STUDY OF HYPERFRAGMENTS

Part IV. Mechanism for Production of Hyperfragments

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ABSTRACT

Hyperfragments (HFs) produced in interactions of high energy pions and protons with emulsion nuclei have been investigated to deduce information on their mechanism of production. From these studies it is concluded that (*a*) long-range HFs ($R \geqslant 20\,\mu$m.) which are due to fragments with mass number $\lesssim 15$, are produced in the evaporation stage of the disintegrations of Ag and Br nuclei of emulsion, (*b*) short-range HFs ($R \leqslant 10\,\mu$m.) are mainly due to residues of the target nuclei and a small fraction ($\approx 10\%$) of them in the range $5 < R_{HF} \leqslant 15\,\mu$m. are due to fission type of processes that occur in high energy interactions and (*c*) the relative probability of sticking of Λ° to fragments with $Z = 2$ to that with $3 \leqslant Z \leqslant 6$ is roughly in the ratio 1 : 10.

1. INTRODUCTION

AMONG hyperfragments (HFs) emitted from high energy interactions produced by pions and protons with emulsion nuclei, a large fraction ($\approx 50\%$) is found to be due to non-mesic hyperfragments with ranges $\leqslant 10$ microns. A detailed study of these short-range HFs by Ganguli *et al.* (1965) and Burte *et al.* (1965) (hereafter referred to as Part I and Part II respectively) has shown that an appreciable proportion ($\sim 45\%$) of these have mass numbers, $A \lesssim 50$. It is also found that as far as HFs of range $\geqslant 20\,\mu$m. are concerned, they have mass numbers, $A \lesssim 15$. In order to understand the production mechanism of HFs, it is necessary to have information on the mass and frequency of emission of HFs as a function of the energy of the incident

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beam particles and also the frequency of production of multiply charged ordinary fragments in such interactions. With this in view we have analysed HFs produced in interactions caused by pions of momentum 3·5 GeV/c. and 17·2 GeV/c. and protons of momentum 23 GeV/c. with emulsion nuclei; the results are presented in this paper.

2. EXPERIMENTAL DETAILS AND RESULTS

2·1. *Experimental Details*

Three stacks A, B and C, which were exposed to beams of pions of momentum 3·5 GeV/c., protons of momentum 23 GeV/c. and pions of momentum 17·2 GeV/c. respectively, have been used in this investigation. The details regarding stacks A and B are given in Part II of this series and that of stack C is given below:

Stack C.—It consisted of 150, Ilford G-5, 600 μm. thick emulsion pellicles each of size 7·5 cm. × 10 cm. It was exposed to a beem of negative pions of momentum 17·2 GeV/c. of the proton synchrotron, CERN. The flux of pions in the stack was $\approx 10^5$ pions per cm.^{2} across the stack.

The details of scanning the plates and the selection criteria adopted for HFs are described in Parts I and II. In stacks A, B and C there are in all 210, 553 and 410 HFs respectively. Detailed information on the HFs from these stacks is summarised in Tables I and II.

2·2. *Experimental Results*

From the observations summarised in Tables I and II, it becomes possible to draw the following conclusions:

(*a*) The average number of heavy prongs, $\bar{N}_h$, of parent stars of HFs is found to be almost independent of the incident primary energy (column 4 of Table I). Further from the N_h distribution of the parent stars, it is found that over 90% of the HFs are produced in high energy disintegrations of heavy nuclei (Ag, Br) of emulsion. The rate of production of HFs is found to be independent of the energy and nature of the incident particles; it is $\approx 1 \times 10^{-3}$ per interaction for stars with $N_h \geqslant 3$.

(*b*) The frequency of parent stars of HFs, that have an additional short track, increases significantly with increase in the range of HFs (column 5 of Table I).

(*c*) HFs associated with tracks of range, $3 \leqslant R \leqslant 30\,\mu$m. at their decay vertices are usually attributed as due to HFs of mass number $A \lesssim 50$ (Part I).

