CHAPTER III

GENERAL CHARACTERISTICS OF STARS

3.1 INTRODUCTION - FORMATION OF STARS :

The phenomena known as stars are a prominant feature of high energy nuclear disintegrations, in which set of tracks of several heavily ionising particles radiating from a common origin is obtained. This was first observed during the study of cosmic rays by cloud-chamber photographs.

These cosmic ray stars were extensively studied by Hazen and Powell by cloud-chambers containing lead plates. But the draw back of the cloud-chamber in studying these stars is that only a few stars are obtained over a long period of operation. On the other hand, many more stars could be obtained in photo-nuclear emulsion with reasonably short period of observation and less trouble. The prongs of the stars are due to the ionising particles, such as, protons, deuterons, alphas or heavier fragments emitted from a common centre. Blau and Wambacker[1] were the first to observe the cosmic ray stars in nuclear emulsion in the year 1937. They actually measured the angular distribution and energy of the low energy particles produced in these disintegrations. Since then a large number of workers in different laboratories of the globe have been engaging themselves in theanalysis of various characteristics of the stars produced in photo-nuclear emulsion by cosmic rays and machine accelerated particles.

The nuclear emulsion contains mainly two groups of elements. The heavier group consists mainly of silver and bromine and the lighter group contains hydrogen, carbon, nitrogen and oxygen. A silver or bromine nucleus is an assembly of about hundred nucleons, spherical in form and four to five nucleons in diameter. The observed characteristics of disintegration of these nuclei produced by particles of specific energy will depend upon the impact parameter which defines the line of motion of the incident particle with respect to the centre of the nucleus. This nuclear disintegration may roughly be divided into two classes, viz., (1) those involving the peripherial collisions and (2) central penetration of the nucleus. In central collisions, the nuclear thickness of a heavy nucleus, can be taken to be four or five nucleons and for peripherical collisions from one to three. The two types of the phenomena are approximately equally frequent[2].

When a high energy particle strikes the nucleus, it makes within a time of the order of 10^{-23} sec a series of collisions with the individual nucleons of the nucleus. These collisions may either be radiative or elastic. In the radiative type of interactions, pions, both charged and neutral are produced. In most cases, according to 'Plural Theory[3,4], only a single meson is created in a single nucleon, nucleon collisions. However, this theory is discarded at present. But as per 'Multiple Theory[5-10], several mesons are created in a single collisions which is so highly inelastic that primary has often insufficient energy to generate further meson in subsequent impact.

The meson produced in the first impact have velocities commonly in the relativistic region and may produce sometimes other mesons in collision with the necleons lying near their line of motion. In doing so they may communicate some energy to the recoiling nucleons, but they contribute little directly to the general excitation of the stars. On the other hand, the recoiling nucleons produced in primary impact are generally interact with other nucleons which in turn, have further collisions. The initial energy of the recoiling nucleon is thus rapidly shared with a number of others and the process is known as 'nucleon cascade'.

The mesons and baryons created in the impact of the primary particle traverse the nucleus in a very short time of the order of 10^{-22}sec., and they tend to be collimated strongly about the direction of motion of the incident particles. The cascade nucleons having kinetic energy large compared to the binding energy per nucleon have relatively long mean free path in nuclear matter and they commonly escape by making one or two collisions. Forthose of lower energy, the nucleus is much more opaque, and they make several collisions, so that their directions of emission are less closely collimated with respect to the primary particle. The cascade particles are also emitted soon after the impact of the primary particle.

The nucleon cascade leaves the nucleus in a very highly excited state and it subsequently emits individual nucleons and heavier particles. The emission of particles from this state, however, takes place relatively slowly. The excitation energy is distributed uniformly over the whole volume of the nucleus and a particle must await for a favourable statistical fluctuations to come out of it. After the emission of this particle, a further relatively long period of the order of 10^{-17} sec will commonly escape before a second particle attains a condition favourable to escape. This process will continue until the excitation energy of the residual nucleus is so small that transition to the ground state is likely to be affected by the emission of gamma rays only as particle width becomes small.

3.2 THE NUCLEAR EVAPORATION PROCESS :

The emission mechanism of slow particles from a highly excited nucleus, left after the ejection of cascade particles, may be compared to the cooling down of a heated drop of liquid by the process of evaporation. However, the analogy, is not very exact, since the number of particles in the nucleus is small and the emission of a single particle results in considerable reduction in excitation energy and hence in so called nucleon temperature. Secondly, the ratio of the surface area to volume for a nucleus is much larger than for a droplet of liquid. As a result of this, thermal excitation in the form of surface as well as volume waves becomes important. Thirdly, the emission of charged particle is complicated by the effect of coulomb barrier.

