was experimentally observed by Albers-Schönberg *et al.*[2] by using a metallic indium single crystal. Qualitatively, the observed phase shift can be explained from the present theory as due to the thermal vibrations of the lattice points. The effect of these thermal vibrations is to produce, at the site of the radioactive nucleus, an asymmetric fluctuating electric field gradient which is responsible for the phase shift in the rotational pattern of anisotropy.

IV. CONCLUSION

In this formalism one has a systematic treatment which contains a description of the effects of the changes of the state of the environment. For a solid-state environment the present theory predicts a temperature dependence of the anisotropy.

The rotational dependence of the angular correlation has been developed for the cases of asymmetric crystalline fields. This will greatly increase the interpretability of experiments and the possibility of investigating nuclear quadrupole moments in excited states. For the case of an axially symmetric crystalline field, Eq. (5.5) predicts the phase shift in the rotational pattern of anisotropy as a function of crystal temperature.

The accuracy of the calculation of the nuclear electric quadrupole moment depends highly on the computations of the electrostatic field gradient at the nuclear site. The calculation of this crystalline field is very difficult and a model for the charge distribution in the lattice system is needed. Here we use the point-charge model and introduce an adjustable parameter ξ_i, to take the shielding, antishielding, and covalent effects into account. For the determination of this parameter one has to rely entirely on other measurements.[20]

Since a sufficient knowledge of the wave function of the electronic shell is available,[23] the present theory [i.e., Eqs. (2.12) and (2.13)] will be suitable to investigate the effect of the nuclear spin relaxation due to coupling with atomic electrons on the angular correlation.[24]

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Λ-Binding Energies in Heavy Hyperfragments ($35 \lesssim A \lesssim 80$)

B. Bhowmik, T. Chand, D. V. Chopra, and D. P. Goyal
Department of Physics and Astrophysics, University of Delhi, Delhi, India
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Analysis of 16 short-range ($\leqslant 10\mu$) hyperfragments, produced from 1.5-GeV/c K^- interactions in L_4 hypersensitized emulsions and decaying π^--mesonically, is presented. Of these, 9 are classified as due to the residual spallation products of silver and bromine nuclei, 5 as belonging to lighter species ($A \leqslant 20$), and 2 as ambiguous. The masses of the 9 spallation hyperfragments are determined using the "spallation model." It is concluded that for hyperfragments of masses $A \simeq 35$ to 80, the upper limits of B_Λ could vary from 21.9 to 24.5 MeV.

I. INTRODUCTION

FOLLOWING Jones *et al.*,[1] it is now generally believed that the majority of hyperfragments (HF's) of ranges $\leqslant 10\,\mu$ produced by high-energy K^- interactions at momenta 0.8,[1–3] 1.3 and 1.5,[4] 2.2,[5] and 3.0[6] GeV/c and of ranges $\leqslant 3\,\mu$ produced by K^--at-rest[7] interactions are the residual spallation products of silver and bromine nuclei, and possess mass numbers in the range $A \simeq 20$ to 100, the limits on A depending on the K^- momentum used. The determination of the Λ binding energies (B_Λ) and masses of these heavy[8] HF's is of great interest since these can be effectively utilized for estimating the potential well-depth D_Λ seen by a Λ particle in nuclear matter.

In their first investigation, Davis *et al.*[9] used K^- interactions at momenta 0, 0.8, and 1.5 GeV/c and reported 5 examples of π^--mesonic decays of short-range HF's attributed to mass numbers $A \simeq 60$ to 100. Although the calculated values of the upper limits of

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[8] Henceforth we shall denote HF's having $A > 20$ as "heavy," $A \leqslant 20$ as "light."
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B_Λ of these HF's were found to range from 23.1 to 38.5 MeV, the authors considered an upper limit of B_Λ at about 25 MeV as valid for the total sample of HF's, keeping in view the fact that the excitation of the decay recoil and neutron emission in the decay pass undetected. Further examples of π^--mesonic decays of heavy spallation HF's were subsequently reported by other groups.[6–7,10–17] The latest work is that of Lemonne *et al.*[18] who report 20 spallation HF's, decaying π^--mesonically, produced by the interactions of K^- mesons at rest (also reported are 2 HF's produced by Σ^- captures at rest). The upper limits of B_Λ of six $\pi-p-r$ decays of these HF's are found to vary from 22.8 to 26.6 MeV. These authors, however, consider an upper limit of B_Λ at 22.8 MeV as valid for the whole sample of HF's ($60 \leqslant A \leqslant 100$).

