CHAPTER IV.

GENERAL CHARACTERISTICS OF STARS WITH AND WITHOUT HEAVY FRAGMENTS.

4.1 INTRODUCTION.

Before entering into the detailed study of the production mechanism of heavy fragments with charge \( Z \geq 4 \) in high energy interactions of silver and bromine nuclei, we intend to make a brief study of the general characteristics of the stars. Such a study is expected to reveal the distinctive features, if there be some, of the disintegrations involving the production of the fragments under consideration. For this purpose we have collected two distinct samples of stars produced by \( 24 \text{ GeV/c} \) protons. One of these samples consists of stars associated with heavy fragments and the other includes only those which are absolutely free from heavy fragments. We have carried out analyses of the black tracks due to alpha particles, the gray tracks due to cascade particles and the thin tracks of shower particles and have made a comparative study of the two types of disintegration of silver and bromine nuclei.

The disintegration of complex nuclei like silver or bromine by the action of high energy projectiles is a complicated phenomenon involving a large number of nucleons. The production mechanism of energetic heavy fragments from such interactions of nuclei has not yet been satisfactorily explained with the
help of an explicit model. In view of the complexity of the phenomenon it would be worthwhile to make a careful study of the general characteristics of the two types of star mentioned above.

Most of the data used in this investigation have been collected from a single pellicle of G5 emulsion exposed to 24 GeV/c protons. The data on the shower particles have been collected from this pellicle and also from another pellicle irradiated by 17 GeV/c negative pions.

In cloud chamber photographs and in emulsions, the disintegration of a nucleus reveals itself as a cluster of tracks emanating from a common centre; and hence the disintegrations are commonly known as 'stars'. Early studies of cosmic ray stars undertaken by Hasan Powell with cloud chambers and by Blau and Wambacke with photographic emulsion led to the recognition of the principal physical processes involved in the production of stars. At present we know that disintegrations of heavy nuclei induced by high energy particles involve two distinct processes separated in time: the fast cascade process followed by the slower evaporation process.

An energetic incident proton or neutron, for instance, is associated with a wavelength short as compared to the distance between the nucleons of the target nucleus. In the initial stage of the reaction, there may be a few collisions of the incident particle with the individual nucleons within a short time of the order of $10^{-22}$ seconds, the time required by
the particles to traverse the nucleus. In these collisions some of the nucleons are knocked out directly, and others make further collisions such that a cascade of particles is developed within the nucleus. Some of these cascade particles having high energies may escape from the nucleus while others with low energies are reflected back from the nuclear surface. The cascade particles are mostly collimated along the direction of the incoming particle.

The collisions may be elastic or radiative. In the later case shower particles consisting of charged and neutral pions are produced. There are two theories of the production of the shower, vis. 'plural' and 'multiple'. According to the plural theory $^{68,69}$, production of meson has large damping effect so that only a single meson can be produced in a single collision between the nucleons. The primary loses only a small fraction of its energy in the first collision; and if the cross-section for collision is sufficiently large, a single primary makes several collisions, thus creating a shower of mesons in traversing a large nucleus. The multiple theory $^{70-75}$, on the other hand, assumes that several mesons can be produced in a single collision for which the damping effect is so large that the primary has often insufficient energy to create further mesons. In a large nucleus comprising many nucleons, the final result as seen in the form of shower of mesons, is likely to be same for both the processes.

The mesons produced in the first collisions
commonly have velocities in the relativistic region and may either escape without imparting their kinetic energy to the nucleons lying in their path or may create other mesons in collision with nucleons, but their energy is not spent in the production of recoiling nucleons. It was pointed out by Serber\[76\] that very high energy particles have small interaction cross-section, so that the incident particle might pass through the nucleus making only one or two collisions and losing a small part of its energy. Therefore, the nuclear excitation energy is small as compared to the energy of the incident particle. It may be mentioned that the nuclear excitation is due to the distribution of the energy of the primary among the cascade nucleons.