The statistical treatment of particles evaporated from the excited nucleus was first suggested by Bohr and Kelchar[11]. Later Weisskopf[12] from regorous calculations showed that in a large nucleus with excitation energy greater than the binding energy per nucleon, the probability of a neutron being emitted with energy between E and E + dE is

$$p(E)\ dE = E/T^2\ e^{-E/T}\ dE \qquad \ldots \qquad 3.2a$$

where T is the nuclear temperature measured in Mev. Making allowance for the coulomb barrier of height 'v' measured in Mev the probability of emission of charged particles becomes,

$$p(E)\ dE = (E - V)/T^2\ e^{-E - V/T}\ dE \ldots \qquad 3.2b$$

Bagge[13] took into account of cooling down of the nucleus during evaporation. He treated the nucleus as a degenerate gas of particles satisfying fermi statistics and neglected the interaction between the nucleons. The total excitation energy of a nucleus having A nucleons as calculated by him was given by,

$$U = KAT^2 \qquad \ldots \qquad 3.2c$$

$$\text{where } K = \pi^2/\ 4G$$

G- being the kinetic energy of the highest occupied state in the unexcited nucleus.

Bagge[13] also assumed that there would be surface oscillation on the nuclear surface at high excitation energy and those oscillation would increase the nuclear radius thereby decreasing the barrier height. Bethe[14] observed that the effect of interaction between the nucleons will increase K by a factor 2, and hence K will nearby be equal to 0.1. The average energy loss du of the nucleus when dA neutrons are evaporated is obtained by using the relation,

$$du / dA = 2\ KA.\ dT / dA + KT^2$$

$$= 2T + E_0 \qquad \ldots \qquad 3.2d$$

where 2T is kinetic energy (average) of the particles, E_0 the binding energy per nucleon and T the instantaneous temperature. The process is treated as continuous and neutron emission is assumed to be independent of proton emission.

Taking into account the correlation between neutron and proton emission and also the effect of thermal expansion of the nucleus, Le Couteur[15] obtained the probabilities of emission of six different types of particles, proton, neutrons, deuterons, tritons, alpha particle and He^3 nuclei.

According to evaporation theory the energy spectrum of the emitted particles is of Maxwellian type, their angular distribution is isotropic and emission frequency of the particles of different charge is given by exponential curve showing an exponential decrease in frequency with increase in charge.

Somewhat similar calculations were made by Fujimoto[16] and Yamaguchi[17] by taking into account of the correlation between neutrons, protons and alpha particles. They, however, neglected the thermal expansion which was supposed to be small but took into account of the fluctuations in the number of particles emitted for fixed values of U.

The energy spectra of the cascade particles has been estimated by Goldberger[18] using Monte carlo technique. In recent times detailed calculations on the basis of this method have been made by number of worker in their attempts to the proper explanation on the emission of different particles by cascade evaporation method.

3.3 EXPERIMENTAL METHOD AND SELECTION CRITERIA :

For the present investigation, we have used K5 emulsions exposed to 1.8 Gev/c negative keons (Sample A), and G5 emulsions exposed to 5 Gev/c antiproton (Sample B). In order to detect the stars with prong number (heavily ionising) more than eight, the emulsion sheets are scanned within limitted volume avoiding the peripherial region, under low magnification with objective of 10X and eyepiece 15X. The lower limit of prong multiplicity is taken just to avoid stars that are due to the disintegration of the lighter elements of emulsion. This selection rule covers approximately fifty percent of the interactions occuring in the emulsion and most of the disintegration thus selected are due to central collisions[19] of heavier group of emulsion nuclei. The interactions on silver and bromine nuclei have been estimated to be in the ratio of 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[20].

The tracks emitted from a star in nuclear emulsion can be classified into three distinct types according to their ionisation which is expressed in terms of grain density g as compared to g_{min}, the grain density of singly charged relativistic particles[21]. It is shown that for

(1) Shower tracks, $g_{min} < g < 1.4\ g_{min}$

(2) Grey tracks, $1.4\ g_{min} < g < 6.8\ g_{min}$

(3) Black tracks, $g > 6.8\ g_{min}$

Now the number of heavily ionising prongs in a star is given by the total number of black (N_b) and grey prongs (N_g) and is denoted by N_h ($= N_b + N_g$).

