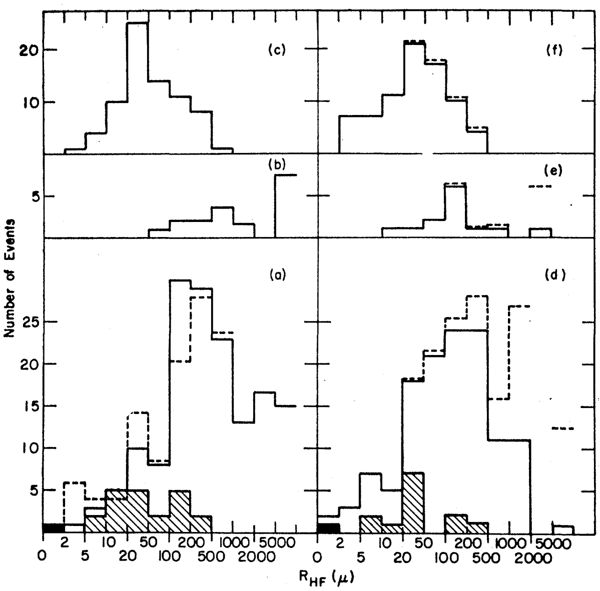

FIG. 3. Range distributions of (a) mesic hyperfragments at rest, (b) mesic hyperfragments in flight, and (c) Li^8 fragments in the 1.5-GeV/c K^- Li-loaded stack; broken lines indicate the normalized distribution from normal emulsions. Figures 3(d), (e), and (f) are the corresponding events in the 0.8-GeV/c K^- stack; in these figures the flat chamber correction is indicated by broken lines; hatching indicates hyperfragments of $Z>2$, black areas possible mesic spallation hyperfragments.

In fact, these are the spallation hyperfragments of Jones *et al.*[2] and the cutoff of the distribution at 10 μ suggests this limit be taken as a boundary value for our further analysis.

The range distributions (corrected for flat chamber effects) of the mesic hyperfragments from the lithium loaded and normal emulsions[3] are shown in Fig. 3(a). These two distributions are again in fair agreement.[14] Figures 3(c), (d), and (f) show for further comparison the range distributions of Li^8 fragments from both the 1.5- and the 0.8-GeV/c stacks and of kinematically analyzed mesic hyperfragments from the 0.8-GeV/c stack. Among the features to be noted are an over-all remarkable similarity between the range distributions for Li^8 fragments as well as for mesic hyperfragments at the two K^- momenta. It can also be pointed out that the range distributions of the Li^8 fragments cover the same interval as that for hyperfragments of $Z>2$, at both K^- momenta.

Of relevance with regard to the study of mesic decays of spallation hyperfragments[15–17] is the fact that, as

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[12] R. Levi Setti and O. Skjeggestad, Nuovo Cimento, Suppl. **26**, 219 (1962).

[13] In deriving the correction it was assumed that the K^- events are uniformly distributed over the depth of the emulsion and that the dip angles of the hyperfragment tracks are isotropically distributed. It is expected that any asymmetry should favor flat angles; in this case the above correction would give an upper limit in the number of events. The lower limit is then given by the uncorrected number of the events. Mention is made in the text whenever data have been corrected for flat chamber effects. These data, however, would not be changed significantly if no correction were applied.

[14] The range distributions in Fig. 3(a) are normalized up to $R_{\mathrm{HF}} \leq 1000\,\mu$ only, due to the uncertainties for longer ranges in the normal emulsion data.

[15] D. H. Davis, R. Levi Setti, M. Raymund, O. Skjeggestad, G. Tomasini, J. Lemonne, P. Renard, and J. Sacton, Phys. Rev. Letters **9**, 464 (1962).

[16] J. Cuevas, J. Diaz, D. Harmsen, W. Just, H. Kramer, H. Spitzer, M. W. Teucher, and E. Lohrmann, Nuovo Cimento **27**, 1500 (1963).

[17] A. Perlmutter, Phys. Letters **4**, 336 (1963).

TABLE I. General results.