After the emission of cascade particles, which have energies above 25 MeV, the nucleus is left in an excited state, but it is not yet in a thermodynamic equilibrium. Since no particle has sufficient energy to escape by overcoming its binding energy to the nucleus, a thermodynamical equilibrium has to be established before evaporation of further particles. During this process every evaporating particle undergoes several collisions, so that it can gather an amount of energy that exceeds its binding energy to the residual nucleus and must move in an outward direction in order to escape from the nucleus. After the emission of one particle by this process, a further long period of the order of $10^{-17}$ sec. commonly elapses before another particle is evaporated following the same
sequence of events.

The disintegration from excited states is quite independent of the process which causes the excitation and is similar to the process of evaporation of a heated liquid drop. The analogy is, however, made with reservations, because the number of particles in a nucleus is comparatively small and the statistical fluctuations about the mean energy per nucleon is correspondingly large. Further, the ratio of the surface area to the volume for a nucleus is large as compared to that of a liquid droplet; and consequently, the excitation energy is transformed into surface and volume waves which have great effect on the emission of particles from the nucleus. The excitation energy of the nucleus, which is defined as the nuclear temperature, falls much rapidly during the process of de-excitation by particle emission; and it may be ultimately so low that no particle inside the nucleus can pick up the energy required for its escape from the nucleus. At this stage transition to the ground state is likely to be effected by emission of gamma rays.

4.2. THE NUCLEAR EVAPORATION PROCESS.

The cooling behaviour of a highly excited nucleus is quantitatively interpreted within the frame work of the statistical model first suggested by Bohr and Kalckar\(^77\) and subsequently developed by Weisskopf\(^78\).

According to Weisskopf\(^78\), the binding energy per nucleon in a large nucleus with high excitation, is often
superseded by the excitation energy and, as a result, the level density becomes so large that the levels may be treated as a continuum. The nucleons in the nucleus share the excitation energy in a complex manner and have strong interactions which is too complicated for detailed analyses. In this state the cooling behaviour of the nucleus is best depicted by the statistical model introducing the classical thermodynamical concept of temperature, entropy and heat capacity; and then the emission of a neutron becomes analogous to the evaporation of a molecule from a heated liquid drop. This model, known as the evaporation model, enables one to make quantitative estimation of the probability of emission of different types of particle as functions of the thermodynamical parameters. Thus the probability of a neutron being emitted with energy between \( E \) and \( E + dE \) is approximately given by

\[
P(E) dE = \frac{E}{\frac{3}{2}} \exp \left( -\frac{E}{T} \right) dE,
\]

where \( T \) is the nuclear temperature in MeV. For the emission of charged particles the effective coulomb barrier must be taken into account. Thus if \( V \) is the coulomb barrier measured in MeV for a particular charge, the probability of emission for the charged particle becomes

\[
P(E) dE = \frac{E-V}{\frac{3}{2}} \exp \left( -\frac{E-V}{T} \right) dE.
\]

Bagge calculated the energy distribution of evaporated protons taking into account the cooling down of the
nucleus as evaporation proceeds. By treating the nucleus as a degenerate gas of particles obeying Fermi statistics and neglecting interactions between the nucleons, he obtained the total energy of excitation in terms of $A$, the total number of nucleons and $T$, the nuclear temperature as

$$U = kT^2,$$

where $k = \frac{E}{4\pi}$, $E$ being the kinetic energy of the highest occupied state in the unexcited nucleus (= 22 MeV.). Thus $k$ is nearly equal to 0.1. Bethe showed that the effect of nuclear interaction would increase $k$ by a factor of the order of 2. The average energy loss $dU$ of the nucleus when $dA$ neutrons are evaporated is derived from equation (4.3) as

$$\frac{dU}{dA} = 2kA \frac{dT}{dA} + kT^2$$

(4.4)

where $2T$ is the average kinetic energy of a particle, $E_0$ is the binding energy per nucleons assumed to be constant, and $T$ is the instantaneous temperature. The process is treated as continuous and protons and neutrons are assumed to be independently emitted.

Bagge assumed the possibility of formation of surface waves on the surface of the nucleus when its energy $U$ is high. The surface waves result in a mean increase of the nuclear temperature and consequent decrease in the potential barrier. Later, Le Couteur made an extension of the evaporation theory in which the correlation between protons and neutrons was taken
into consideration. He also took into account both the neutron excess and the effect of thermal expansion of the nucleus and obtained the probabilities at any instantaneous temperature for the emission of six different types of particles: neutrons, protons, deuterons, tritons, alpha particles, and $^3$H nuclei. Integrating the probabilities over the whole process, as it was performed by Le Couteur, is equivalent to allowing for the cooling down of the nucleus. Le Couteur found that the best fit with experimental data was obtained on the assumption of a decrease in potential barrier with the increase of excitation energy which was in accordance with theoretical expectations of Bagge.