In the present paper we report the analysis of 16 short-range mesonic HF's produced in 1.5-GeV/c K^- interactions in nuclear emulsions. We find that for HF's having $A \simeq 35$ to 80 the upper limits of B_Λ could vary from 21.9 to 24.5 MeV. The plan of the paper is as follows. In Sec. II details of the experimental procedure followed are given. The selection of heavy spallation HF's among observed short-range HF's and the analyses leading to their B_Λ and A determinations are presented in Sec. III. The discussion and final conclusions are given in Sec. IV.

II. EXPERIMENTAL PROCEDURE

A. Exposure and Scanning of the Stack

An emulsion stack consisting of 100 L_4 hypersensitized pellicles of dimensions, 20 cm$\times$15 cm$\times$600 μ, was exposed to a 1.5-GeV/c K^- beam at CERN. The beam composition was $K:\pi:\mu = 2.7:0.4:0.6$. A total of about 3×10^5 K^- particles entered the stack. The choice of fine-grain L_4 emulsion (grain size $\sim 0.3\ \mu$ in developed emulsion) was made in order to attain a higher accuracy in the measurement of the ranges of short recoil tracks and also to obtain a greater spatial resolution between double-centered stars.

Area scanning for obtaining the HF-like stars was performed in the usual manner.[1,4] A total of 31 223 interactions caused by beam particles was observed of which 1656 were classified as due to the production and subsequent decay of HF's. 93 hyperfragments were found to decay π^--mesonically, of which 16 had ranges $\leqslant 10\ \mu$. Although some contamination, due to the background phenomena of (1) scattering or interaction in flight of a low-energy stable particle and (2) slow π^-, K^-, or Σ^- captures, is expected in the total sample of HF's, the sample of mesonic decays is expected to be free from any such contamination. This is because the only source of contamination among the mesonic HF's would be due to the re-emergent K^- mesons having ranges $<20\ \mu$ (whence the discrimination between a HF and a K^- track becomes poor) and which produce stars with a π^- meson having kinetic energy (T_{π^-}) in the interval 0–60 MeV (chosen on the basis of the observed T_{π^-} distribution of the classified HF's; see, for example, Fig. 1). This contamination can be found as follows. In our total sample of primary interactions, we observed only 2 possible re-emitted K^- mesons having ranges in the interval 20–100 μ. It might therefore be reasonable to assume that in the range interval 0–20 μ not more than 2 re-emergent K^- mesons were produced. It is known, further, that only $\sim 8\%$ of the K^- captures give rise to a π^- meson of energy 0–60 MeV.[19] Thus in our sample the expected number of re-emitted K^- mesons in the range interval 0–20 μ which could simulate mesonic HF's would be $2\times0.08 \sim 0.16$. It is, therefore, evident that the sample of mesonic HF's is free from any contamination, and we have applied no correction to this effect.

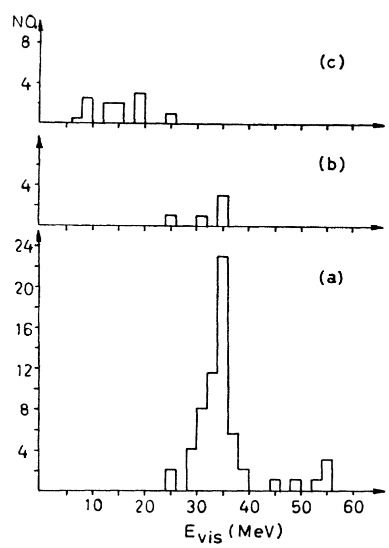

FIG. 1. Distributions of the total visible energy release (E_{vis}) in the decays of mesonic hyperfragments having (a) $R_{HF} > 10\ \mu$, (b) $R_{HF} \leqslant 10\ \mu$ and parent stars with $\Sigma Z_i \leqslant 6$, and (c) $R_{HF} \leqslant 10\ \mu$ and parent stars with $\Sigma Z_i > 6$.