	$R_{HF}\leq 10\,\mu$		$R_{HF}>10\,\mu$		$R_{HF}>0\,\mu$	
	Fletcher *et al.* (Ref. 3)	This work	Fletcher *et al.* (Ref. 3)	This work	Fletcher *et al.* (Ref. 3)	This work
Fraction of HF of ranges R_{HF}	76.3±5.9%	71.0±4.4%	23.7±6.1%	29.0±2.7%		
Fraction of mesic HF	1.1±0.5%	0.4±0.3%	55 ±22%	41.1±7.5%		
Fraction of stars with $^*N_t>7$[a]		84.0±4.3%		60.0±5.8%	82.0±3.9%	78.1±3.5%
$\bar{N}_t$		9.6		11.2	11.1	10.6
Fraction of nonmesic HF stars containing short prongs	9±2%	12±3%	59±11%	36±11%		
Fraction of parent K stars with short prongs		9±2%		45±9%		
Fraction of nonmesic HF stars containing recoil tracks	42±4%	36±5%	27±7%	14±7%		
Fraction of parent K stars with recoil tracks		2±1%		15±5%		
Fraction of HF emitted forwards	76.0±4.2%	72.1±4.3%	68.5±8.6%	63.3±6.3%		

[a] $^*N_t$ is total prong number of both the parent K^- star and hyperfragment decay star.

seen in Fig. 3, an appreciable proportion of Li^8 fragments as well as hypernuclides of $2\leq Z<6$ have very short ranges. At 800 MeV/c, in fact, $\sim$10% of the Li^8 have ranges $\leq 5\,\mu$, while as much as $\sim$20% are shorter than 10 μ. These proportions are about a factor of 2 smaller for mesic hyperfragments. At 1.5 GeV/c, about 10% of the Li^8 and 5% of the mesic hyperfragments have ranges less than 10 μ. These results suggest that the selection of mesic decays of spallation hyperfragments be made with very conservative criteria as to range of acceptance. In fact, the possibility of contamination from "light" hypernuclides may not be negligible, especially when accepting events of range greater than 5 and even 10 μ. Only one event in our[15] 800-MeV/c and only one event in our 1.5-GeV/c stacks *may* be interpreted as mesic decays of heavy spallation hyperfragments. The latter one is described here. The hyperfragment decayed into a low-energy $\pi^-(T_\pi=2.6$ MeV); R_{HF} is about 1 μ. There is no evidence of a recoil. If the event is interpreted as the decay of a heavy spallation hyperfragment into a pion and a (invisible) recoil, an upper limit for the Λ binding energy is $\approx$43 MeV. There is the possibility that one of the prongs of the primary (K^-) star comes, in fact, from the hyperfragment decay. Assuming this prong to be a proton, the binding energy would be then 31.6 MeV ($T_p=3.4$ MeV).

Various quantities pertinent to the present analysis are tabulated as a function of two or three groups of hyperfragment ranges ($R_{HF}\leq 10\,\mu$; $R_{HF}>10\,\mu$; $R_{HF}>0\,\mu$) in Table I. where a comparison is also made with the analogous data of Fletcher *et al.*[3] These values for the Li-loaded stack do not change significantly even if the ranges of the hyperfragments are increased by as much as 20%.

B. Hyperfragment Production in Light and Heavy Elements

The yields of hyperfragments from the 1.5-GeV/c K^- interactions in Li-loaded and normal emulsions[3] are (3.2±0.1)% and (4.4±0.3)%, respectively, after correcting for flat chamber effects. Due to the uncertainties in the beam compositions, it is impossible to obtain the true frequency of hyperfragment production for K^- interactions in the two stacks. It is to be noted, however, that in both cases the beam compositions were the same and that at these momenta, hyperfragment production from π^- interactions can still be neglected. From the known compositions of the two different emulsions[11] one can infer from these data that the frequencies of hyperfragment production in Ag, Br, and C, N, O are (6.5±0.9)% and (0±1)%, respectively. It is known, however, that the majority of the hyperfragments produced are spallation hyperfragments with $R_{HF}\leq 10\,\mu$, which must originate from Ag, Br. Thus, it may be more sensitive for the detection of production in light nuclei to consider only hyperfragments of $R_{HF}>10\,\mu$. For this fraction of the events, the frequencies of production in heavy and light elements are (1.2±0.3)% and (0.6±0.4)%, respectively. The statistics are obviously still inadequate to yield a meaningful result concerning production in light nuclei by this method.