Analogous calculation was made by Fujimoto and Yamaguchi by taking into account the correlations between neutrons, protons and alpha particles. They, however, neglected the thermal expansion which was supposed to be small but considered the fluctuation in the number of particles emitted for fixed values of $V$.

The energy spectra of the cascade particles has been calculated by Goldberger using Monte Carlo technique. This method has been extensively used by various authors in their investigations into the emission of various particles of known identity for the entire cascade-evaporation process.

4.3. EXPERIMENTAL METHODS AND NOMENCLATURE.

In the present investigations we used 68 emulsions exposed to 84 GeV/c protons and 17 GeV/c negative pions. In
order to detect the stars with prong number greater than seven, the emulsion sheets are area scanned within limited volumes under the low magnification of 10X objective and 15X eyepiece. The lower limit of the prong multiplicity excludes the stars due to disintegrations of the lighter elements of emulsion. This selection rules covers roughly about 50 percent of all interactions; and most of the disintegrations thus selected are due to central collisions. The interaction of silver and bromine has been expected to be in the ratio 1.2 to 1 which may be derived from the knowledge of the composition of the emulsion and the geometric cross-section of the nuclei.

The tracks produced by charged particles in nuclear emulsions are classified into three types according to their grain-density \( g \) as compared to \( g_{\text{min}} \), the grain-density of singly charged relativistic particles:

(i) Thin tracks, \( g_{\text{min}} < g < 1.4g_{\text{min}} \)

(ii) Grey tracks, \( 1.4g_{\text{min}} < g < 6.8g_{\text{min}} \)

(iii) Black tracks, \( g > 6.8g_{\text{min}} \)

The multiplicities of black, grey and thin tracks are denoted by \( N_h \), \( N_g \) and \( N_s \) respectively. The number of heavily ionising tracks \( N_h \) of a star is constituted by the black and the grey tracks together.

The particles of nuclear disintegrations producing black, grey and thin tracks in emulsion are believed to be
resulting from three distinct mechanisms. It is commonly accepted that most of the black tracks are due to evaporation of the excited nuclei. For a proton the limit $6.8\text{g}_{\text{min}}$ corresponds to an energy of 25 MeV. Most of the protons emitted in the evaporation process have energies less than this value.

The protons of energy above 25 MeV produce grey tracks and are supposed to originate in the cascade stage. Thin tracks are produced by protons of kinetic energy above 500 MeV, and by pions of energy more than 80 MeV. Most of the particles producing the heavily ionising tracks are protons, deuterons, tritons and alpha particles and majority of the shower tracks are due to pions. The number of protons producing thin tracks has been found to be very nearly equal to the number of pions of relatively low energy producing grey tracks. Therefore, the number of charged pions in the disintegrations can be estimated from the observed values of the shower particles. Neutral mesons and neutrons do not produce any track in emulsion. It is generally assumed that, for energetic primaries, the ratio of the charged meson to the total number of mesons, charged and neutral, is $\frac{2}{3}$ and that the number of neutrons is slightly higher than the number of protons.

The energy transferred to a target nucleus can be estimated from the total number of black and grey prongs in the star resulting from disintegration of the nucleus. The excitation energy of the residual nucleus, i.e. the nucleus left after the cascade particles have escaped, can be expressed
in terms of the number of black prongs which are emitted during the evaporation process. It was empirically deduced by Powell et al.\textsuperscript{68} that for stars produced at primary energies above 1 BeV, the energy carried away by the black and grey prongs is

\begin{equation}
E(N_b) = 124N_b + 30 \text{ MeV},
\end{equation}

while the excitation energy of the residual nucleus left behind by the cascade particles is expressed as

\begin{equation}
U = 42(N_b + 1) \text{ MeV}.
\end{equation}

This empirical formula holds good provided that the initial excitation energy $U$ exceeds 100 MeV.