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TABLE I. Analysis of the five short-range ($R_{HF} \leqslant 10\ \mu$) mesonic hyperfragments (HF's) having parent stars with $\Sigma Z_i \leqslant 6$.[a]

Event No.	N_h	ΣZ_i	R_{HF} (μ)	Decay products: Identity	Range (μ)	Azimuth (deg)	Dip (deg)	Kinetic energy (MeV)	Probable HF—identity and decay mode	B_Λ (MeV)
(1)	4	$4+\pi^\pm$	9.7	π^-	15 982	0	+1.8	30.54	$_\Lambda H^3 \rightarrow \pi^- + p + p + n$	−0.59
				p	110	179.1	+51.1	3.89		
				p	2.1	193.7	−32.1	0.23		
				(n)						
(2)	2	$4+\pi^\pm$	8.8	π^-	14 750	0	−35.1	29.16		
				p	254	161.2	+32.6	6.23	$_\Lambda He^4 \rightarrow \pi^- + p + He^3$	1.91
				$He^{3,4}$	blob	...	...	0.30,0.23	$_\Lambda He^5 \rightarrow \pi^- + p + He^4$	1.98
(3)	3	$4+2\pi^\pm$	8.4	π^-	7988	0	+70.6	20.33		
				p	462	49.1	+41.7	8.90	$_\Lambda He^5 \rightarrow \pi^- + p + He^4$	3.20
				He^4	22	218.7	−53.3	5.17		
(4)	3	3	6.4	π^-	14 849	0	−50.0	29.25		
				Be^7	1.4	180	+54.0	0.80	$_\Lambda Li^8 \rightarrow \pi^- + Be^7 + n$	5.82
				(n)						
(5)	3	3	4.8	π^-	10 720	0	+36.7	24.14		
				d	5.7	147.1	−22.7	0.62	$_\Lambda Li^8 \rightarrow \pi^- + d + Li^6$	7.57
				Li^6	~1.0	267	−17.3	0.24		

[a] Explanation of symbols: R_{HF} = range of the HF: N_h = number of stable particles emitted at the HF-production star; ΣZ_i = total charge of emitted particles (other than HF) from the production star.

B. Standards Adopted

The kinetic energies of singly charged particles were calculated using the range-energy relations of Barkas.[20] The masses of nuclides were taken from the table of Everling *et al.*[21] The Q_0 value in $\Lambda \rightarrow p + \pi^-$ decay was taken as (37.60 ± 0.12) MeV.[22]

III. ANALYSIS OF MESONIC DECAYS OF SHORT-RANGE HF's

A. Selection of Heavy Spallation HF's

Some arguments[14,16] have recently been put forward which tend to indicate that the short-range HF's, generally assumed as spallation products, may contain an appreciable proportion of light HF's. We therefore proceed to select a sample of heavy spallation HF's, as "pure" as possible, in the following manner: We divide our sample of 16 HF's into two groups, Tables I and II, such that the total charge $\sum Z_i$ of the emitted particles (other than the HF) at the production star is $\leqslant 6$ or >6, respectively. Attributing at least one charge to the HF, it is seen that the events recorded in Table II belong exclusively to Ag and Br interactions, whereas those in Table I could be from either C, N, O or Ag, Br interactions. The 5 events in the latter group, on kinematical analysis, are found to be consistent with the interpretations $_\Lambda H^3$, $_\Lambda He^{4,5}$, $_\Lambda He^5$, $_\Lambda Li^8$, and $_\Lambda Li^8$ (see Table I). The remaining 11 events of Table II are now examined as follows.

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[21] F. Everling, L. A. König, J. H. Mattauch, and A. H. Wapstra, Nucl. Phys. **18**, 529 (1960).

[22] B. Bhowmik and D. P. Goyal, Nuovo Cimento **28**, 1494 (1963).