We found that a more sensitive method consists in the study of the prong number distributions of the hyperfragment parent stars. These distributions are shown in Fig. 4 separately for the parent stars of nonmesic hyperfragments with $R_{HF}\leq 10\,\mu$ [Fig. 4(a)], of nonmesic hyperfragments of $R_{HF}>10\,\mu$ [Fig. 4(b)], of

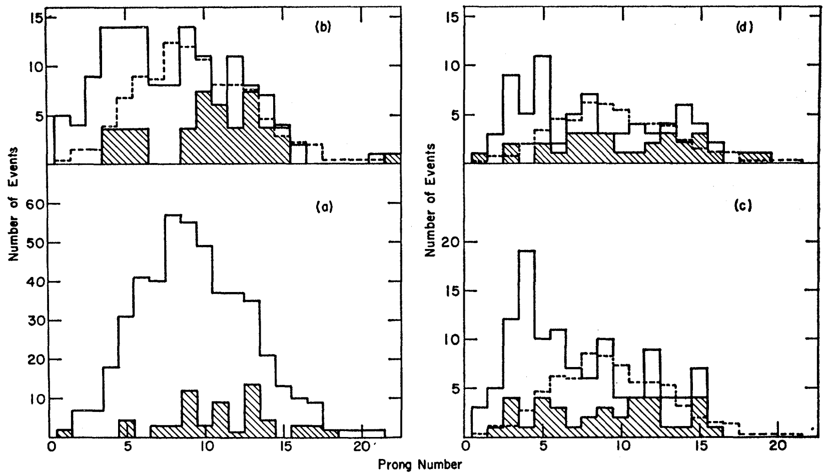

FIG. 4. Prong number distributions of parent stars for the 1.5-GeV/c K^- Li-loaded stack with (a) spallation hyperfragments, (b) nonmesic hyperfragments of $R_{HF}>10\mu$, (c) mesic hyperfragments, and (d) Li^8 prongs ($3.5\mu\leq R\leq 35\mu$); broken lines indicate normalized distributions of Fig. 4(a).

mesic hyperfragments [Fig. 4(c)], and of Li^8 fragments [Fig. 4(d)]. (These distributions refer to the 1.5-GeV/c Li-loaded data and the prong number does not include mesons, the recoils and the hyperfragments or Li^8 fragments.) The latter three distributions are significantly different from that for nonmesic hyperfragments with $R_{HF}\leq 10\,\mu$ in that they show a larger proportion of events with small prong numbers. If one attributes the entirety of $R_{HF}\leq 10\,\mu$ events to spallation hyperfragments originating in heavy nuclei, such an excess at small prong numbers can be attributed to production in light nuclei of the longer range hyperfragments and Li^8 fragments. Assuming that the prong number distribution of the parent stars in Ag, Br is independent of the hyperfragment range (this assumption is consistent with the evidence in all distributions of Fig. 4) an estimate of the frequency of production in light nuclei was obtained by subtracting the histogram of Fig. 4(a) from those in Figs. 4(b), (c), (d). This estimate depends (not critically) on the lower limit in the prong numbers that implies the disintegration of a heavy nucleus in the emulsion. This limit was determined by calculating the production rate in light nuclei as a function of increasing prong number cutoffs until the rate remained constant. The fractions originating in light nuclei and prong number cutoffs are, respectively: For mesic hyperfragments $(38\pm 7)\%$ and 7, for nonmesic hyperfragments of $R_{HF}>10\,\mu$ $(26\pm 5)\%$ and 7, for Li^8 fragments $(29\pm 7)\%$ and 6. This would correspond to a production rate of hyperfragments of $R_{HF}>10\,\mu$ in C, N, O of $(0.6\pm 0.11)\%$, a value consistent with, although more accurate than, the one found above on the basis of different emulsion compositions. For Li^8 the production rate in C, N, O is $(0.20\pm 0.04)\%$. These values may be slightly underestimated, if the sample of hyperfragments with short ranges contained a contamination of light hyperfragments which then cannot be attributed to production in Ag, Br alone.

