EMISSION OF HEAVY FRAGMENTS ($A \gtrsim 20$) FROM SILVER AND BROMINE NUCLEI DURING HIGH ENERGY INTERACTIONS.

A THESIS SUBMITTED TO THE UNIVERSITY OF GAUHATI
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY
IN THE FACULTY OF SCIENCE

By

Kamaleswar Goswami, M.Sc.
Department of Physics,
Goalpara College
Goalpara - 783 101
Assam :: India

Department of Physics
Gauhati University
Guwahati—781 014
ASSAM :: INDIA

October 1989

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GAUHATI UNIVERSITY

Dr. T. D. Goswami
Prof. & Head,
Department of Physics.

Phone No. 88531
Guwahati-781014
Assam : India

Ref. No ....

Date 23.10.89

This is to certify with great pleasure that **Mr. Kamaleswar Goswami,** *M. Sc., Department of Physics, Goalpara College, Goalpara, has completed his works on "* **emission of heavy fragments (A $\gtrsim$ 20) from silver and bromine nuclei during high energy interactions** *" for the award of Ph.D. Degree of Gauhati University under my supervision and guidance. Mr. Goswami has fulfilled all the requirements prescribed under Ph. D. regulations of the Gauhati University. The thesis, he has submitted, is the result of his own investigations and to the best of my knowledge this work as a whole or part thereof has not been submitted to any other universities for any research degree.*

Goswami

(T. D. Goswami)

PREFACE

The high energy disintegration of complex nuclei is a field of active research all over the world. Plenty of energy is available in such high energy reactions. The energy becomes sufficient to disassemble the target nucleus into a number of its products. Moreover, particles are produced copiously. The bulk of our present knowledge about the elementary particles and their interaction properties have been derived from the nuclear collision experiments. Also, during high energy disintegration the constituents of a nucleus probably shuffle and reshuffle, and produce a variety of nuclear species. The production and emission of heavy fragments from such nuclear disintegrations are creating a great deal of interest.

Inspite of a large number of experiments done with highly energetic beams of particles and nuclei, important gaps still remain in our knowledge about the phenomenon of nuclear disintegration. Still shortages are felt for a clear-cut model so as to explain all the salient features in respect of formation of disintegration stars as observed in nuclear emulsion and their characteristics. The two-step model, called the "cascade-evaporation" model (or the "abrasion-ablation" model) has come into use. But the role played by the cascade-evaporation process during high energy disintegrations is not yet clear. For example, the emission of fragments like Li^8 and Be^8 is not well understood. Also, the statistical model, which is the only quantitative model for high energy nuclear disintegrations so far, is supposed to break down at excitation energies greater than or of the order of the total binding energy of the nucleus.

The high energy reactions produce various nuclei with mass smaller than that of the target (or projectile). The mass yield curve attains a typical U shape with upturns towards the lightest products and the target, around a "deep" observed somewhere in between the upturns. A sizable cross-section of the products are heavy. Important informations regarding the disintegrations are likely to be obtained from the study of emission of heavy fragments caused by such reactions. However, during high energy interaction of particles with medium weight nuclei the role played by various processes of heavy fragment emission is not yet clear.

The present work is based on the author's investigation relating to a few aspects (such as spallation, fission and multifragmentation) of high energy nuclear disintegration by emission of heavy fragments from silver and bromine nuclei of photonuclear emulsion. As it becomes convenient to discriminate the various processes of heavy fragment emission by visualizing the events, the present investigation is carried out by the photographic method. Two stacks of photonuclear emulsion have been used for the purpose, one of them is exposed to 1.8 GeV/c K^- beams while the other to 20 GeV/c p beams.

A brief report on his history and developments relating the nucleus and its artificial disintegration has been furnished in Chapter I. This is done in order to get an easy acquientance with the topic of interest of the present investigation. Some of the informations regarding the experimental procedures and the techniques of measurements are given briefly in Chapter II. The Chapter III is formed out of a brief report on the studies of the general characteristics of the disintegration stars observed in nuclear emulsion.

The results of some of the studies on spallation events have been reported briefly in Chapter IV. The report on the studies of fission events has been presented in Chapter V. Chapter VI contains a raport on the studies of multifragmentation events which may otherwise be called to be ternary and higher order fission events also. The investigations have been made in the light of the idea that the phenomena of fission and multifragmentation, like the recoiling evaporation residues, mark the last stage of the disintegration. Also, here it has been aimed at finding similarity (if any), that may exist in respect of the stages of production of the events. The discussions on the charge and mass of the products are also presented. The studies on the production of heavy hypernuclei have been reported in Chapter VII. The results have been classified in order to see if all of the above mentioned processes of heavy fragment emission are involved in the disintegration of the nucleus when it contains a lamda hyperon also.

Some of the results of the present investigation have been summarized in the concluding chapter (Chapter VIII). The position of our present knowledge about the emission of heavy fragment during high energy disintegration of the complex nuclei has been discussed. The scope and usefulness of further investigations on some of the relevant topics have also been indicated.

Kamaleswar Goswami

(Kamaleswar Goswami)

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CHAPTER I

INTRODUCTION

1.1. THE ATOMIC NUCLEUS - AN INTRODUCTION :

Matter is made up of a set of particles called atoms having chemical identities of elements occupying respective places in Mandeleeff's (1869) periodic table. With the discoveries of X-rays (1895), radioactivity (1896) and the electron (1897), attempts were also made to understand the composition of atom. From the observation of large angle scattering of alpha particles by matter Rutherford (1911) showed that all the positive charges of the atom were concentrated in a very small region-"the nucleus". The success of explaining the observed hydrogen spectra from motion of electrons along quantized orbits (1913) around the nucleus proved beyond doubt the existence of the small, positively charged atomic nucleus in which practically whole of the mass of the atom was concentrated. Positively charged "protons" (1919) and electrically neutral "neutrons" (1932) were also identified.

Protons and neutrons are very minute particles of root mean square radius close to 0.8 fm or 0.9 fm/1/. A free proton, hither to known as a stable particle, is a subject of investigation for its decay /2, 3/, while a free neutron has an average life of about 17.3 min. after which it undergoes a beta-decay. Theoretical and experimental works exploring the substructure of protons and neutrons observe that these individual particles may be composed of a core or "Nucleor" surrounded by a pi-meson (or pion) cloud made up of one or more pions. On the other hand, with the suggestion that a meson or a baryon may be made up of quarks /4/, it has also been assumed that such particles are made up of a quark-antiquark pair or a three quark combination, the massless gluons mediate quark-quark interaction/5/.Very large forces on the very heavy quarks on one hand ensures a large mass defect of the quarks in hadrons and on the other, prevent them from being emitted. Attempts have been made to explain the permanent detention of the quarks inside the hadrons in logically consistant ways - in particular quark "bag models" have been suggested /2, 6/. In principle, quarks may be freed if the hadron acquires sufficiently high energy. Even with the expected differance of bound protons and neutrons with the free ones /7/, the quark-gluon plasma is likely to be observed /8-10/. Such an abnormal state of matter, viz. the quark-gluon plasma, may be observed by depositing very high energy to the nucleus so as to attain a very high density and temperature /10-12/. Promising results are comming from some of searches for abnormal state of matter /13/. Search for "strange matter" characterized by strange multiquark states are also being contemplated /14/. These, in turn, are expected to provide more information towards the understanding of the nucleus as a whole.

The nucleus, regarded as made of protons and neutrons i.e., nucleons packed together approximately in the form of a sphere of radius R (measured in fm), is very small in comparison with the atomic diamension (measured in Å. U.). If A be the number of nucleons, then R is approximately given by

$$R = r_o A^{\frac{1}{3}} \qquad (1.1.1.)$$

where r_o, the radius constant, may show different values mostly depending on the methods of measurements or estimations /15/. However, to a first approximation the average value of r_o can be taken to be about 1.2 fm /16, 17/. Normal nuclei on earth have density nearly equal to 0.17 nucleons/fm^3 and temperature is almost zero /11/. On depositing energy if the nuclear temperature is raised to 1 MeV, the corresponding temperature in the thermodynamic scale becomes 1.16×10^{10} °K.