In Fig. 1 we display the distributions of the visible energy release (E_{vis}) in the decay of three groups of HF's: (a) long-range ($>10\ \mu$) HF's (these are expected to belong exclusively to the light HF category), short-range HF's originating from parent stars having (b) $\sum Z_i \leqslant 6$ (Table I), and (c) $\sum Z_i > 6$ (Table II). It is evident from the figure that the distributions (a) and (b), each belonging to light HF's, are similar; however, the distribution (c) is distinctly different from both and shows relatively small values of E_{vis}. The events in distribution (c) are, therefore, likely to belong to the heavy-HF category.

A close scrutiny of the production stars of these 11 HF's, however, reveals that two events (Nos. 15 and 16) are of ambiguous nature. Event No. 15 displays at its production star a recoil of range $\sim 2\ \mu$ and also three short tracks of ranges 9 μ, 14 μ, and 18 μ; this observation therefore suggests that the struck nucleus might have undergone fragmentation and the observed short-range HF may belong to the light-HF category. In another event, No. 16, a recoil of range $\sim 2\ \mu$ (partly obscured by the neighboring tracks) is observed at its production star which again indicates that this event may also belong to the light-HF category. There is also an indication of a recoil of range $\lesssim 0.5\ \mu$ at the decay star of this event which for the observed π^- momentum, 88 MeV/c, can arise only for $A < 20$. It may be further noted from Fig. 1 that this even, having $E_{vis} = 25$ MeV, falls in the border-line region of these distributions. From the above considerations we therefore discard these two events (Nos. 15 and 16) from the category of heavy spallation HF's. The remaining 9 events appear "clean" from all considerations but for the possibility that a short recoil at the production star may escape detection, either because it is too short to be visible or

TABLE II. Analysis of 11 short-range ($R_{HF} \leqslant 10\ \mu$) mesonic hyperfragments (HF's) having parent stars with $\Sigma Z_i > 6$.[a]

Event No.	$R_{HF's}$ (μ)	N_h	ΣZ_i	Mass numbers[b] of HF's for K^- int. in Ag	Br	HF decay products Identity	Range (μ)	Kinetic energy (MeV)	Recoil momentum (MeV/c)	Assumed decay mode	Upper limit of B_Λ[c] (MeV)
(6)	4.6	15	20	61±5	36±5	π^- (p)[d]	3376 88	12.4 3.3	138	$\pi-p-r$	21.9
(7)	2.4	11	13	74±5	49±5	π^- (p)	2879 85	11.3 3.3	114	$\pi-p-r$	23.0
(8)	2.6	9	$12+\pi^\pm$	76±5	51±4	π^- (p)	2332 79	10.0 3.1	105	$\pi-p-r$	24.5
(9)	2.1	11	$13+\pi^\pm$	76±5	49±5	π^- (p)	373 183	3.5 5.1	105	$\pi-p-r$	29.0
(10)	4.4	7	$7+2\pi^\pm$[e]	88±5	63±4	π^- (p)	10 357	0.4 7.6	113	$\pi-p-r$	29.6
(11)	4.0	14	~27[f]	~45	~20	π^- (p)	1894 122	8.9 4.0	97	$\pi-p-r$	24.7
(12)	4.1	11	11	80±5	55±5	π^-	7069	18.9	75	$\pi-r$	26.7
(13)	1.2	7	$8+\pi^+$	86±4	60±4	π^-	6649	18.3	74	$\pi-r$	27.3
(14)	3.2	8	9	83±5	58±4	π^-	1785	8.6	50	$\pi-r$	37.0
(15)	6.1	$12+r$	>25[g]	ambiguous		π^-	7500	19.6	76	$\pi-r$	26.0
(16)	3.0	$11+r$	$>13+\pi^-+\pi^\pm$[f]	ambiguous		π^- r	11,893 ~0.5	25.6 ?	88	$\pi-r$	20.0