For purposes of comparison, Fig. 5 shows the prong number distributions of the parent stars of mesic hyperfragments and Li^8 fragments at 800 MeV/c in normal emulsions. The grouping at small prong numbers is even more pronounced than in the loaded stack at 1.5 GeV/c, again indicating substantial production in C, N, O for these hyperfragments known to have $Z<6$ from kinematic analysis of their decay.

Jones *et al.*[2] and Fletcher *et al.*[3] regard the presence of short prongs (of energy below the effective α-particle Coulomb barrier for high-Z nuclei) of length between 3 and 30 μ in a hyperfragment decay star as an indication of the disintegration of a light hypernucleus. They

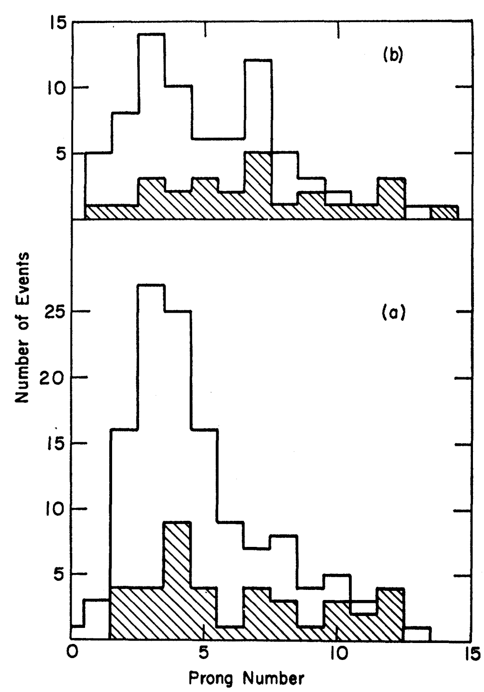

FIG. 5. Prong number distributions of parent stars in the 0.8-GeV/c K^- stack with (a) mesic hyperfragments and (b) Li^8 fragments. Hatching indicates parent stars with short prongs ($3\,\mu\leq R\leq 30\,\mu$).

further showed that such short prongs occur less frequently in the case of short hyperfragments than for long range ones. The frequency of occurrence of short prongs from our analysis of the 1.5-GeV/c data and that of Fletcher *et al.*[3] are compared in Table I and found to be in agreement (due to the lower density of the Li-loaded emulsions; a short prong is defined as one of length between 3.5 and 35 μ). Lagnaux *et al.*[4] applied this criterion to the parent 50–300-MeV/c K^- stars as well in order to explore the hyperfragment production rate in light nuclei. However, the predominant part of our hyperfragment (and Li^8 fragment) production stars, at both 0.8 and 1.5 GeV/c, which shows the emission of short prongs, is known to involve the disintegration of heavy nuclei rather than of light nuclei as seen from the shaded areas in the prong number distributions of Figs. 4 and 5. These results suggest that the presence and the frequency of short prongs among the higher momenta K^- stars may not be taken as indicative of an interaction with C, N, O. To examine this point further, all prong ranges $\leq 106\,\mu$ in a sample of parent and hyperfragment decay stars were measured. The results are shown in Fig. 6, where no evidence is found for a sharp falloff of the number of short prongs for any particular range. A gradual falloff is observed for both spallation hyperfragment decay stars and primary K^- stars. The customary choice in plotting these range distributions of range intervals 3–10–32–100 μ[6,18] would yield for our data, too, a much more pronounced falloff at 32 μ than is indeed present.

A search was further made for the existence of a possible correlation between the length of the shortest stable prong ($3.5\,\mu \leq R < 100\,\mu$) and the prong number of the hyperfragment parent stars. As seen in Fig. 7, the data are not consistent with the assumption that the short prongs originate predominantly in the disintegration of C, N, O.