The short range but very strong nuclear forces, having characteristics similar to those of Van der Waal gas but differing in scale, are chiefly responsible /18/ for keeping the nucleons together against very high repulsive forces due to protons existing in the nuclei. The Coulomb force is associated with electromagnetic field which is identified with the quanta of radiation-"photon". On the other hand, the mesons(mostly the pions) which may modify the electromagnetic properties of the individual nucleons also to a certain extent, mediate the field of nuclear forces. Uptil now only a very limited number of experiments have shown that the position of a nucleon in the nucleus may affect the location of another /19/, i.e., there may be a spatial correlation between nucleons. However, the observed saturation properties of the nucleus, viz, that the density of the nucleus and the binding energy per nucleon are roughly equal for all nuclei, are well explained by the "exchange forces". As the threshold energy of the incident nucleon beam for production of pions in free nucleon-nucleon collisions is about 290 MeV and as the mesons may not necessarily be an integral part of the nucleus either, it is taken that under normal conditions they donot exist as free particles and the exchanged pions (and heavier mesons at shorter distances) are referred to as virtual particles.

A random combination of nucleons may not form a nucleus. Some 327 isotopes are known to occur in nature, out of which 272 are stable and 55 are radioactive /20/. In all stable nuclei, with the exception of ${}_1H^1$ and ${}_2He^3$, the number of neutrons is greater than or equal to that of protons, i.e., there is always at least one neutron for each proton. It is noticed that for the practically stable nuclei the number of protons Z and the number of neutrons N are arranged in such a way that for light nuclei the values of N and Z are almost equal but as one goes towards the heavier nuclei, N increases much more rapidly than Z. The neutron excess is about 15% for Iron and about 59% for Uranium. The predominance of neutrons over protons is believed to provide necessary attractive force to balance the long-range Coulomb repulsion due to the increased number of positive charges - the protons.

Radioactive nuclei, be they neutron rich or neutron deficient, would decay to stable ones by emission of beta particles, alpha particles, gamma-rays or by fission or sometimes by capture or orbital electron(s) in the nearest orbit or by some combination of these probabilities. In addition to the naturally occurring ones a number of other isotopes (about 2000), produced during nuclear reactions, have been detected and investigated. Some of them have excess neutrons while some of the others are neutron deficient species /17, 21/. The farther they stand from their most stable isotopes, the shorter are their life time. Some of the investigations show existance of multi-neutron systems /22/. Further investigations for similar bound or unbound exotic systems are also in progress /23/ as they are likely to provide more information on interaction between nucleons in the nucleus.

In principle a prompt nuclear process, followed by a slow beta reaction , should make it possible to transmute any type of nuclear material to another. During synthesis of transuranic elements, it has been found that projectiles like n^1, H^1, H^2, H^3 and He^4 may be adequate to produce elements with Z upto 101. But to produce still heavier elements, with the present advancement, heavy ion projectiles are essential /24, 25/. In a bid to produce "super elements" with Z about 114, already elements with

Z upto 109 have been produced; processes concerning synthesis and identification of the element with Z = 110 are also in progress /25/. Such nuclei due to their high charge and mass, consequently inherent deformations, are mostly vulnerable to fission. Nuclei produced with high spin /26/, as they stretch into an elongated shape, are also relatively vulnerable to fission. However, the threshold for fission of such rotating nuclei depends on the properties of the isotopes also. It has been observed that Dy^{152} can sustain a deformation of major-minor axes ratio 2:1 accrued due to about 2 x 10^{20} rotations per second /27, 28/. It has been apprehended that superdeformed nuclei with a 3:1 major-minor axes ratio may perhapes exist /28/.

The nucleus, a preferantial combination of atmost about 300 protons and neutrons confined in a small volume, is an unambiguously dense material having important surface properties. The microparticles viz, the nucleons, being acted on by the forces of interaction, move inside the nucleus rendering a variety of properties - such as the energies, spins, parities, electric and magnetic moments, stability, binding energies and masses. Though hindered by some of the factors like Coulomb barrier for charged particles, Pauli principle, nuclear potential and surface effects, under favourable circumstances the nucleus admits in-coming and out-going of particles. As the nuclei contain too many particles to deal with individually for exact treatment, yet not enough particles to permit simplified assumptions like those of nuclear matter /29, 30/ without surface effects, their properties and structural characteristics are normally studied by constructing "models", which are the approximations nearest to the actual systems.

1.2. MODELS OF THE NUCLEUS :

The development of nuclear models has been followed along two different lines. While in the "strong interaction models" a number of closely coupled particles are considered to form the nucleus, in the "independent particle models" it is assumed that the nucleus is formed by rather independently moving particles. All models have the common feature that they single out for consideration only a few of the large number of degrees of freedom of the nucleus. This may be evident from a few features of some of the models.

1.2A. The liquid drop model :

In the liquid drop model /31/basically the nucleus is regarded as an incompressible (and charged) drop of liquid. The energy of the nucleus is made up mostly of a volume energy, a surface energy and a Coulomb energy. When necessary, the deviation from sphericity is characterized by a set of deformation parameters. The excited states of the nuclei may be contained in the deformations and the oscillatory motions of the liquid drop, the most important of which are the surface vibrations which entail a change in the deformation parameters with time. The lowest excitation levels are thought to be only due to the rotation of the nucleus as a whole.

In addition to providing a good overall account of nuclear mass and binding energy systematics, the model serves as an important tool to account for the phenomenon of fission. Comprehensive description of the compound nucleus formation and the alpha-, beta-decay probabilities are also provided by the model. However, the model falls short of yielding accurate predictions concerning excitation energies, moments etc.

The droplet model /32/ and the rotating liquid drop model /33/ may be considered as some extensions of the liquid drop model.

1.2B. The cluster model :

The sponteneous emission of alpha clusters from heavy radioactive nuclei, the observed ragularities of binding energies of even-even $Z = N$ nuclei and an increased stability of clusters like alpha particles (helium nucleus) over the neighbouring nuclides led to the belief that some of the substructures like alpha particles, either permanent or temporary but with long life time compared with the natural period of their vibration and rotation, may exist inside the nucleus /34, 35/. By this model the state of a nucleus may be viewed as a coupled system of a few clusters. As seen from its use, particularly to some of the low lying states of light nuclei, the model has found limited success in its application /36/. On the otherhand, the observed spontaneous emission of some of the heavier nuclides /37/ and reduced alpha-decay widths /38/ has led some of the workers to treat the cluster emission to be only a decay channel /39/. However, it is consistant with the spirit of cluster model to use different clusters not only for different nuclei but for different states of the same nucleus also /40/. It has also been pointed out that protons and neutrons may not be equally distributed over the nucleus such that the ratio of their densities would be Z/N everywhere /17/. Further, important tests may also be expected from the study of nuceli far from the beta stability /41/.

1.2C. The shell model :

The shell model /42/ is a description of the nucleus in which individual nucleons are supposed to move independently in a common static average potential along defined orbits or "shells" as defined by their energy. The constituent nucleons in the ground state nucleus fill the proton and neutron shells in sequence until all the particles have been accomodated in the respective shells, the common uppermost level being the Fermi level. An even number of protons and neutrons in a specified shell pair off to zero angular momentum leaving the unpaired valence nucleons to ascribe the net total angular momentum of the nucleus. The behaviour of magic nuclei are suggestive of the shell closure phenomena /43/. The long mean free path (about the diameter of the nucleus) /44, 45/ of the nucleons can be understood as an effect of Pauli principle. The excited states of the nuclei may correspond to particle-hole configurations.

The model is capable of providing a good account of a number of energy levels, spin, parity, and to a certain extent the transition probabilities, moments and transfer reactions. The method of shell correction /46/ provides a good explanation of asymmetric mass division and causes a modification of the barrier heights in connection with fission.

Despite manifold successes of the shell model, its applicability gets restricted as the number of nucleons constituting the nucleus goes on increasing. Because, the single particle picture does not remain sufficiently accurate and mixing of other states becomes important.

The single particle shell model, the many particle shell model and the j-j coupling model are a few versions of the shell model.

1.2D. The collective and the unified models /47/ :

In the collective model the extra-core nucleon(s), located in the unfilled shell(s), are assumed to move around the core which is treated macroscopically rather like a drop of deformable nuclear liquid. It is supposed that the deformation (which vanish for closed shell nuclei) is produced by a polarizing effect due to motion of nucleon(s) outside the closed shells. The core loses its spherical symmetry. Consequently, though the total angular momentum of the nucleus remains unchanged as it is shared by the orbital nucleon(s) and the core, the effect of deformation on the moments will be observed. It not only explains the large quadrupole moments but also predicts a fine structure of the nuclear level spectrum owing to energies associated with vibrational and rotational motions of the core.