TABLE I

Characteristics of parent stars of non-mesic HFs

Range group of HFs (μm.)	Stack	Number of HFs in the sample	Average N_h of the parent stars	Percentage of parent stars that have HF and at least a short track ($\leqslant 10\,\mu$m.)
1	2	3	4	5
$R_{HF} \leqslant 5$	A	84	10·7	15·5± 3·9
	B	94	10·5	13·8± 3·5
	C	96	10·7	4·2± 2·0
	Total ..	274	10·6	11·0± 1·9
$5 < R_{HF} \leqslant 10$	A	58	12·4	22·4± 5·5
	B	98	12·0	30·6± 4·8
	C	53	12·4	26·4± 6·2
	Total ..	209	12·3	27·3± 3·1
$10 < R_{HF} \leqslant 20$	A	25	13·8	40·0± 9·8
	B	78	14·0	36·0± 4·5
	C	51	13·7	37·3± 6·8
	Total ..	154	13·9	37·0± 3·9
$20 < R_{HF} \leqslant 50$	A	18	11·8	55·6±11·8
	B	103	15·7	39·8± 5·6
	C	71	12·7	33·8± 5·6
	Total ..	192	14·1	39·1± 3·5
$R_{HF} > 50$	A	16	12·9	43·7±12·4
	B	152	13·5	43·0± 3·9
	C	104	12·3	48·1±15·5
	Total ..	272	13·0	44·9± 3·0

TABLE II

Data on the decay products of HFs and the mass estimation of short-range HFs

Range group of HFs (μm.)	$\bar{N}_h$ of HFs	% of HFs with secondary recoils of range(< 3 μm.)	% of HFs with decay prong of range ($3 \leqslant R \leqslant 30\,\mu$m.)	% of HFs of $A \lesssim 50$ with range criteria for secondary track as ($3 \leqslant R \leqslant 30\,\mu$m.)
1	2	3	4	5
$R_{HF} \leqslant 5$	2·6	33·2±2·8	14·6±2·1	30·8±4·6
$5 < R_{HF} \leqslant 10$	2·5	28·2±3·1	33·5±3·2	70·7±9·6
$10 < R_{HF} \leqslant 20$	2·4	28·1±3·6	42·2±4·0	..
$20 < R_{HF} \leqslant 50$	2·5	17·7±2·8	52·1±3·6	..
$R_{HF} > 50$	2·2	19·5±2·3	46·7±3·0	..

Using this criterion it is found that HFs with mass number $A \lesssim 50$ constitute about 30% and 70% of events in the range groups of $R \leqslant 5\,\mu$m. and $5 \leqslant R \leqslant 10\,\mu$m. respectively (column 5 of Table II). The average mass of short-range HFs (*i.e.*, $R_{HF} \leqslant 10\,\mu$m.) is $A \approx 50$.

(*d*) The ratio of the number of HFs of range $R_{HF} \geqslant 20\,\mu$m. to the total number of HFs increases from 0·17 to 0·49, as the incident momentum increases from 3·5 GeV/c. to ≈ 20 GeV/c. (column 3 of Table I).

3. DISCUSSION OF THE RESULTS

3·1. *Mechanism of Production of HFs*

Since it has been shown that an overwhelming proportion ($\gtrsim 90\%$) of HFs are produced in disintegrations of heavy nuclei of emulsion, the " cascade-evaporation " model will be first examined to see whether one can understand the observed mass spectrum of HFs. Production of HFs, on this model, can take place in the following three stages of disintegrations:

(*a*) ' Fragmentation Process ' which can be considered as the direct ejection of aggregates of nucleons in a nuclear reaction,

(*b*) ' Evaporation Process ' in which low energy multiply-charged fragments are emitted, and (*c*) Residues of target nuclei, that are left after the completion of evaporation process, give rise to short tracks; not more than one short track per disintegration is expected due to the residue.

The mechanism of production of light HFs ($R \geqslant 20\,\mu m.$) and heavy HFs ($R \leqslant 10\,\mu m.$) will now be discussed in the light of the above model.

Light HFs.—It is found that the range distributions of long-range multiply-charged ordinary fragments and light HFs, both of ranges $> 20\,\mu m.$, produced in high energy disintegration are similar. From this observation Gagarin and Ivanova (1964), Cuer *et al.* (1963) and Chaudhari *et al.* (1966) have concluded that long-range HFs are due to trapping of Λ° by multiply-charged nuclei emitted in the evaporation stage of excited heavy nuclei. It is expected that the contribution to HFs from the fragmentation process is comparatively small.