C. Search for a Double Hyperfragment

It is expected that emulsions with an increased content of light elements favor the detection of double hyperfragments from Ξ^- absorptions at rest because, due to the decreased stopping power of loaded emulsions and the increased probability of light hyperfragment production, it is more likely that the centers of the production and decay stars will be visibly separated. We found no event from our 31 635 beam stars which could be explained by the production and interaction of a Ξ hyperon with the subsequent production and decay of a double hyperfragment.

Furthermore, no "triple" centered stars were found which could be the cascade decay of a double hyperfragment formed in the K^- interaction. Although several stars appeared to be triple centered with assumed connecting tracks of range of only a few microns in range, in no case could one exclude the possibility that only two centers were present, and so they were classified as double stars.

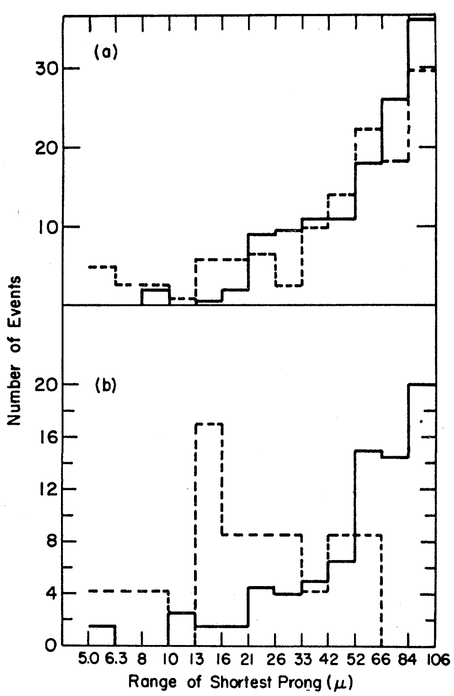

FIG. 6. "Short" prong distribution (excluding hyperfragment tracks) of (a) parent K^- stars and (b) hyperfragment decay stars. Unbroken lines indicate spallation hyperfragments; broken lines nonmesic hyperfragments of longer range ($R_{HF} > 10\mu$).

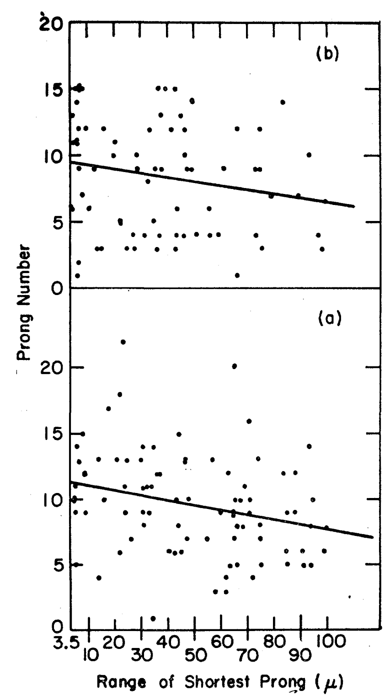

FIG. 7. Scatter diagram of prong numbers versus range of shortest stable prong for parent stars of (a) nonmesic and spallation hyperfragments and (b) mesic hyperfragments. The corresponding regression lines are given.

[18] J. Zakrzewski, D. H. Davis, and O. Skjeggestad, Nuovo Cimento 27, 652 (1963).

TABLE II. π^+ decays of hyperfragments.