The Unified model, a true modified version of the shell model, assumes that the nucleons move nearly independently in a slowly changing non-spherical potential. The distortion corresponding to which the minimum of the single particle energy is obtained, is considered as the deformation (involved) of the nucleus. Also, here both excitations of individual nucleons and the collective motion(s) involving the nucleus as a whole are considered.

1.2E. The Fermi gas model :

In this simple model /48/ the neutrons and the protons, obeying Pauli principle and Fermi-Dirac statistics, are independently regarded as a completely degenerate Fermi gas that make up the nucleus. The two-body interacting particles, confined in the nuclear volume, may be ascribed to plane waves. At ground state, all the two-fold spin degenerate discrete energy states are filled up by the fermions in the Fermi sea upto a maximum energy called Fermi energy which is given by $k^2_f/2M$, where k_f = Fermi momentum, M = effective mass of the nucleon.

The total number of states n_o in the Fermi sea may be estimated to be

$$n_o = n_n + n_p = \sum_{k_f}^{n,\,p} \frac{4}{9\pi} \left(\frac{2\pi k_f r_o}{h}\right)^3 A \tag{1.2.1}$$

where A = Z + N is the number of nucleons.

r_o = radius constant.

The Coulomb interaction between protons reduces their well depth and also introduces Coulomb barrier for charged particles. It may be observed here that the estimated potential well depth (about 41 MeV when r_o = 1.2 fm) becomes somewhat less than that obtained from the shell model calculations (about 50 MeV /49/). However, the particle velocity at the Fermi level can be assumed to be about 0.2c .

During the strong interaction of a particle with another as the particle may find itself in another state which has been already occupied (i.e., which is forbiddened), the number of allowed interactions becomes limited. This not only explains the long mean free path but also provides justification for assumed free motion of the particles.

Excitations create hole(s) in the level scheme and thereby provide more phase space to the nucleons in the nucleus. Also, lowering of barrier heights and increase in the nuclear radius are two important considerations.

Though this model gives a good qualitative picture of the nucleus, it completely ignores factors like the surface effects. Consequently, the numerical results like those of energy levels are unlikely to be accurate.

This model does not forbid to picture the nucleus at its ground state rather like a solid in the sense that all of the available phase space in the ground state are completely filled up.

The model finds some application in heavy nuclei and is particularly useful in describing the collision phenomena in high energy nuclear processes.

1.2F. **The statistical model :**

The inherent complexities of nuclear structure and actual microscopic interactions, particularly when high energy is deposited to the nucleus, may be bypassed by invoking a macroscopic approach which avails the statistical mechanics and thermodynamics to furnish the overall predictions without going to the minute details of interaction.

There are a number of models of nuclear collision that involves statistical methods and/or thermodynamics in both quantal and classical domains providing valuable insight into the various aspects of nuclear collision /50-53/. Here, however, the description of a number of reactions in terms of the decay of an equilibrium system of long life time in which the phase relations can be neglected is called the statistical model /54-56/.

In this model it is assumed that the equilibrated system does not remember the particular channel through which it has been formed except the constants of motion like energy, angular momentum etc., /31, 56/. Constraints imposed by conservation laws and geometry on the level spacing, and probable existance of quasi-bound, unbound and bound Fermi systems of liquid-gas like mixture under statistically available configurations of the equilibrated system has also been considered /57-62/. It has been observed that as more and more excitation energy is deposited to the nucleus, the number of available states and their density becomes very large; and an equilibrated system may be formed with overlapping levels also /55/. Thus it becomes suitable to obtain the statistical information by averaging over many excitation configurations with approximately equal energy than to try to describe the properties of individual (but may be non-resolvable) nuclear states. However, the phase space available to the nucleus is finite. One must use a quantity that measures the density of the bound component of the compound nuclear levels for such a description /59/.

The relaxation time of the nucleus may be expected to be one or two magnitude longer than the time required for an average nucleon to traverse the nucleus, as a perturbation of the nuclear matter will have a typical velocity of the order of an average nucleon velocity. The assumed thermalisation /18/ or equilibration may be attained by the nucleus on completion of the relaxation - during which the excitation energy may be evenly distributed over the whole nuclear system. Such a time may be expected to be small enough (may be about 10^{-21} sec. /61/ also) for a highly excited system.

A thermalized system may be characterized by the uniform temperature (which may be instanteneous) attained due to the available energy. The ground state may be characterized by the lowest available temperature. The higher the excitation energy contained in the system, the higher would be its nuclear temperature. A component of the available energy may be contained in other modes of excitation also /55, 63/.

At higher temperature the nuclear shell structure disappears /56, 58, 59/. Due to abundance of available nuclear states the phase-space restrictions on interaction between fermions also practically disappear. Pairing effects reduce greatly. Nuclear transperancy decreases. Fermions acquire relatively higher momenta. The interaction mean free path decreases but remains still long enough for adopting free particle approximation. Thus it becomes convenient to describe the system as a gas of fermions - the fraction of which having momenta in the interval p and p+dp may be represented /64/ by

$$\frac{\delta n}{n} \propto \frac{p^2 dp}{\exp\left(\frac{p^2/2m - G}{T}\right) + 1} \tag{1.2.2}$$

where T may be referred to as nuclear temperature and has the dimension of energy. The expression for $\delta n/n$ may be reasonably approximated by considering Boltzman statistics also.

The predictions connected with the actual number of states in an energy interval i.e., the normalisation of level density depends on the detailed model used for the description and also on the parameters used /55, 65/.

The decay may proceed mainly by emission of particle or fragment leaving the nucleus in another state characterized by factors like level density, nuclear temperature etc. The isotropically emitted particles and fragments may affect the kinematical conditions (obeying conservation laws) of the residual nuclei.

The gross features of emission of particles and fragments from the highly excited system may be looked in a comprehensive manner as evaporation /66, 67/ from a heated, charged drop of liquid by introducing evaporation approximation /31, 55, 56/. However, other process(es) such as fission competing with particle evaporation may also appear at various stages of the decay.

There are a number of other models by which some of the features of the nucleus may be explained. Spheroidal-core model, superfluid model, nuclear vibron model, interacting boson and boson-fermion models are a few of them. There are some models which are based on many-body and nuclear matter approaches. There are occasions where models based on quark-structure have also been used.

Attempts have also been made to relate properties of individual nucleons with effective parameters of most of the established models, they are generally referred to as microscopic approach to nuclear structure.

In order to explain the observed features of the nucleus although various models have been adopted, it appears that the assumptions of the independent particle models are more nearly correct though the coupling among the nucleons by virtue of their mutual interactions and the frequently observed various collective effects can by no means be neglected. The observations during heavy ion collisions like the resamblance of gases passing through each other /68/, side-splash and bounce-off /69-71/, and the possible shock waves /72/ seem to support the gas-like and liquid-like behaviour of the nucleus as has been assumed in various models. It may, however, be observed that added interests have also been produced for involving the solid-like state of matter /73/ during investigations on the properties of the nucleus.

1.3. THE ARTIFICIAL DISINTEGRATION OF THE NUCLEUS :

All nuclei, stable or radioactive, may be excited by depositing energy using external agencies. Whenever such excitation energy becomes adequate, nuclei begin to emit particles and fragments in the act of releasing additional energy supplied to it and thus the artificial disintegration is caused. The products so obtained may be stable or radioactive. The higher the deposited energy, the more violent the reaction will be. The reactions may have a number of steps too. One may conveniently use particles, radiations and ions with appropriate energy to induce such reactions. Consequently particles may be produced, and disintegration of the nucleus may proceed through emission of fast and slower particles (and fragments) of the target.

At very low energies no particle is produced but with the increase of energy of the projectile the process of production of particles, mostly pions, begins and at high energy ($\sim$1 GeV) particles are produced quite abundantly. Strange particles are also produced. Almost all the produced particles normally leave the target in a forward cone with relativistic velocities (excluding a few instances of exception /71, 74/).

Emission of high energy target particles (kinetic energy interval about 30 MeV/n to about 400 MeV/n), constituted principally by fast nucleons, generally does not depend on produced pion /9, 75, 76/. These fast target particles are considerably anisotropic in the laboratory system. In the nucleus-nucleus collision events, to a first approximation, their emission may be considered as due to a composition of hadron-nucleus collisions /9, 12, 77/.