The particles producing black, grey and shower in a nuclear disintegration in emulsion are believed to be resulting from three distinct mechanisms. Generally it is agreed that most of the black tracks are due to the evaporation of excited nuclei. The limit 6.8 g_{min} for a proton corresponds to an energy of about 25 Mev. But most of the protons emitted in the evaporation process have energies less than this value. The protons with energy more than this value are supposed to produce the grey tracks and they have their origin in the cascade process. The thin tracks are produced mostly by pions[22,23] having energy more than 80 Mev. Also protons having kinetic energy more than 500 Mev make a small contribution to this group. The particles producing heavily ionising tracks are mainly due to protons, deuterons, tritons and alpha particle and other heavier fragments emitted from the disintegrating nucleus. 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[24]. Therefore, the value of N_h for disintegration is a good estimate of the charge of the nucleus and similarly n_s gives a good estimate of pions produced. Neutral meson can not produce any track in the emulsion. It is generally assumed that for high primary energy, the ratio of charged meson to the total number of meson produced is $n_s/N_s = 2/3$. The number of neutrons emitted from a star, which also do not leave any trace in emulsion is slightly greater than the number of protons.

3.4 RESULTS:

The general characteristic of stars produced by (Sample A) and (Sample B) are studied. The prong distributions of about 200 and 150 disintegrated centres of the stuck nuclei collected from both the samples have been observed. These stars have been selected at random from the volume of the emulsion scanned already for the search of fission events. All the stars in the volume having $N_h \geq 8$ were collected. Stars which were within 20 microns from both the surfaces of the emulsion surfaces have not been included in the sample. The distribution of N_h of these stars in two samples are shown in fig. 3.1 and fig. 3.2 respectively.

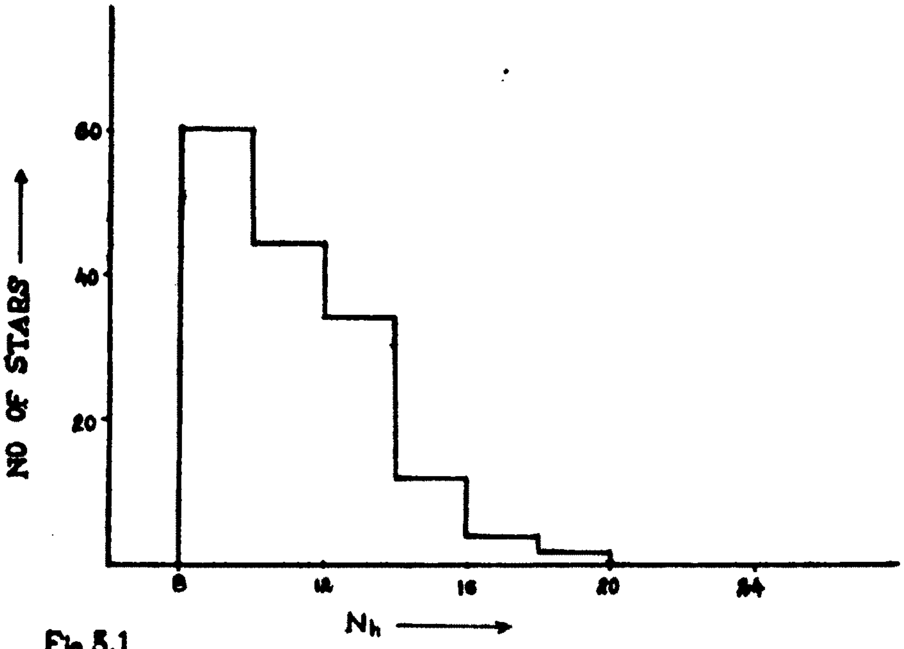

Fig 5.1

N_h DISTRIBUTION OF GENERAL STARS IN K^- INTERACTIONS (156 EVENTS)

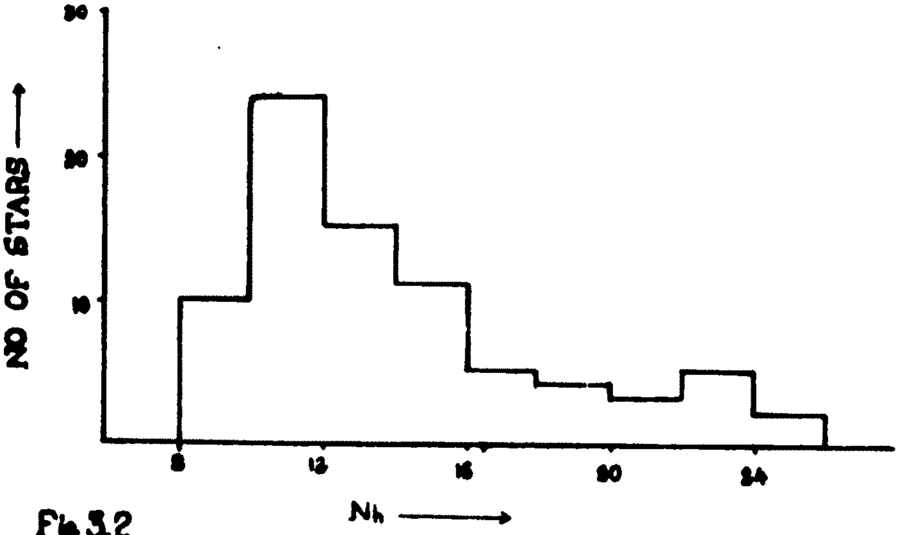

Fig 3.2

N_h DISTRIBUTION OF STARS (GENERAL) IN $\bar{P}$ INTERACTIONS (170 EVENTS)