(a) \textit{Selection of the Alpha Tracks:-} Most alpha tracks identified as being due to the decay products of Be$^8$ nuclei showed a 'hook' at the extreme end of the residual range. This is due to multiple coulomb scattering over the last few microns of the range where the velocity of the particle is very low. In emulsion the longer tracks commonly show multiple scattering over the last few hundred microns; this phenomenon is more prominent in the tracks of light particles, such as protons or pions, and almost absent in the tracks of heavier nuclei.

When a black track is suspected to be due to alpha particle, it is identified by careful examinations of the delta-ray density, the ionisation and the features mentioned above. In doing this, the suspected alpha tracks have been frequently compared to those of Be$^8$ nuclei, alpha tracks of thorium stars.
and hammer tracks present in the same emulsion sheet. Width measurements performed on various tracks have helped us considerably in identifying the alpha tracks by visual inspection. Since the steep tracks cannot be properly identified, we have to limit our observations to those tracks which have dip angles less than $15^\circ$ in the processed emulsion. With this procedure we have collected two samples of alpha tracks of various ranges above 5 microns. One of the samples comprises 260 tracks selected from 206 stars associated with heavy fragments of charge $Z \geq 4$; and the other contains 270 tracks observed in the same number of stars having no such fragments. The samples so collected are believed to be practically free from other types of nucleus. However, the group of slower particles having ranges less than 20 microns may have some contaminations of other nuclei.

(b) Identification of Shower Particles:— In the disintegrations of silver and bromines nuclei, the shower particles are mostly collimated along the direction of the primary beam. Occasionally, however, they make larger angle with the primary and, in a few cases, are emitted in the backward hemisphere. In order to detect the shower particles, we have examined the thin tracks along their trajectories by visual inspection. The tracks for which the grain density is conspicuously large have been excluded. The selected tracks are identified by grain density measurements performed over 200 to 500 microns of their ranges starting from near the star.
FIG. 6. DISTRIBUTION OF $N_h$

SOLID HISTOGRAM - FOR STARS WITHOUT HEAVY FRAGMENTS (EVENTS-276).

DOTTED HISTOGRAM - FOR STARS WITH HEAVY FRAGMENTS (EVENTS-248).
FIG. 7. DISTRIBUTION OF $N_b$

SOLID HISTOGRAM - FOR STARS WITHOUT HEAVY FRAGMENTS (EVENTS-276).

DOTTED HISTOGRAM - FOR STARS WITH HEAVY FRAGMENTS (EVENTS-248).
Since the grain density varies with the depth of the emulsion, though slightly, we have to ascertain the proper value of $e_{\text{min}}$ for each series of measurements performed at different depths. The mean grain density of the shower particle is found to be approximately $3.0 \pm 0.1$ grains per 50 microns. We have collected four samples of shower tracks: two, at 246 ev protons and the other two at 17 GeV negative pions. The former two samples of 490 and 536 shower particles are collected respectively from 115 stars with heavy fragments and 119 stars without them. The later two samples consist of 644 and 500 shower particles observed in 155 stars with the fragments and 125 stars without them respectively.

4.4 EXPERIMENTAL RESULTS AND DISCUSSIONS.

In Figs. 6a and 6b we show frequency ($N$) versus prong multiplicity ($N_p$) histograms respectively for the stars with and without heavy fragments of charge $Z \geq 4$. The histograms showing the distributions of black prongs ($N_b$), for the former and the later types of stars, are shown in Figs. 7a and 7b. For stars with and without heavy fragments, the mean values $\bar{N}_H$ are estimated to be $19.8 \pm 0.3$ and $15.3 \pm 0.2$ and the mean values $\bar{N}_B$ to be $14.6 \pm 0.2$ and $11.3 \pm 0.2$ respectively. The prong distributions of the two types of stars differ in two respects: the one that corresponds to stars with heavy fragments has its peak more shifted towards higher values of $N_p$ and reveals a wider range of the prong multiplicity than

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FIG. 8. DISTRIBUTION IN ANGLES OF ALPHA TRACKS WITH THE BEAM DIRECTION

SOLID HISTOGRAM - FOR STARS WITHOUT HEAVY FRAGMENTS (EVENTS-270).