The relatively slower target particles and fragments (kinetic energy within about 30 MeV/n) are also not related to the number of created pions /9, 78-80/. The emission of these particles may be affected by various modes of excitations and deformations of the nucleus developed during the receipt of energy, and also on the kinematical conditions of the nucleus during the process of de-excitation /18, 58, 81-84/. Consequently their emission may proceed through various competing channels that may arise at any stage of de-excitation. In total, on the average, they are generally only marginally anisotropic in the laboratory system. Also, they are mostly responsible for producing the gross-features of the observed mass yield distributions.

It may however be observed that, in general, the numbers of the emitted charged fast target particles bear a correlation with the numbers of charged slow target particles and fragments /75, 80, 85-88/ except when very high energy is deposited to the target /88/. Again, for the disintegration of any target, induced by any projectile, there always exists a large difference in the average kinetic energies /89/ and a difference between the angular distributions /80/ of fast and slow target particles and fragments.

Typically in the low energy reactions, the product masses tend to consist of one or a few nucleons or cluster of a few number of nucleons and the mass of all the residual products are spread-over within just a few mass numbers less than that of the target. For heavy nuclei, fragments of mass approximately half that of the target are produced with appreciable cross-section which forms the "fission-peak". As the projectile energy is increased gradually, in general, the distributions broaden. The products from high energy reactions are well spread and all mass numbers lower than that of the target are formed with substantial yields /83, 90-97/; no clear-cut separation of products from various contributing processes can be made in the mass yield distribution. Though there may be certain changes in the individual details, the over-all mass yield curves obtained from the interaction of GeV protons are rather insensitive to the bombarding energies /98/. The observed distribution reaches a typical U shape and the cross-section of heavy fragments becomes approximately energy independent /99/. The distribution for particles and fragments of relatively lower mass may also be represented by power laws /100, 101/. The suffling and resuffling of the nucleons by the nucleus to produce the mass distribution is of considerable interest.

With the advent of machines capable of accelerating particles and heavy ions in the TeV energy range it will be interesting to see the "abnormal states of matter" and their impact on the process of suffling and resuffling of nucleons responsible for the mass yield distribution during the nuclear interactions.

The features shown by the nucleus are numerous. No single approach has been found to describe with desired degree of accuracy for the variety shown by the nucleus. Thus to study the high energy disintegrations also, a few basic considerations are normally made.

1.4. THE BASIC CONSIDERATIONS :

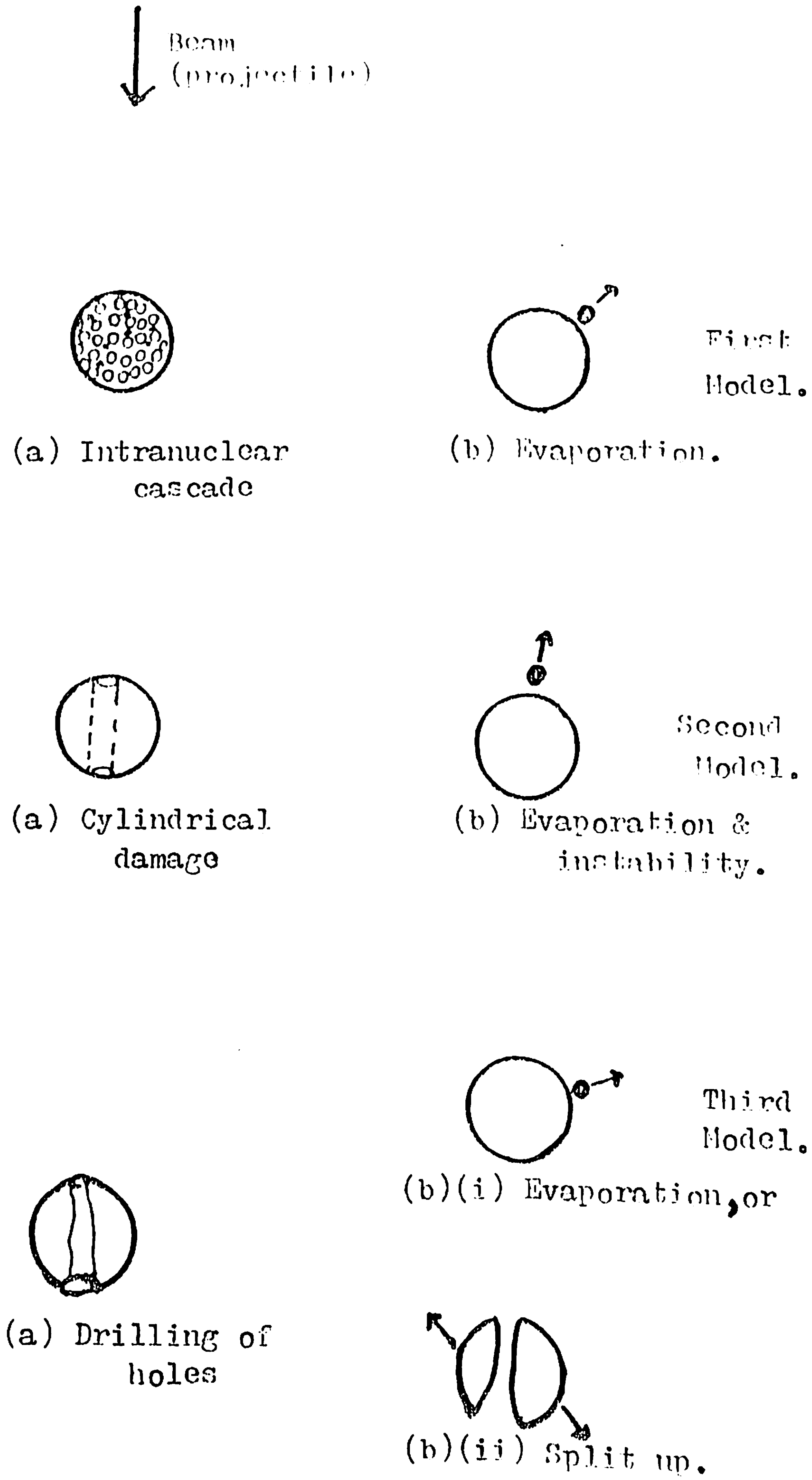
During high energy reactions various products including exotic nuclei are observed. These high energy interactions are capable of bringing out informations on the constituent nucleons and the nucleus as a whole. Further, one can study the developments inside the nucleus as it acquires high energy from the projectile. Although there is no sharp line of demarcation between a high energy and a low energy reaction, observations on particle production and the mass distribution of the disintegration products provide a basis for the demarcation. Thus all reactions induced by particles of kinetic energy of about 1 GeV and above may be called to be the high energy reactions.

Generally it is assumed that the reactions leading to the disintegration of nuclei proceed in two steps. Normally in the first step the target acquires energy and distributes it among the constituents in a fast process (10^{-22} sec.). The target nucleus may be "heated up". A few nucleons are also emitted in this process leaving the excited target with a variety of nucleonic compositions. In the second stage, usually a much slower process, the excited nucleus decays by emitting particles and fragments from it. As opined for the average evolution of large scale collective motion for a highly excited system /79/, the slower process may start even after the elapse of about 10^{-21} sec.

The basic features of a few of the approaches adopted to discuss the excitation and de-excitation process may be presented as follows (Fig. 1.1 shows the schematic representations):

In the intranuclear cascade process the positions and momenta of all the constituents are assumed to be known. The mean free path is assumed to be large enough to make the free particle approximation valid. The total collision cross-sections are calculated neglecting any possible phase relationship to previous and following collisions. The energy deposited to the target nucleus shows dependence on the number of nucleons removed in the process /51/.

Processes initiated by linear cascade produced by systems like "Leading particle systems" /53/ or "generons" /102/ or composite systems of "quarks and gluons" /9,



Here (a) represents the first stage
and (b) represents the subsequent stage.

Fig. 1.1 :- Models for nuclear disintegration.

88/ developed from the interaction of high energy incident particles with constituents of the target, may also be responsible for depositing energy at the target.

The de-excitation of the excited thermalised nucleus that remains after the emission of the fast particles is normally envisaged in a manner similar to that of the excited compound nucleus that figures in the Bohr's model for low energies. It is expected and is observed as well that the characteristics of some of the particles emitted in the high energy reactions are sensitive to parameters such as binding energy and Coulomb barriers, the values of which may to a certain extent depend on the excitation energy. They are the particles emitted in the process of evaporation - most likely in an evaporation cascade /103/. The statistical theory assumes independence of emission of such particles from each other. Competing processes, which may also appear during the decay, contribute to the observed mass yield /104/. Near independence of the mean kinetic energy of the emitted particles on energy as well as identity of the impinging particle /80, 89/ stands for a correlation between the number of emitted particles and the available excitation energy /105/.