Heavy HFs.—The range distributions of short-range HFs and short tracks, of ranges $\leqslant 10\,\mu m$, have been shown to be quite similar in Part II. It was also concluded in that paper that the majority of the short tracks are due to residues of target nuclei left after the evaporation process, and that about 7–10% of them are due to fission type of processes. In order to see whether the latter type of process makes any contribution to the production of short-range HFs, we have determined the percentage of parent stars of HFs that have an associated short track. The results are given in column 5 of Table I. It is seen from Table I that 11% of the parent stars of short-range HFs in the range group $R_{HF} \leqslant 5\,\mu m.$ and 27·3% of those with $5 < R_{HF} \leqslant 10\,\mu m.$ are associated with a short track. If fission process does take place in the parent star, the short track as well as the short-range HF are expected to have mass numbers $A \lesssim 50$. The expected range of fission products, of Ag and Br, of mass 30–50 lies between 5–15 $\mu m.$; their contribution is expected to be small for range values $< 5\,\mu m.$ and $> 15\,\mu m.$ Therefore for this analysis we choose HFs with ranges between 5 and 15 $\mu m.$ (310 in number).

Though the masses of fragments producing short tracks cannot be individually distinguished, those producing short-range HFs can be identified by examining their decay vertices for associated tracks in the range 3–30 $\mu m.$; short-range HFs with a secondary track of range 3 to 30 $\mu m.$ at their decay vertices are of mass $A \lesssim 50$ (*see* Parts I and II). Therefore if fission process plays a part in the parent disintegrations, it is expected that the short tracks should occur more frequently in parent stars of short-range HFs that have a secondary track in the range 3 to 30 $\mu m.$ at their decay vertices than in others. We have therefore grouped events in which there is an associated

HF of range between 5 and 15 μm. as follows: (1) events have an associated short track ($5 < R \leqslant 15\,\mu$m), and (ii) that have no such associated short track in their production star. It is found that the percentages of HFs that have a decay prong in the range 3–30 μm. in the above two groups are $46{\cdot}5 \pm 4{\cdot}2$ and $31{\cdot}4 \pm 2{\cdot}5$ respectively; the difference of $(15{\cdot}1 \pm 4{\cdot}9)\%$, strongly suggests that fission type of process contributes to the production of HFs in the range 5 to 15 μm. However no such effect is seen among parent stars of HFs in the range 0–5 μm.; this is however what one would expect on the basis of (*a*) the range criteria used here for the selection of events and (*b*) the observation that $\approx 70\%$ of the HFs of range 0–5 μm. have masses $A > 50$, and are mostly residues of the target nuclei.

Quantitative estimation of the contribution of fission process in HF production.—Having shown in a qualitative manner that fission type of process contributes to the production of HFs, we will now attempt a quantitative estimate of this from two approaches:

(*a*) The first approach is based on the distribution of the angle ψ between the short-range HF and the associated short track. As is mentioned earlier, the range of the fission products is expected to lie between about 5 and 15 μm.; hence in order to study this mechanism we measured the angle in all parent stars of HFs ($5 < R_{HF} \leqslant 15\,\mu$m.) that have associated short tracks of range 5–15 μm. The results are summarised in Table III. The angular distribution of ψ for the events given in row 2 of Table III is shown in Fig. 1.

TABLE III

Short track ($R \leqslant 15\,\mu m.$) association with parent stars of HFs ($5 < R_{HF} \leqslant 15\,\mu m$)

No.	Short track association with parent stars of HFs		Total number of HFs
1	No short track		189
2	One short track of range $5 < R \leqslant 15\,\mu$m	$\psi^* > 90°$	42
		$\psi < 90°$	19
3	Two short tracks of range $5 < R \leqslant 15\,\mu$m		21
4	A short track of range $R \leqslant 5\,\mu$m		39
5	Total ($5 < R_{HF} \leqslant 15\,\mu$m)		310

* ψ represents the space angle between HF and the short track.

It is expected that in a fission type of disintegration the space angle ψ, between the HF and the short track, will be $> 90°$. It is found from row 2 of Table III that there are 19 events where ψ is $< 90°$, these short tracks associated with parent stars of HFs could be due to multiply charged particles emitted in the evaporation process (Part II), and they will be considered as spurious fission events. In the spurious fission events, the associated short track can be considered to have an isotropic angular distribution; therefore their contribution among the events with $\psi > 90°$ will be 19. In this way the number of genuine fission type of events is estimated to be $42 - 19 = 23$, *i.e.*, 7% of the total number of events. Since in this calculation we have not considered events given in rows 3 and 4 of Table III, the value of 7% is probably a lower estimate.