DOTTED HISTOGRAM - FOR STARS WITH HEAVY FRAGMENTS (EVENTS-334).
FIG. 9. ENERGY DISTRIBUTION OF ALPHA PARTICLES.

SOLID HISTOGRAM - FOR STARS WITHOUT HEAVY FRAGMENTS (EVENTS-270).

DOTTED HISTOGRAM - FOR STARS WITH HEAVY FRAGMENTS (EVENTS-266).
the other. The energy carried away by the emitted particles corresponding to the former type of disintegrations is, on the average, 2466 MeV, while the average excitation energy is 654 MeV approximately. For the later type disintegration these values have been estimated to be about 1932 MeV and 517 MeV respectively.

The angular distributions of all alpha particles of energies ranging from 5 MeV to 70 MeV with respect to the direction of the primary have been plotted in the laboratory system as shown in Figs. 8a and 8b. These figures show the distributions corresponding to stars with heavy fragments and those involving no heavy fragments. The forward-to-backward ratios of 270 tracks of the former and 333 tracks of the later types of star have been estimated to be 1.4 ± .2. For both types of star, the $\frac{F}{B}$ ratio of alpha particles of energies below 30 MeV has been found to be 1.3 ± .2. For energies above 30 MeV, the ratio has been found to increase to 2.0 ± .4 for stars with heavy fragments and to 2.2 ± .4 for those without heavy fragments. This analysis shows that the emission of heavy fragments from the nucleus has no effect on the angular distribution of other fragments of low as well as high energies. For both types of disintegration, the slow particles are more isotropically distributed than the energetic ones.

The energy spectra of the alpha particles observed at 24 GeV protons have been shown in Figs. 9a and 9b. The continuous histogram containing 270 tracks depicts the energy
spectrum of alpha particles emitted from stars without heavy fragments and the dotted one containing 266 tracks represents the same distribution for stars with the fragments. The tracks have been collected from the two groups each comprising 206 stars. Thus the average frequency of emission of alpha particles per star of each group is same. Both distributions seem to be identical as regard the position of the peak and the width. However, it has been observed that, in the stars involving heavy fragments, the number of slow particles of ranges below 25 microns is substantially higher than that in the stars without the fragments. In the samples of stars examined for the presence of alpha tracks, the number of slow particles in stars with and without heavy fragments have been estimated to be 86 and 38 respectively. Thus, the stars involving heavy fragments possess about 23 percent more slow particles.

In order that an alpha particle might have a range of 25 microns in standard emulsion, it must have an energy of 6 MeV nearly; and for the same range, a lithium nucleus should possess an energy of about 12 MeV. On reducing the range to 10 microns, the corresponding energies will be 2.8 and 5.8 MeV. The effective coulomb barrier of silver and bromine nuclei experienced by alpha particles and lithium nuclei are normally 11 and 15 MeV respectively. Thus the probability of these particles (of ranges less than 25 microns) being evaporated over the normal barrier should be very low. But the frequency
of occurrence of such particles is substantially higher than the expected value. A possible explanation of this phenomenon is the fact that at high excitation energies, the coulomb barrier of the nuclei is much reduced which enables the slow particle to escape from the nucleus.\cite{35,81,82,92,93}

In order to investigate whether the observed higher frequency of slow particles is associated with the emission of heavy fragment or simply depends on the excitation energy, we have collected more data for both types of stars, and have estimated in each group of stars, the mean number of light particle per star for the same values of excitation energy. In this estimate we have included only those tracks which have ranges below 15 microns. The results are summarised in Table 2

<table>
<thead>
<tr>
<th>Excitation energy (MeV)</th>
<th>Mean no. of slow particles of range &lt; 15 microns per star.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Stars with heavy frag.</td>
</tr>
<tr>
<td>&gt;210 - 378</td>
<td>1.5 ± .5</td>
</tr>
<tr>
<td>&gt;378 - 546</td>
<td>1.6 ± .3</td>
</tr>
<tr>
<td>&gt;546 - 714</td>
<td>1.7 ± .2</td>
</tr>
<tr>
<td>&gt;714 - 882</td>
<td>2.0 ± .4</td>
</tr>
</tbody>
</table>