Though there are a number of limitations, as the model can describe reasonably some of the basic experimental results /67, 106/, in general this two-step model involving intranuclear cascade for excitation and evaporation for de-excitation is taken as the predominant mechanism for describing high energy disintegrations.

In another approach /107, 108/ it is assumed that the high energy hadrons (or systems arising out of them) while passing through the target nucleus lose energy monotonously causing slow pions to appear around its course a like the appearance of electrons around the course of a fast charged particle while passing through material medium. It is suggested that the fast nucleons be treated as emission from few-nucleon systems which absorb slow pions. The most affected region may be the cylindrical volume with its centre coinciding with the path of the incident hadron /108, 109/.

It is assumed that on the walls of the cylindrical damages, caused as a results of emission of fast nucleons, the equilibrium forces acting on the nucleons are disturbed and subsequently nucleons may be evaporated from the walls. The decay of the locally destroyed and unstable residual targets into smaller stable fragments proceed probably due to unstable configuration /80, 108/. The energy lost by the projectile in the target nucleus may be assumed to be spent during fast nucleons emission and target fragment evaporation /108/.

In developing this model, the thickness of target material travelled by the incident hadron and the role of pions are considered to be important for production of fast nucleons /109/. Evaporation is often considered as an effect from the deformed surface. The collective effects, as may be envisaged from the liquid drop model, seems to be poorly understood.

In some of the other models it is assumed that the fast moving projectiles while drilling hole(s) through the nucleus, blows out some of the fast moving particles /18, 84/. As the wounds heal out, the excitation energy is distributed over the entire volume of the nucleus and forms the equilibrated (thermalised) system; the source of energy being the fast nucleons and the surface created by the wounds /18/. Consequently it decays by particle evaporation and competing processes. Occasionally the drilled nucleus may split-up into fragments due to Coulomb forces /84/ or due to a number of factors like internal strain, effect due to recoiling secondary nucleons, Coulomb repulsion and statistical evaporation /18, 110/.

Also, there are a number of other models developed to describe the high energy nuclear disintegration by involving mechanical or thermal or hydrodynamical or phase-transition considerations.

Although there may be some process(es) by which some of the target nuclei may disintegrate prior to thermalisation, conventionally a sequential decay of the target nucleus may be assumed /111/ to describe the general nature of the disintegration. The cascade-evaporation process along with the competing processes of heavy fragment emission seems to be a good starting point for studying the nuclear disintegrations.

For a system decaying under cascade-evaporation mechanism, unless otherwise affected by emission of extranuclear nucleons /58, 59/ or unstable (excited) nucleonic clusters /78, 111/, one expects a correlation between the numbers of fast and slow target particles (and fragments). Because, the higher the energy deposited, the higher will be the energy carried away by evaporated particles and consequently the lower will be the mass of the cascade-evaporation residue /112/.

Competing processes for emission of fragments may be broadly classified into four categories /18, 113, 114/.

(i) **Spallation :** It is a process in which nucleons and small clusters of nucleons are emitted; only one heavy fragment is observed. Such a heavy fragment may be obtained after a long chain of evaporation /18/. Some of them may not be a consequence of evaporation also /83, 115/.

(ii) **Fission :** It is a process which leads to emission of two heavy, almost oppositely directed fragments. Such a process mostly occur late in the de-excitation chain. On occasions such a division may occur in a fast process /84, 116/ but may be with a small cross-section /117/.

(iii) **Multifragmentation /18/ or Cracking /113, 114/ :** It is a process by which at least three fragments are produced almost simulteneously. Most of the produced fragments are expected to be heavy. It has been shown that some of the fragments may be of lower charges also /118/. Thus the conventional ternary and higher order fission events /119/ get classified as multifragmentation events.

(iv) **Vaporisation /113, 114/ :** All of the fragments produced in this process will be light. Such a process, may be like "explosive decay" /120/ also, may appear when excitation energy becomes as high or even higher than the total binding energy of the target nucleus /121/. The average number of fragments with $Z \geqslant 3$ per such event is shown to be about 0.55 /121/. Thus it is very probable that a good number of such events may not be associated with a heavy fragment.

The characterisation of a heavy fragment by its mass has originated from two different approaches.

The process of nucleosynthesis by accretion for such a small interval of time as applicable for high energy disintegrations may terminate for $A < 10$. So, the fragments with $A \geqslant 10$ have been taken as the disintegration products of the target and defined as the heavy fragments /18, 114/ in some of the investigations.

On the other hand it has been observed that the cross-section of heavy fragments produced at sufficiently high energies are approximately energy independent /99/. From the study of the mass yield curves, fragments with $A \gtrsim 20$ may be termed as heavy fragments /113/.

Here, however, a heavy fragment is defined by taking fragment mass number as $A \gtrsim 20$ by keeping it in conformity with mass yield curve studies and also keeping provisions to include most of the fragments obtained in multifragmentation process.

1.5. AIM AND IMPORTANCE OF THE PRESENT STUDY :

The investigations on the mechanism of interaction of high energy particles with complex nuclei like Cu, Br, Ag, Xe, Pb, U etc. have been carried out in various laboratories all over the world with a view to gaining precise knowledge over it. The process is extremely complicated and has many aspects. As such, better understanding of nuclear reactions is very much essential. Such reactions produce nuclei far off from the beta stability providing scope to study their structure and properties. These reactions are also capable of furnishing important insights into the structure of nucleus. One of the most important facts is that the behaviour of the nucleus to high energy projectiles is not well understood.

Cascade-evaporation model of high energy nuclear disintegration, though capable of producing a good account of emission of secondary particles with $Z \lesssim 3$, cannot satisfactorily account for all the characteristics of the emitted heavier nuclear fragments. One normally takes recourse to competing characteristic processes to explain production and emission of heavy fragments. This requires the knowledge of the process due to which a fragment may originate. At lower energies, the mass yield curve itself serves as an important guide line but the situation differs at high energies.

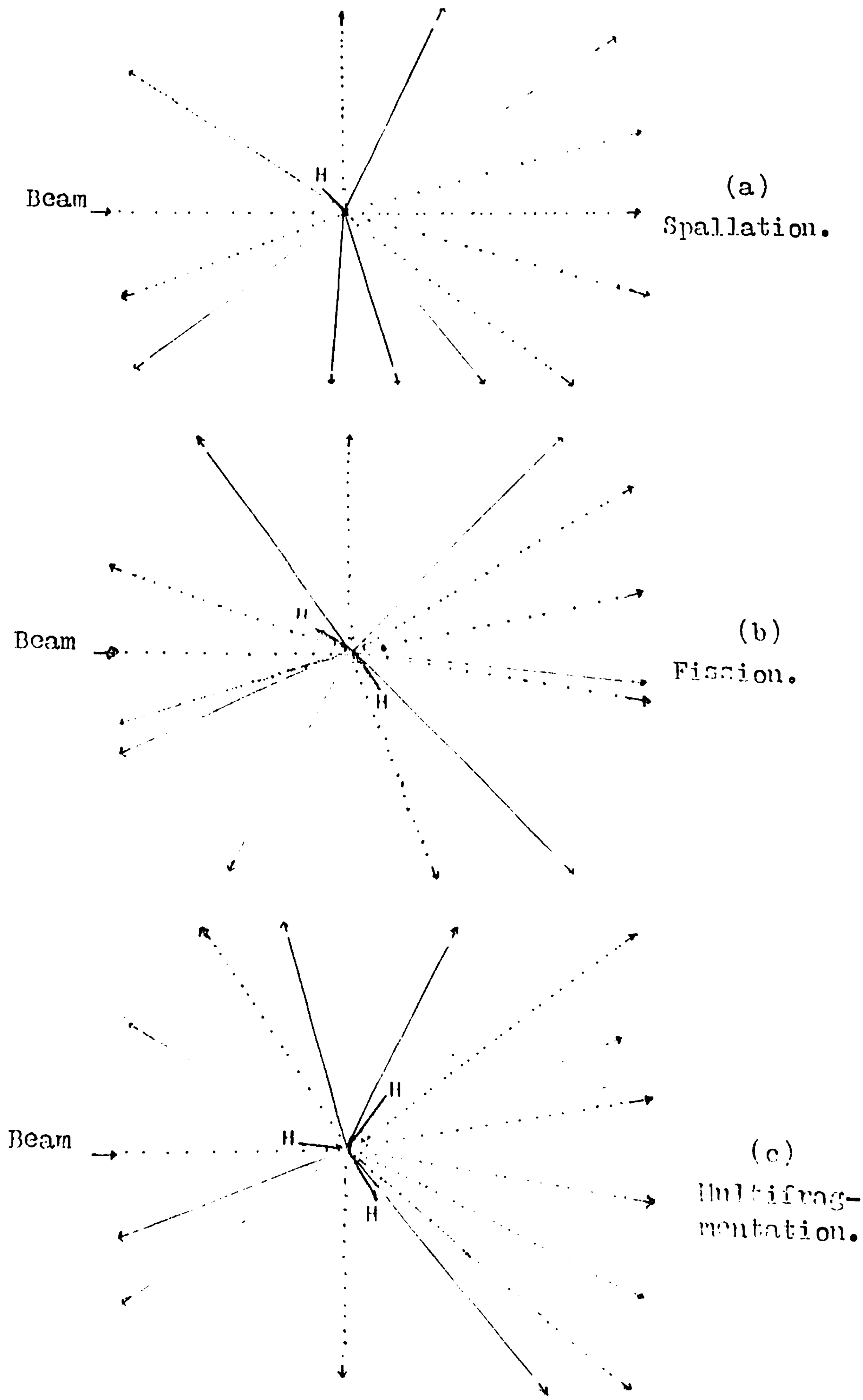
It has been shown /122/ that the mass yield curve from intermediate mass nuclei exposed to beams like 300-660 MeV protons is likely to produce a small "fission peak" at $Z \sim 20$. The lower mass product cross-section rises sharply with decreasing Z from about Z = 15, while for higher mass region it rises from about Z = 25.