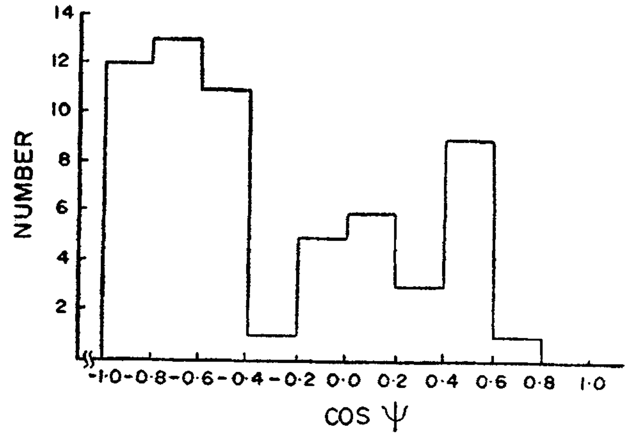

FIG. 1. Angular distribution between short track and short-range HF.

(*b*) It has been estimated from the data described in Part II that among two short track type of events (both the short tracks in the range $5 < R \leqslant 15\,\mu$m.) about 50% of the parent nuclei undergo fission. Applying this result to parent stars of short-range HFs, we find that 13·2% of the HFs in the range group 5–15 μm. have to be attributed to fission type of process.

It is thus concluded from methods (*a*) and (*b*) that about 10% of the short-range HFs ($5 < R_{HF} \leqslant 15\,\mu$m.) are produced in a fission type of process.

3.2. *Sticking Probability of* Λ°

In order to understand the charge spectrum and range distribution of HFs, it is essential to know the dependence of the sticking probability P_Λ of Λ° with mass number (or charge) of HFs. An attempt has been made here to get some information on P_Λ from a study of the charge spectrum of HFs.

The relative frequencies of emission of HFs and ordinary fragments from high energy disintegration are summarised in Table IV as a function of charge. All frequencies are normalised to the frequency of emission of helium fragments as unity. The experimental data presented in Table IV can be understood if the sticking probability, P_Λ, is a function of (i) the relative velocity between the Λ and the nuclear fragment, and (ii) the mass of the nuclear fragment; further P_Λ increases with the decrease of the relative velocity and with the increase of mass of the nuclear fragment.

TABLE IV*

Relative charge composition of HFs and ordinary multiply-charged fragments in high energy disintegrations

Momentum of the incident beam	References	Charge of fragments emitted Type of fragments	$Z=2$	$3 \leqslant Z \leqslant 6$	$Z \approx 25$
1	2	3	4	5	6
1. 3·5 GeV/$c\pi^-$	Chaudhari *et al.* (1966)	Hyperfragments	1	$1{\cdot}7 \pm 0{\cdot}5$	$9{\cdot}1 \pm 2{\cdot}4$
2. 17·2 GeV/$c\pi^-$ and 23 GeV/cP	Chaudhari *et al.* (1966)	Hyperfragments	1	$2{\cdot}8 \pm 0{\cdot}3$	$2{\cdot}8 \pm 0{\cdot}3$
3. A few GeV/c	Burte *et al.* (1965), Baker and Katcoff (1961)	Ordinary fragments	1	0·28	0·13

* All frequencies are normalised to the frequency of emission of fragments of $Z = 2$ as unity (column 4). Data of HFs in columns 4 and 5 refer to HFs of range $\geq 20\,\mu$m. Results in column 6 refer to short-range HFs (rows 1 and 2) and short tracks (row 3) of range $\leq 10\,\mu$m. Results given in row 3 for light fragments (columns 4 and 5) refer to the ratio obtained by Baker and Katcoff (1961).

It is seen from Table IV that the short-range HFs ($Z \approx 25$) and HFs with $3 \leqslant Z \leqslant 6$ are much more abundant than the helium HFs, while the majority of ordinary fragments are alpha-particles. This clearly demonstrates the mass dependence of P_Λ.

From studies made on fragments associated with high energy disintegration of Ag and Br target nuclei by various workers (Skjeggested and Sorensen, 1959; Baker *et al.*, 1960; Part II) it becomes possible to make a few inferences regarding their velocity distribution and frequency of emission. The following experimental observations have been made from such studies:

(i) The velocity spectra of alpha-particles and Li^8 fragments are found to be the same at a primary energy of ~ 3 GeV.