The data in the table show that, irrespective of the presence of heavy fragments in the disintegrations, the average number
FIG. 10. PLOT OF $N_b$ AGAINST $N_g$ AT 24 GeV/c PROTONS
CIRCLES - FOR STARS WITHOUT HEAVY FRAGMENTS
DOTS - FOR STARS WITH HEAVY FRAGMENTS.
of slow particles per star is, within the limit of experimental errors, same for a given value of the excitation energy. The mean value slowly increases with the excitation energy for both types of disintegration. The greater abundance of slow particles in stars with heavy fragments may be attributed to the fact that the effective coulomb barrier height for this group of stars is much lowered as a consequence of much higher degree of excitation as compared to that for the other group of stars.

We have plotted the mean values of black prongs $\bar{N}_b$ against different values of grey prongs $N_g$ for stars with heavy fragments and for those without them as shown in Fig. 10. The figure shows that for the same values of $N_g$, $\bar{N}_b$ (shown by dots) for stars with heavy fragments is appreciably higher than that for the other type of stars (shown by circles). The values of $\bar{N}_g$ have been estimated to be $5.6 \pm 0.1$ and $5.9 \pm 0.1$ for stars with and without heavy fragments respectively and the corresponding values of $\bar{N}_b$ to be $14.6 \pm 0.2$ and $11.5 \pm 0.2$. Thus the values of $\frac{\bar{N}_b}{N_g}$ for the former and the later types of star have come out to be $2.6 \pm 0.4$ and $2.8 \pm 0.6$ respectively. This shows that for both types of star, the black and the grey tracks constitute about 75 percent and 25 percent of the total number of heavily ionising prongs respectively. Although for stars with heavy fragments, the value of $\bar{N}_b$ is greater than that for the other type of stars for a given value of $N_g$, the values of $\frac{\bar{N}_b}{N_g}$ are
DISTRIBUTIONS OF SHOWER MULTIPICITIES AT 24 GeV/c PROTONS AND 17 GeV/c NEGATIVE PIONS

SOLID HISTOGRAMS - FOR STARS WITHOUT HEAVY FRAGMENTS (EVENTS-119 AND 125).

DOTTED HISTOGRAMS - FOR STARS WITH HEAVY FRAGMENTS (EVENTS-115 AND 155).
almost same.

The difference in the values of $\overline{N}_b$ for the two kinds of stars can not be reconciled with the possible experimental errors in estimating the grey prongs in the stars. If some of the black prongs actually originate in the cascade stage, the error introduced by this in estimating the grey prongs must be equally probable for both kinds of star, particularly when the stars are of equal size. If we include the heavy fragments in the group of grey prongs, which are supposed to be produced during the cascade stage, the average values of $\overline{N}_b$ for different values of $N_g$ become nearly identical for the two types of star. This apparently conforms to the hypothesis that most of the heavy fragments originate in the cascade stage of de-excitation of the nucleus.

In Figs. 11 and 12 we show the shower multiplicity versus frequency histograms for stars with and without heavy fragments observed at the interactions of 24 GeV/e protons and 17 GeV/e negative pions with silver and bromine nuclei. The superimposed histograms in dotted lines show the observations in stars associated with heavy fragments. The number of shower particles are found to vary widely from star to star ranging from 0 to a maximum of 11. In 234 stars examined at 24 GeV/e protons, as many as 13 stars are found to have no shower while at 17 GeV/e pions, out of 280 stars 18 stars are found to possess no shower. These amount to an average of 5 percent stars which do not possess the shower
FIG. 13. PLOT OF $\bar{n}_s$ AGAINST $\bar{N}_h$ AT 24 GeV/c PROTONS
CIRCLES - FOR STARS WITHOUT HEAVY FRAGMENTS
DOTS - FOR STARS WITH HEAVY FRAGMENTS.
FIG. 14. PLOT OF $\bar{n}_s$ AGAINST $\bar{N}_h$ AT 17 GeV/c NEGATIVE PIONS
CIRCLES - FOR STARS WITHOUT HEAVY FRAGMENTS
DOTS - FOR STARS WITH HEAVY FRAGMENTS.
particles. It appears from the figures that irrespective of the type of disintegrations or the type of the projectile under consideration, the distributions of the light tracks are, within experimental errors, identical as regard the position of the peak and the width. For the former projectile, the mean shower multiplicity \( \bar{n}_s \) in stars with and without heavy fragments are \( 4.1 \pm 0.2 \) and \( 4.5 \pm 0.2 \) respectively. For the later projectile the corresponding values are \( 4.1 \pm 0.2 \) and \( 4.0 \pm 0.2 \). Thus the mean number of light tracks in stars involving heavy fragments in the interactions of 26 GeV/c protons is 10 percent less than that for stars without the fragments. In 17 GeV/c pion interactions, \( \bar{n}_s \) is found to be practically same for both types of stars.