One of the interesting features of the mass yield curve in the high energy (GeV proton region) interactions is the typical U shape and its over all insensitivity to the bombarding energy, eventhough there may be certain changes in the individual mass yield as may be evidenced by the charge dispersion curves and the shapes of the excitation functions of different nuclides. The individual yields near the "deep" of the mass yield curve cannot be explained as arising out of just a single mechanism of heavy fragment emission /98/. It will be interesting to identify at least some of the processes, those are likely to contribute to the products in the "deep" region.

As for the fragments of $A < 30$ while it has been arugued in some of the works /120/ that they might arise out of a single process like liquid-gas phase transition at the critical point, in some other work it has been opined that the emission may be a combination of a number of processes /111/.

While analyzing the charge distribution of projectile fragments /123/ for Ne^{22} it has been shown that the inclusive charge yield distribution of fragments may not be caused by a single process. It has also been commented that the mechanisms claiming one hot source at certain excitation energy for explaining the inclusive charge distribution is conflicting.

The aim of the present study is to investigate the emission of heavy fragments ($A \geq 20$) from silver and bromine nuclei during high energy interactions by using photonuclear emulsion. The photonuclear emulsion is a 4π detector with which tracks due to emitted charged fragments from a nuclear disintegration can be visualized. (Fig. 1.2 shows some of the schematic representations.) Thus it becomes convenient to discriminate various processes by which fragments are emitted. Using this detector already some of the systematic studies on spallation residues (RR) / 124/, fission events /125/ and multifragmentation in the form of ternary and higher order fission events



Here H represents the heavy fragments.

Fig. 1.2:- Schematic co-planer diagrams of some of the events observed in photonuclear emulsion.

/119, 126/ have been done. Reasonable studies have also been made /115, 127/ on some of the energetic heavy fragments producing short tracks (ST) in photonuclear emulsion; they are also considered as spallation products because the heavy fragment multiplicity has been found to be unity. From a correlated study of these types of events one may expect more information on emission of heavy fragments during high energy disintegrations.

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CHAPTER II

EXPERIMENTAL PROCEDURE AND TECHNIQUE OF MEASUREMENT

2.1. THE NUCLEAR RESEARCH EMULSION :

The nuclear particles (and fragments) are to tiny to be studied by observing them directly. However, they can very well be studied by their properties, behaviour and action on suitable detectors. The formation of 'track' along the path of an ionizing particle in appropiate medium is one of such properties. While detectors like scintillating fibres (glass or plastic) and imaging chambers or optical avalanches /1-3/ are designed to visualize tracks for an advantage of analysing complex and rare events obscured by background, some others like bubble chamber, streamer chamber, solid state nuclear track detector and nuclear emulsion derive most of the informations from the study of the tracks formed in them. In order to get more information with precision, like those on other detectors /4/, further studies on these track detectors are in progress for using them under improved techniques and methods /5, 6/. However, by now the tracks of some members of the nuclear family in detectors like nuclear emulsion, are almost familiar and readable at ease.

A photonuclear emulsion consists of myriads of crystals (grains) of silver halides (mostly bromides with a small admixture of iodide) having linear dimension between 0.1 to 1.0 microns embeded in gelatine. As the ionising particles pass through them, latent images in silver bromide grains are formed in a manner similar to that produced by ordinary light in photographic emulsion. The images, marking the tracks of the moving particles, are rendered visible by transforming the affected grains during development (sec. 2.3). After processing, the gelatine becomes transparent and the path of a charged particle through emulsion appears as a trail of minute dark grains (due to metalic silver) when viewed with an optical microscope. Thus the nuclear emulsion records the true three dimensional images of the path of the charged particles (tracks) moving through it. However, the characteristics of the individual tracks may differ from each other depending on the extent to which the silver halide grains are affected.

Following the discovery that the radioactive substances (1896) and also the alpha particles (1910) are capable of affecting photographic plates, tracks due to individual alpha particles were first recognised by Reinganum /7/. This method, with further modifications later on, received wide appreciations and applications due to constant efforts of a number of workers - Powell, Occhialini, Blau, Demers, Yagoda, Barkas, Myssovsky, Perfilov /8/ are only a few of them.

Most of the nuclear emulsions, like G-5, K-5 etc. have very similar composition. The average chemical composition of standard emulsion at 58 per cent humidity and normal room temperature (20°C) is shown in table 2.1.

Table 2.1 Composition of standard (G-5, K-5 etc.) emulsion.

Element	No. of atoms/mol. x 10^{22}	Geometrical mean free path (cm.)	Probability of interaction with different nuclei (per cent)
$Ag^{107.9}$	1.04	70.9	38.0
$Br^{79.8}$	1.03	87.1	31.0
O^{16}	0.96	269	12.0
N^{14}	0.39	876	3.1
C^{12}	1.41	224	10.0
H^{1}	3.15	495	5.5
$I^{126.9}$	5.7×10^{-3}	1.16×10^{4}	0.2
$S^{32.1}$	13.5×10^{-3}	1.16×10^{4}	0.2

The geometrical mean free path /9/ for interaction with each element of emulsion and the corresponding relative probability has also shown in the table 2.1. The estimated values shown in the table may, however, differ marginally from the actual experimental values for particular samples of emulsion.

Due to the small size of the developed grains, the nuclear research emulsion has very high degree of angular and spatial resolutions. Because of the high stopping power of emulsion (about 1800 times that of air), it becomes very compact and useful to study most of the unstable particles like hyperons and charmed particles /10/. Emulsion may also be used to measure time interval as small as 10^{-16} sec. /11/. Some of the properties of the particles and fragments may also be studied safely by using external agencies like strong magnetic field /12/. The nuclear emulsion is relatively simple, less expensive, light weighted, clean and convenient device for detection and qualitative analysis of the disintegration products of a nuclear reaction in a small volume. Despite all these remarkable merits the nuclear emulsion has certain limitations also. For example, its composition cannot be changed arbitrarily, and consequently it becomes impossible to distinguish the target nucleus of individual interactions, although a statistical separation among them is possible. Loaded (with specific nuclei) and enriched emulsions are also in use but with limited success /13/. Also, emulsion cannot be used by keeping it in a very elevated temperature or in very low pressure (near vacuum). It is damaged by exposure to light or in contact with active metals like aluminium.

The special characteristics of emulsion technique have made it very convenient for collaboration of high energy research works. The events obtained in nuclear emulsion pellicles from the irrediations made with accelarating machines or in rocket flights or in balloons may be analysed almost simulteneously in laboratories situated far apert.

Also, the events may be scrutinized after a long interval of time, if necessary.