From the figures, it is found that the average number of heavily ionising tracks for these two types of interaction are given by $N_h = 11.0 \pm 0.19$ (for k^- interaction) and $N_h = 12.0 \pm 0.21$ (for p^- interaction) respectively.

The total energy carried away by grey and black tracks in such nuclear disintegration in standard nuclear emulsion can be estimated by using the empirical formula due to Powell[2] et al which is given by,

$$E = 124\ N_h + 30 \text{ Mev} \qquad \ldots \qquad 3.4a$$

which is valid for stars with primaries of energy greater than 1 Gev.

This E in these samples of stars in K5 emulsion exposed to 1.8 Gev k^- and G5 emulsion exposed to 5 Gev p^- estimated to be about 1460 Mev and 1550 Mev respectively. Of this total amount about 75 p.c. is carried away by cascade particles and the rest by the evaporated ones. The average excitation energy υ before the begining of evaporation is calculated with the help of the following relation due to the same author[2].

$$U = 42\ (N_b + 1) \text{ Mev} \qquad \ldots \qquad 3.4b$$

Now considering the fact that out of the total number of heavily ionising prongs 70 p.c. constitute black prongs and the rest grey[2], we calculate the excitation energy with the help of above formula. The values so obtained are 380 Mev for Sample A stars and 410 Mev for the stars of sample B. However, this relation is valid provided that the initial excitation energy exceeds about 100 Mev.

The relative frequencies of different types of particles emitted in such nuclear disintegrations have been experimentally verified by the number of workers and theoretically computed by others with plausible assumptions and hypothesis. The values obtained by different groups are found to be closely similar[20, 25, 26].

In the present study use has been made of the table 3.1 due to Key[20] et al on the relative frequencies of emission of different particles on the basis of the evaporation theory of nuclear disintegration. All heavy fragments from Li^6 to B^{11} are represented by an average fragment $\langle Be^8 \rangle$ the energy of which had been estimated from the observed Li^8 mean energy adjusted for coulomb barrier effects. The average kinetic energy of deuterons and tritons are assumed to be equal to that of the nucleon though it is usually slightly higher. The average momentum per observed evaporated particle is about $(p^2 f)^{1/2} = 275$ Mev/c. In estimating the total charge and mass of the cascade evaporated particles use has been made of the same table due to Key[20] et al. Also it is assumed that all the cascade particles (grey particles) are due to the protons. The total charge and mass thus carried away by the cascade evaporated particles for $N_h = 11$ in k^- interactions are found to be 14 and 28. This gives the mean charge and mass of the evaporation residue of bromine nuclei to be 21 and 51 respectively and for silver nuclei it is estimated to 33 and

79 respectively. For antiproton interactions the respective values of charge and mass carried out by disintegrating particles are found to be 16 and 31. Therefore the mean charge and mass of the evaporation residue in case of bromine interaction are estimated to be 19 and 48 respectively and that for silver nuclei the respective values are found to be 28 and 76.

Table 3.1

Emission probabilities of different particles

Types of emitted particles	Percentage of evaporated particle	Relative frequency f per charged particles	Assumed momentum p = Mev/c	Assumed energy E - Mev	No. of particles expected to be emitted
^{1}n	36.2	0.567	75	3	7.0
1H	24.3	0.381	125	8	4.7
2H	10.7	0.168	173	8	2.1
3H	7.0	0.110	213	8	1.4
4He	18.4	0.288	346	16	3.5
^{8}Be	3.4	0.055	650	28	0.7

3.5 DISCUSSION :

The results discussed above are consistent with those of the earlier workers[2, 27, 28, 29] from their studies on disintegrations produced by cosmic rays and artificially accelerated particles. The general characteristics of nuclear disintegrations indicate the overall validity of the cascade evaporation model for explaining the emission of particles producing heavy prongs. Now the cascade evaporation residue is heavy and the residual momentum is as such that it cannot produce any recognisable tracks in the emulsion or even if any it results only in 'Goks'. However, a brief discussions of this recognisable short tracks due to the spallation, i.e., cascade evaporation residue is presented in the next chapter.

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