(ii) The velocity spectrum and frequency of emission of Li^8 fragments as also heavy fragments (short tracks) do not change appreciably when the primary energy increases from about 3 GeV to about 20 GeV.

Since Li^8 is representative of the light fragments of $3 \leqslant Z \leqslant 6$ and that both helium as well as light fragments are predominantly produced in cascade evaporation processes, we can make the following generalisation: The velocity spectrum and frequency of emission of fragments of $Z = 2$ and $3 \leqslant Z \leqslant 6$ are the same at any given high primary energy; further they do not change significantly with increase of primary energy. It will now be possible to understand the results summarised in Table IV.

It is seen from Table IV that the ratio of the number of HFs with $Z = 2$ to that of HFs with $3 \leqslant Z \leqslant 6$ increases only from $1{\cdot}7 \pm 0{\cdot}5$ to $2{\cdot}8 \pm 0{\cdot}3$ when the momentum of beam particles increases from 3·5 GeV/c. to ≈ 20 GeV/c. In view of the weak dependence of this ratio on the energy of the incident beam particles, and the inferences made in the previous para, we are justified to assume that this ratio does not change with primary energy covered in the present experiment. If so, the results given in row 3 and columns 4 and 5 (using proper statistical weight to the number of HFs used in rows 1 and 2), leads to the conclusion that the sticking probability of Λ° to $Z = 2$ and to $3 \leqslant Z \leqslant 6$ fragments, is in the ratio 1 : 10.

The production of short-range HFs, as is seen from column 6 of Table IV, decreases by a factor of ~ 3 in interactions produced by ≈ 20 GeV/c beam particles (pions and protons) compared to those produced by 3·5 GeV/c π^-. This observation can be understood as (*a*) due to the shift of the velocity spectrum of the Λ° towards higher velocity region for increasing bombarding energies and (*b*) due to the near constancy of the velocity spectrum of light and heavy fragments mentioned in (ii) above. This also would explain the increase in the ratio of the number of long-range HFs ($R \geqslant 20\,\mu$m.) to that of all HFs, with the increase in incident energy of the beam particles.

In order to get a relative value of P_Λ for short-range HFs compared to helium HFs, it is necessary to know the explicit dependence of P_Λ on the relative velocity of Λ and the nuclear fragment, because the velocity spectra of short tracks and helium fragments are quite different. Since this information is not known at present, it is not possible to estimate the relative magnitude of P_Λ for short-range HFs. It could however be stated from the results presented in column 6 of Table IV that P_Λ is likely to have a value which is very high for short-range HFs when compared with that of helium HFs.

4. CONCLUSIONS

The following conclusions can be drawn from the present investigation:

(i) The long-range HFs are produced in the evaporation process of the excited nuclei. The short range HFs are mostly due to trapping of Λ° by the residues of target nuclei after the evaporation process. About 10 % of the short-range HFs ($5 < R_{HF} \leqslant 15\,\mu$m.) are produced by the trapping of Λ° hyperons in fragments arising from fission type of process.

(ii) The range distribution and the charge spectrum of HFs are qualitatively understood by assuming the sticking probability of Λ° as a function of mass of nuclear fragment and the relative velocity of the Λ° and the fragment. The relative sticking probability of Λ° to helium and $3 \leqslant Z \leqslant 6$ fragments is roughly in the ratio 1 : 10.

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REFERENCES

1. Skjeggestad, O. and Sorensen, S. O. *Phys. Rev.*, 1959, **113**, 1115.
2. Baker, E. W., Katcoff, S. and Baker, C. P. *Ibid.*, 1960, **117**, 1352.
3. Baker, E. W. and Katcoff, S. *Ibid.*, 1961, **123**, 641.

4. Cuer, P. .. *Proceedings of Int. Conf. on Hyperfragments,* CERN, 1963, **64** (1), 123.
5. Gagarin, Yu. F. and Ivanova, N. S. *Sov. Phys.* JETP, 1964, **18**, 1228.
6. Ganguli, S. N., Rao, N. K. and Swami, M. S. *Nuov. Cim.*, 1965, **36** (Part I), 35.
7. Burte, D. P., Ganguli, S. N., Rao, N. K., Ray, A. K., Rengarajan, T. N. and Swami, M. S. *Ibid.*, 1965, **36** (Part II), 733.
8. Chaudhari, K. N., Ganguli, S. N., Rao, N. K. and Swami, M. S. To be published in *Proc. Ind. Acad. Sci.*, 1966, (Part V).