2.2. EMULSION STACKS AND THEIR EXPOSURES :

Two stacks of photonuclear emulsion one exposed to 1.8 GeV/c K^- beams at AGS machine (Brookhaven), and the other to 20 GeV/c p beams at CERN, are used in this investigation. Professor A. J. Herz of CERN (Geneva) was kind to send 60 pellicles of K-5 emulsion, measuring 20x10x0.06 cm^3 each, exposed to K^- beams of total intensity about 2×10^5 K^- per cm^2 with a large pion contamination ($K^-/\pi^- \sim 1$) arising out of one stage separation of the beam /14/. The 4 pellicles of G-5 emulsion, measuring 15x10x0.06 cm^3 each, exposed to proton beams of total intensity about 5×10^4 protons per cm^2/15/, were kindly sent by Dr. G. Vanderhaeghe and professor A. J. Herz.

2.3. PROCESSING OF NUCLEAR EMULSION :

Emulsions used to record cosmic ray and high energy nuclear events have larger thickness and higher concentration of silver halides than in photographic films. For precise works, as the development of the pellicles should be uniform with minimum distortion, it becomes very essential not only to develop the exposed materials by refined processes but also to take special care at every stage of such works /16/. Further, the entire stack of emulsion should be developed uniformly so that long tracks due to energetic particles travelling at an angle to the plane (surface) of emulsion can be followed from plate to plate.

The general photographic processes such as development, stopping, fixing, washing and drying are to be carried out for nuclear emulsions also. The difficulties faced for development to thick emulsions with high concentration of silver halides may be removed by adopting the temperature cycle method.

The principle of this technique is based on the fact that a developer, such as amidol, is chemically inactive at a low temperature (about 4° -5°C). The plates are soaked in cold developer solution until diffusion in emulsion is completed. The plates are then removed from the solution to the required temperature in a "hot bath". At this stage development proceeds rapidly. After necessary development, the plates are immerged in a "stop bath" consisting of a 0.5 per cent aqueous solution of acetic acid at about 5°C, which stops further developments. The fixation is done by maintaining a slow flow of fixing solution over the horizentally placed plates in a "fixing bath" kept at a temperature below 10°C. After the plates are "cleaned" a slow flow of water replaces the fixing solution just to dilute it. The plates are thus washed to remove all fixing reagents.

The plates are then soaked in a solution of glycerine of strength 2 to 5 percent and dried in order to avoid stripping off of dried emulsion from glass. The final drying is generally carried out by placing the plate horizentally in a gentle current of air. Alternatively, a concentration of alcohol is gradually built-up in the final water glycerine bath until it reaches about 90 percent of alcohol, 4 percent of glycerine and 6 percent of water. The alcohol tends to harden the gelatine and removes water so that the final drying takes place very rapidly.

2.4. CALIBRATION OF THE STACK :

2.4A. Shrinkage factor :

During the processing of emulsion, its original volume is considerably reduced as the silver halide crystals are dissolved by fixer. The ratio of emulsion thickness before and after processing is called the shrinkage factor (S). This determines the ralationship between the geometrical conditions during exposure and during observations.

The shrinkage factor is generally determined from measurements of the alpha particle ranges /17/ i.e., length of the alpha particle tracks from stars of a particular source. The ranges of the longer and flat alpha tracks are first measured in order to obtain the actual range (R). Then measuring the projected range (P) of steep tracks along with the difference of depth at the end points i.e., dip (d), and repeating the procedure for all possible dip values, the shrinkage factor can be calculated out by using the relation.

$$R^2 = P^2 + S^2 d^2 \qquad (2.4.1)$$

The shrinkage factor varies from plate to plate and also at different points of the same plate. Hence, it should be determined at various positions of the emulsion where events are recorded. In the present investigation the average value of S is found to be nearly 2.4 for both of the emulsion stacks. To get the actual dip, the observed (measured)dip should be multiplied by this value.

2.4B. Stopping power :

The stopping power (K), or relative stopping power is defined as the ratio of the range of a muon in standard emulsion to that in the emulsion under observation. This value depends upon the composition of the emulsion material and the moisture content at the time of exposure. It is essential for determining the energy of a particle from the observed range.

In order to determine the stopping power, a few flat muon tracks, obtained in the pellicles from decay of pions, have been selected and ranges are measured. The average range in the K^- stack is found to be about 605 ± 3 microns while that in the p stack is about 603 ± 3 microns. From the UCRL range-energy relation /18/, the mean range of a muon of energy 4.12 MeV in standard emulsion is found to be about 600.5±3 microns. Therefore the relative stopping powers are

$$\text{for } K^- \text{ stack, } K_1 = \frac{600.5}{605} = 0.993 \pm 0.001 \qquad (2.4.2)$$

$$\text{for p stack, } K_2 = \frac{600.5}{603} = 0.996 \pm 0.001$$

In estimating energy from the ranges by using UCRL range-energy relations /18/, the observed range should be multiplied by this value.

2.5. TECHNIQUE OF MEASUREMENTS :

2.5A. Ionisation measurements :

The grain density (g), which is the number of developed grains per unit length along the track corresponding to a particular value of specific ionisation depends on factors like charge, mass, velocity of the particle, and also the degree of development of the emulsion.

The grain density of a track can be determined directly by counting the number of developed grains in a measured length of the track. But when the grain density of a track is large enough, two or more adjacent grains form 'blobs' - the individual grains of which cannot be resolved by the microscope. In such cases, the blobs are counted and converted /19/ to grain density g by the relation.

$$H = Be^{-gl} \qquad (2.5.1)$$

where B = blob density, H = gap density, 'l' is the gap length between two neighbouring developed blobs and its value is adjusted in such a way that the value of H is approximately equal to B/4. The true length l of a gap is related /20/ to the observed length l_o by the relation.

$$l = l_o \sec\delta \qquad (2.5.2)$$

where δ is the dip angle in unprocessed emulsion. The dip angle may be obtained by measuring the dip d for the projected length l_o from the relation

$$\delta = \tan^{-1}\left(\frac{S.d}{l_o}\right) \qquad (2.5.3)$$

where S is the shrinkage factor.

The measured grain density g is normalised with respect to the grain density g_o of a minimum ionising track. The normalised grain density given by

$$g^* = \frac{g}{g_o} \qquad (2.5.4)$$

is independent of the degree of development and the type of emulsion used.

The grain density (g_o) is determined from the observed blob density (b_o) by using /21/ the relation

$$b_o = g_o e^{-g_o \alpha} \qquad (2.5.5)$$

where α is a parameter that depends on the developed grain size, optical resolution of the microscope and the observer.

2.5B. **Measurement of range :**

The range of a particle is taken to be the distance along the trajectory from its point of origin to the last developed grain.

The range of a particle can be determined by measuring the projected range (P) parallel to the surface of emulsion with the help of a micrometer eye piece (or an eye-piece graticule) without parallex and the dip (d) by the dip-screw(or Z-Screw).

If the track is straight and projected range is less than the diameter of the field of view, direct measurements may be done. A long or a curved track may be devided into appropiate number of segments, straight enough for measurements. Distinctive features on the tracks may be used as fiducial marks and the microscope stage may be moved as and when necessary.

From the measured values of P, d and shrinkage factor S, the range R may be determined by the equation (2.4.1) or by

$$R = P \sec \delta \qquad (2.5.6)$$

where $\delta = \tan^{-1} \left(\frac{S.\, d}{P} \right)$ is the dip angle.

For the long or curved track, however, the range may be obtained by adding the various "R" values obtained for the various segments.

Factors like (i) uncertainity in the determination of origin of the tracks, (ii) distortion of emulsion, and (iii) range straggling may introduce errors in range measurements.

2.5C. Measurement of angles ; Direction of emission :

The space angle θ between two tracks, with a common centre in emulsion, having dip angles δ_1 and δ_2 respectively and projected angle ϕ (measured with an eye-piece goniometer) between them is given by

$$\cos \theta = \cos \phi \cos \delta_1 \cos \delta_2 + \sin \delta_1 \sin \delta_2 \qquad (2.5.7)$$

An uncertainity in determining the true angle may be introduced by the factors like (i) distortion of emulsion, (ii) uncertainity in the direction of tracks due to multiple Coulomb scattering, and (iii) observational error which depends on how accurately the eye-piece cross-wire has been placed along the track of finite width.

The errors, however, may be reduced to certain extent by limiting observations to only flat (lying in the plane of one vision) tracks.

The space angle between the tracks can be determined by the method of steriographic projection also, using a chart called 6-B circle. The method is rapid one and requires the knowledge of projected angle between two tracks and their corresponding dip angle. The angle so measured is expressed in degrees.