[a] Explanation of symbols: R_{HF} = range of the HF; N_h = number of stable particles emitted at the HF-production star; ΣZ_i = total charge of emitted particles (other than HF) from the production star.
[b] The two mass values shown should normally differ by 28 mass units ($Ag^{108}-Br^{80}$). However, the actual masses differ by a smaller amount, because of the fact that the estimated number of neutrons emitted from Ag interaction is larger than that from Br interaction.
[c] The error in B_Λ due to measurement and straggling is typically ~0.2 MeV.
[d] See Ref. 27.
[e] The charge of the HF, on decay kinematics alone, is necessarily $\geqslant 2$; therefore, even if both the π mesons are negative, the total charge (ΣZ_i+HF-charge) emitted at the production star would be $\geqslant 7$.
[f] The production star of this event has three prongs with ranges 17.6 μ, 30 μ, and 34 μ which on track-width measurements gave $Z\sim 4$, $Z=2$, and $Z\sim 5$, respectively. The value of ΣZ_i is therefore an order-of-magnitude estimate.
[g] The recoil track (r) in the production star is too short to permit charge measurements. The quoted ΣZ_i is therefore a lower limit.

because of obscuration by the neighboring tracks. Within this limitation, the 9 events, Nos. 6 to 14, can be classified as belonging to the residual spallation products of silver and bromine nuclei.[23]

B. Mass Determination of Spallation HF's

On the basis of the "spallation model"[1] one can assign, for each hyperfragment, two possible mass numbers as $(108-\Delta A)$ or $(80-\Delta A)$,[24] where ΔA represents the total nucleonic mass carried away by the charged nuclides and neutrons emitted from the production star. We determined ΔA in an individual event as follows. All the grey prongs were followed to rest or till they escaped the stack. Protons having energy $\geqslant 35$ MeV were assumed to be emitted during the "cascade" stage[25] and for these an equal number of neutrons were assumed to be emitted. The remaining nuclides were then assumed to be emitted during the evaporation stage. The charges of these nuclides were determined from track-width measurements,[26] or constant sagitta scattering method, or blob density versus range technique, depending on the available track length of the particle. Each charged nuclide was then assigned a mass number corresponding to the most abundant isotope (e.g., p, He^4, Li^7, etc.). Necessary corrections to take into account the emission of d, t, and He^3 were made on the basis of the calculations of Dostrovsky *et al.*[25] on nuclear evaporation. For each event the number of neutrons emitted during the evaporation stage was also estimated on the basis of these calculations. The masses of all the charged particles and neutrons estimated as above were summed up to yield the value of ΔA. The statistical uncertainty in ΔA of an individual event was estimated as $1+(n_{ev}+n_{cas}+n_{dtHe^3})^{1/2}$, where n_{ev} and n_{cas} represent the number of evaporated and cascade neutrons, respectively, and n_{dtHe^3} is the estimated number of neutrons accounting for the presence of d, t, and He^3. The first term arises because the target nuclei Ag and Br both have equally abundant isotopes with a mass difference of 12 units. In this way the error in ΔA typically amounted to $\sim\pm 5$ mass units. The resulting pair of mass estimates for each hyperfragment are displayed in the fifth column of Table II.

[23] It may be observed that in none of these 9 events is a charged stable particle of range 2–30 μ (short prongs) emitted in the decay. On consideration of the Coulomb barrier in heavy nuclei, this observation is generally taken (Ref. 9) to support the classification of HF's in the heavy category. It should be remarked, however, that this criterion is not of a definite nature since even in the decay stars of light HF's, short prongs are seen only in ~50% of the events (see, e.g., Ref. 16).

[24] The mass numbers 108 and 80 represent the mean values of the most abundant isotopes of Ag and Br nuclei ($Ag^{107,109}$ and $Br^{79,81}$).

[25] I. Dostrovsky, P. Rabinowitz, and R. Bivins, Phys. Rev. **111**, 1659 (1958). See, however, A. Fliedner, D. M. Harmsen, and L. Schink, Nuovo Cimento **36**, 751 (1965). The experimental ratios, $(d+t)/(p+d+t)$ and $(He^3+He^4)/(p+d+t)$, found by these authors for stars with $N_h>6$ are consistent with the calculations of Dostrovsky *et al.*

[26] See for example, B. Bhowmik, T. Chand, D. V. Chopra, and D. P. Goyal, Phys. Rev. **139**, B1062 (1965).