Author	Decay schemes	No. of events	B_Λ (MeV)	R_{HF} (μ)	T_π (MeV)	Technique
Schneps	${}_\Lambda Li^7 \to He^6+\pi^++n$		5.7			
et al. Ref. 21.	${}_\Lambda Be^7 \to Li^6+\pi^++n$	1	5.4	4	13.8	Emulsion
	${}_\Lambda He^5 \to H^3+\pi^++2n$					
Kang	${}_\Lambda He^4 \to H^3+\pi^++n$	1	1.5	361	8.4	Emulsion
et al. Ref. 22.	$H^2+\pi^++2n$		<9.6			
Ismail	${}_\Lambda He^4 \to H^3+\pi^++n$		5.0			
et al. Ref. 23.	$H^2+\pi^++2n$	1	<12.1	172	7.7	Emulsion
	$H+\pi^++3n$		<14.3			
Allen	${}_\Lambda He^4 \to H^3+\pi^++n$	1	2.7	17	27.9	Emulsion
et al. Ref. 24.						
Ganguli	${}_\Lambda He^4 \to H+\pi^++3n$	1	2.8	87	3.4	Emulsion
et al. Ref. 25.						
Steinberg	${}_\Lambda He^4 \to H^3+\pi^++n$	1	2.0	2820	13.4	Emulsion
and Prem Ref. 20.	$H^2+\pi^++2n$		<7.1			
Blau	${}_\Lambda H^{3,4} \to \pi^++3,4n?$	1		5	25	Emulsion
et al. Ref. 26.						
Block	${}_\Lambda He^4 \to H^3+\pi^++n$					Bubble
et al. Ref. 27.	$H^2+\pi^++2n$	2(+1)			$\sim$14	chamber
	$H+\pi^++3n$					
This work	${}_\Lambda He^4 \to H^3+\pi^++n$		2.9			
	$H^2+\pi^++2n$	1	<11.4	120	6.2	Emulsion
	$H+\pi^++3n$		<14.7			

After eliminating obvious examples of the interactions in flight and stars produced by captures of negative particles, there remained one K^- interaction in which two hyperfragments decaying nonmesically were emitted. The ranges of the hyperfragments were 3 and 106 μ. Similar events were reported by Wilkinson *et al.*[19] and Steinberg and Prem.[20]

D. π^+ Decay of a ${}_\Lambda He^4$ Hyperfragment

An event interpreted as the π^+ decay of a hyperfragment has been found. The hyperfragment emerged from an 11-prong star produced by a beam particle. The fragment appears to come to rest decaying into two charged particles. The π^+ meson is identified by its characteristic π-μ-e decay; the second track has the appearance of a particle of $Z=1$. No other indication of a track or recoil has been observed at the hyperfragment decay. There are only three possible interpretations for this hyperfragment decay. These are ${}_\Lambda He^4 \to n+\pi^++H^3$ $2n+\pi^++H^2$, $3n+\pi^++H^1$. Several π^+ decays of hyperfragments have already been reported.[21–27] A compilation of all published π^+ decays of hypernuclei is given in Table II. Geometrical data of our π^+ event are given in Table III.

The π^+ decay of hyperfragments has possible explanations such as (i) the Λ bound inside the hypernucleus may have transitions to virtual Σ states and then decay from these states[28] and (ii) the π meson from the usual mesic decay modes may undergo charge exchange before leaving the nucleus. Dalitz and von Hippel from preliminary calculations using these models, estimate that the ratio R of π^+ modes/π^- modes for ${}_\Lambda He^4$ is 1.1% from process (i) and 0.4% from process (ii).[29] Experimentally this ratio was found to be $\sim$1.6% (1 event) and $\sim$4% (3 events) by Kang *et al.*[22] and Block *et al.*,[27] respectively. We have re-estimated R using all the data on mesic decays of hyperfragments which have been reported by emulsion groups.[30] In dealing

TABLE III. Data from the π^+ decay of the EFINS ${}_\Lambda He^4$ hyperfragment.

Track No.	Identity	Range (μ)	Energy* (MeV)	Dip angle (degrees)	Azimuth angle (degrees)
1	${}_\Lambda He^4$	120		-66.8	171.1
2	π^+	1269	6.2	20.7	184.0
	H		4.7		
3	H^2	194	6.0	19.1	290.9
	H^3		6.8		

* Using R–E relation for the Lithium loaded emulsion (Ref. 11).