The mode of variation of the shower multiplicity with the increase of the number of black and grey prongs in the stars examined at the same energies of the incident beams are shown in Figs. 15 and 16 in which the mean values \( \bar{n}_s \) are plotted against the corresponding values of \( n_h \). The dots and the circles in the figures correspond to our observation in stars with and without heavy fragments respectively. The figures clearly reveal that for both types of disintegrations and for both types of the incident beams under consideration, the average number of shower particles in a disintegration slowly increases with the increase of the total number of particles due to the cascade and the evaporation processes. Further it appears that the disintegrations with the emission of
heavy fragments involve, on the average, smaller shower multiplicity. This attenuation in the shower production seems to be associated with the increase of prong multiplicity of the star. It can not, however, be ascertained from the present investigations whether or not the emission of heavy fragments is actually due to absorption of pions by the aggregates of nucleons which are believed to be temporarily formed in the nucleus.

From their studies of the production of fragments in cosmic ray stars, Perkins and Sørensen reported that there was no correlation between the emission of a fragment and the production of a shower of mesons. Recently Takibaev et al. have investigated the production of energetic helium nuclei in the interactions of silver and bromine with 2.23 GeV antiprotons and 2.26, 9 and 19.5 GeV protons. They have reported a reduction in shower multiplicities for disintegrations emitting energetic helium nuclei at 2.23 GeV antiproton and 2.26 GeV proton interactions, and an enhancement at 9 and 19.5 GeV proton interactions. Our observations are analogous to those observed at the interactions of 2.26 GeV protons and 2.23 GeV antiprotons by the authors quoted above. According to these authors, emission of energetic helium nuclei can not be attributed to absorption of pions in the nuclei.

4.5 CONCLUSIONS.

From the comparative study of the general features of the two types of disintegration: one involving heavy frag-
ments and the other without them, it may be concluded that both types of disintegrations are basically same. However, the average prong multiplicity in the former type is greater by a factor 1.3 than those in the later type of disintegration. The prong multiplicity, being determined by the energy transfer to the target nuclei by the projectile, reveals that higher energy transfer is more favourable to the emission of heavy fragments.

The angular anisotropy of the group of alpha particles of energies above 30 MeV is nearly identical with that of heavy fragments occurring at the same energy of the incident particles. This aspect of fragment production has been discussed in Chapter VI. The energy distribution of the alpha particles spread out considerably, particularly towards higher energies (Fig. 9). Various authors have studied the production of these particles emitted in high energy interaction of silver and bromine nuclei, and have found that the evaporation theory, embodied with proper values of nuclear temperature and effective coulomb barrier can account for those particles having energies below 50 MeV. The groups of particles with high energies are attributed by a number of authors17,50,61, 94-96 to other processes associated with the initial cascade stage. The evaporation calculations have shown that the values of the effective coulomb barrier assumed for obtaining the best fit of the theoretical energy spectra with the experimental ones are, in most cases, much higher than the values which
can be reasonably applied in the evaporation model. Further, a group of these particles possesses large amount of kinetic energies. Such particles are believed to be ejected as a result of collisions of the alpha clusters in the nucleus with nucleons during the initial cascade stage. We have also observed a long tail in the energy spectra of the alpha particles which is significantly different from what is expected from the evaporation theory. Similar long tails have also been observed in the energy spectra of the fragments much heavier than alpha particles. Such deviations, however, do not allow us to conclude that the de-excitation of a nucleus is not due to particle evaporation. The problem has been discussed in Chapter VI in connection with the energy spectra of fragments with charge $Z > 4$, where we have tested the evaporation theory on the observed energy distributions of beryllium and boron fragments.