C. B_Λ Determination of Spallation HF's

The decay configuration of the 9 spallation HF's (Table II) display either a π^- meson associated with a black track,[27] or just a slow negative pion. The former is classified as $\pi-p-r$ and the latter as $\pi-r$ events, the recoil nucleus generally remaining undetected in both the cases. The upper limits of B_Λ displayed in the last column of Table II have been computed from the visible energies at the decay stars in the usual manner[9] assuming $Q_0=37.6$ and 45.6 MeV for $\pi-p-r$ and $\pi-r$ decay modes, respectively. These values of B_Λ are treated as upper limits because of the possibilities of the decay recoil being left in an excited state and/or of neutron emission in HF decay.[28] It is, however, likely that some of the spallation residues in which the Λ remains trapped may not be on the stability line and therefore the B_Λ's computed in $\pi-r$ events, assuming a mean $B_N=8$ MeV, may be incorrect by a few ($\sim\pm2$) MeV, the actual value depending on the degree of neutron excess or deficiency as the case may be.

IV. DISCUSSION AND CONCLUSIONS

The upper limits of B_Λ obtained for the present events vary over a large range, from 21.9 to 37.0 MeV. As pointed out earlier, these events may involve excited recoils and/or the emission of neutrons in their decays. Assessment of the amount of excitation of the decay recoil seems difficult; however, the effect of the neutron emission can be ascertained. In the case of neutron emission the visible energy in the decay is underestimated by an amount equal to the sum of the separation and kinetic energies of the neutron. The average separation energy in the heavy-nuclei region is $\sim$8 MeV. This value can have an uncertainty of $\sim\pm2$ MeV if the spallation residues do not lie on the stability line (see IIIC). Thus, in the case of neutron emission, the B_Λ is overestimated by $\gtrsim$6 MeV. We now proceed to examine the possibility of neutron emission in the present events. In the light HF region ($A\leqslant20$), the B_Λ's are approximately given by the relation[29]

$$B_\Lambda=(0.97A-1.7)\text{ MeV}.$$

Thus, the B_Λ for an HF of mass $A=20$ should be $\sim$18 MeV. The HF's presented in this paper have masses $\gtrsim$35, their B_Λ's should, therefore, be a good deal higher than 18 MeV. Now, if we postulate neutron emission in events 6 to 8, their B_Λ's would become $\lesssim$18 MeV. We thus rule out the possibility of the emission of even slow neutrons in these events. Neutron emissions are possible in events 9, 10 and 12 to 14. In event No. 11, $B_\Lambda=24.7$ MeV and its mass is inaccurately known as $\sim$45 or $\sim$20. Now, if the higher mass value is accepted, then the neutron emission seems to be unlikely, and in that case the HF belongs to the heavy HF category. In case of a neutron emission the B_Λ would be reduced to $\lesssim$18 MeV, which is consistent with the lower mass value, i.e., $\sim$20. This event is, therefore, an ambiguous event. The last two events (Nos. 15 and 16) are probably light having $A\lesssim20$ for reasons mentioned earlier (Sec. IIIA), and their apparently large B_Λ's can be easily explained by postulating neutron emissions in their decays.

On the basis of our data (considering the events Nos. 6, 7, and 8) we thus conclude that for the HF's having masses in the region $A\simeq35$ to 80, the upper limits of B_Λ could vary from 21.9 to 24.5 MeV. This is in good agreement with the previous estimates[9,10,15,18] of upper limits of $B_\Lambda\simeq23$–25 MeV found valid for heavy hyperfragments having $40\leqslant A\leqslant100$.

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[27] In all cases, these black tracks were identified as having $Z=1$; the characteristic Coulomb scattering at their ends show that they are most probably due to protons.

[28] Since the time for γ emission is much shorter than the HF life time, the decay of an HF from an excited state giving rise to an underestimate of B_Λ is very unlikely (see, for example, Refs. 15 and 18).

[29] W. G. G. James, Nuovo Cimento Suppl. **23**, 285 (1962).