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with a survey of this kind, one meets with the uncertainties arising from the fact that while π^+ decays have been singled out, not all the π^- decays in the corresponding samples may have been analyzed or even reported. Since, however, both the mesic hyperfragment total production rate as well as the partial rates for the production of specific hypernuclides are known for a variety of producing particles and energies, whenever necessary, an estimate of the number of $_\Lambda He^4$ π^- decays could be obtained from the exposure data. For this purpose it was estimated, using data on analyzed mesic decays, that $\sim 6.5\%$ and $\sim 12\%$ of the mesic hyperfragments are $_\Lambda He^4$ and $_\Lambda He^{4,5}$, respectively. Furthermore, from the known binding energies of $_\Lambda He^4$ and $_\Lambda He^5$ and the average binding energy of a sample of $_\Lambda He^{4,5}$, the ratio of $_\Lambda He^4$ to $_\Lambda He^5$ among the nonuniquely identified $_\Lambda He^{4,5}$ could be obtained, consistent with that for the uniquely identified $_\Lambda He$, namely 1:3. We thus estimate that some 219 examples of the π^- mesic decay of the $_\Lambda He^4$ hyperfragments have been found in such circumstances that a π^+ decay, if any, would have been found and reported, and from the six π^+ mesic decays of $_\Lambda He^4$ reported, it follows that $R \leq (2.7 \pm 1.1)\%$. The use of the inequality assumes that all the π^+ mesic decays have been reported whereas the information available to us may not include all the π^- mesic decays.

III. CONCLUSIONS

The hyperfragments produced in Li-loaded emulsions by 1.5-GeV/c K^- interactions show most of the characteristics exhibited by those produced in normal emulsions by K^- mesons of the same energy, i.e., that the majority of the hyperfragments produced, in particular those with ranges from 0 to 10 μ, are heavy spallation products of Ag and Br nuclei. This similarity also indicates that in both cases the production of hyperfragments by K^- interactions with light nuclei is small.

The range distributions for the mesic hyperfragments as well as those for the Li^8 fragments do not vary appreciably for production at 1.5 and 0.8 GeV/c. Furthermore, the range distributions for mesic hyperfragments of $Z>2$ and for Li^8 fragments show some similarity at 1.5-GeV/c as well as at 0.8-GeV/c K^- momenta.

An appreciable proportion of Li^8 fragments and mesic hyperfragments have very short ranges ($0<R_{HF}\leq 10\,\mu$). Since the major proportion of the mesic hyperfragments is known to have $Z<6$, the possibility of contamination from "light" hypernuclides among the assumed mesic decays of heavy spallation hyperfragments may not be negligible, especially when accepting events of range greater than 5 and even 10 μ. The proportion of mesic heavy spallation hyperfragments among mesic hypernuclides may be $\leq 1/116$ and $\leq 1/139$ at 1.5- and 0.8-GeV/c K^- momenta, respectively.

The yields of hyperfragments from the 1.5-GeV/c K^- interactions in Li-loaded and normal emulsions are $(3.2\pm0.1)\%$ and $(4.4\pm0.4)\%$, respectively. More sensitive data in determining the production rate of hyperfragments from K^- interactions with C, N, O than the above ones were obtained by studying the prong-number distributions of the hyperfragment parent stars. $(38\pm7)\%$, $(26\pm5)\%$, and $(29\pm7)\%$ of all mesic hyperfragments, nonmesic hyperfragments of $R_{HF}>10\,\mu$ and Li^8 fragments, respectively, were attributed to production in light nuclei. The production rates of hyperfragments in light (C, N, O) and heavy (Ag,Br) nuclei are $(0.66\pm0.11)\%$ and $(5.20\pm0.20)\%$, respectively.

The Coulomb barrier criterion was shown to fail in discriminating among light or heavy hyperfragment parent nuclei at 0.8- and 1.5-GeV/c K^- momenta.

The branching ratio of the π^+ decay and π^- decay modes for the $_\Lambda He^4$ hypernucleus derived from emulsion experiments is $R\leq(2.7\pm1.1)\%$. This value is in agreement with the one found by the helium bubble chamber collaboration experiment[27] and not inconsistent with that recently calculated by Dalitz and von Hippel.[29]

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