The direction of emission of a particle (or fragment) is determined by measuring the angle θ with respect to the direction of incidence of the primary (projectile). In principle, corresponding to the positive or the negative values of cosθ, the particles should be taken to be emitted in the forward hemisphere, briefly, "forward" or backward hemisphere, briefly, "backward" respectively. However, because of the uncertainity in the angular measurements the following convention, as shown in table 2.2, has been adopted.

Table 2.2 : Convention used for ascertaining direction.

Direction	Cosθ values			
	when only flat tracks are considered		when steep tracks are also considered	
	From	To	From	To
Forward	+ 0.1	+ 1.0	+ 0.2	+ 1.0
Backward	- 0.1	- 1.0	- 0.2	- 1.0
Perpendicular (uncertain) direction	- 0.1	+ 0.1	- 0.2	+ 0.2

2.6. IDENTIFICATION OF CHARGED PARTICLES :

Generally a particle is said to be identified if the charge Z and mass M are known precisely. The characteristics of the tracks of a particle depend on its charge, mass, velocity and interaction behaviour. So, a particle can be identified from the microscopic examination of the track left by it. Neutral particles cannot be registrared in the emulsion as they do not have electrical charge to cause ionisation. They can be detected by secondary processes or by their decay into charged particles. Unstable particles can be recognised by studying their decay also. The different features of particle identification by observation on their track characteristics are summerised as follows :

2.6A. Determination of charge :

The following methods can be applied for determination of charge of a particle stopping in emulsion.

2.6A1. Delta ray counting :

When a particle of mass M (in units of mass of proton), charge Z (in units of electronic charge) and velocity β (in units of c, the velocity of light) passes through a material medium, its electrical field disturbs the atomic electrons. These interactions constitute collisions of varying energy transfer in which the kinetic energy of the particle is dissipated. The energetic electrons, generally knocked out of the atoms in such an encounter, may cause secondary ionisation producing short, thin tracks projecting from the trajectory of the primary particles. The production of such secondary tracks, known as "delta rays", depends on the charge and velocity of the primary particle. For similar velocities the maximum frequency of delta rays n(1) and n(2) of two particles of charges Z_1 and Z_2 respectively may be related by the equation

$$\frac{n\,(1)}{n\,(2)} = \frac{Z_1^2}{Z_2^2} \qquad (2.6.1)$$

From this relation the charge of an unknown particle can be estimated by counting delta rays produced on the track and also on the tracks of particles of known charge. To obtain the maximum value of n(2), all the delta-rays longer than a cut-off value are to be counted in equal interval of ranges along the track of the particle of unknown charge Z_2. This value of n(2) may then be compared with n (1) observed in the same way on tracks of particles of known charge Z_1 and from relation (2.6.1) the value of Z_2 can be found out. Thus the observation of maximum delta ray density is one of the best parameter for determination of charge of the particles. The experimental values show /22/ that the maximum delta-ray density is observed at particle velocity β = 0.2 (approx).

The advantage of this method lie in the fact that an accurate delta ray count over a great length of track is not required and that it is applicable to fragments of velocity greater than 0.14c the tracks of which must lie completely in emulsion. In many cases this method serves as an useful check-up on the charge values determined by other method(s) /23/.

2.6A2. **Tapering length measurements :**

For a stripped, highly charged nucleus moving initially with very high velocity the ionisation increases gradually and attains a maximum value as the velocity of the particle (nucleus) decreases to a value close to that of the first orbital electron. As it slows down further, the loss of charge (due to capture of orbital electrons) result in a decrease in ionisation and the track begins to "thin-down" /23/. Since the process of thin-down or tapering starts by capturing a K-electron /24/, the velocity of which is proportional to Z, the thin down length should be a function of Z of the particle. The features of capture and loss become more pronounced for particles of higher charge.

The relation between the thin-down length L (in microns) and charge Z as obtained in different investigations are shown below :

$$L = 0.5\,Z^2 \qquad /25/$$

$$L = 0.7\,Z^2 \qquad /23/ \qquad (2.6.2)$$

$$L = 10.0\,Z \qquad /26/$$

$$L = 4.7Z\,[\,1+0.33\,\ln(Z-2)\,] \quad \text{for } Z > 2 \qquad /27/$$

Nakagawa et al /28/ have drawn experimental curves showing the thin-down length in G-5 emulsion against charge of particles ($Z > 2$).

The difficulties in measurement of L comes mainly from the confusion arising out of the projected delta-rays. The frictional force may also cause a change in the effective charge which in turn may affect the observed tapering to a certain extent.

However, the value of Z cannot be obtained by this method unless L is completely measured. Thus the method cannot be applied for low energy heavy particles.

2.6A3. **Profile measurements :**

For high velocity particles, when the ionisation is very low, most of the informations can be obtained by grain counting or blob counting method. But at lower velocities the grain counting is impossible. It is the thickness of the tracks which gives useful information. When the track is very short i.e., less than about 100 microns, no other measurement is possible except the average width of the track which depend on Z.

Nakagawa et al /28/, from measurements in G-5 emulsion, have shown that the average width W of a track is approximately proportional to Z. Hence the unknown charge Z_2 of a particle of average track width W_2 can be estimated by knowing the average track width W_1 of a particle of known charge Z_1 from the relation

$$Z_2 = \frac{W_2^2}{W_1^2} \cdot Z_1 \qquad (2.6.3)$$

The method seems to be applicable for tracks near the maximum of their widths.

There has been a few investigations on the formation of tracks which shows dependance of track structure on Z and β of the particle concerned /29-31/ and also on exposure temperature /32/.

Further experimental investigations on dependence of W on Z and β of slow heavy ions /6, 33-35/ of Z greater than 4 show a linear dependence /36/ of W on Z/β for β greater than 0.3. For heavy ions of velocity less than 0.3c, particularly for electron sensitive nuclear emulsions, it has been shown that

$$W \propto Z_e \beta \quad (\beta \text{ from } 0.07 \text{ to } 0.25, \; Z \text{ from } 5 \text{ to } 26) \qquad /34/$$

$$W \propto Z_e^{2/3} \beta^{5/3} \quad (\beta \text{ from } 0.05 \text{ to } 0.13, \; Z \text{ from } 6 \text{ to } 18) \qquad /33/$$

where Z_e represents the effective charge /37/ of the particle at velocity β.

Ogura et al /6/ has shown that the relation between W and Z_e is

$$W \text{ (in microns)} = 8.6 \left(Z_e^{2/3} \beta^{5/3}\right) + 0.72 \tag{2.6.4}$$

(for Z from 6 to 26

β from 0.05 to 0.13)

where Z_e is given by /37/

$$Z_e = Z\left[1 - \exp\left(-125\,\beta / Z^{2/3}\right)\right] \tag{2.6.5}$$

For steep tracks, the actual width may be obtained from the observed width by fitting appropiate polynomials /38/, which can be obtained from the measurements on the widths of the known tracks.

The factors like development, sensitivity of emulsion, straggling and distortion may often lead to large deviations and irregularities thereby impending the exact measurements.

However, it may be observed that the track width of a highly charged particle systematically decrease to a residual range of about 10 microns, during which the nature of dependance on Z may also change. Below a residual range of 10 microns the track width may principally be governed by the developed grain size of the emulsion.

2.6B. Determination of mass :

The mass of a particle stopped in emulsion can be determined by the following methods.

2.6B1. Grain-density and range measurements :

The ranges of two particles of the same charge and velocity are proportional to their masses. Since ionisation is a function of charge and velocity, the mass ratio of the two particles showing same grain density may be obtained from the ratio of their residual ranges. A series of determination can be made for ratio of residual ranges of the two particles for same grain density by drawing curves of normalised grain densities against residual ranges /39/. The mean value gives a measure of the ratio of their masses. Knowing the mass of one, the mass of the other particle can be determined. Similarly, determination may be attempted by gap-count plots also /23/.

The method proves to be useful for particles of lower Z values. For particles of higher Z values the plots and consequently the estimations are extremely difficult /23/.

2.6B2. Scattering and range measurements :

The scattering of a particle passing through a medium is a function of its charge, velocity and mass, and provides useful information for estimations of mass /40, 41/. By comparing the scattering observed in the tracks of two particles of same range, the ratio of their masses can be determined. The constant sagitta scattering measurements /42, 43/ can be used for this purpose. The Coulomb scattering are measured from the end of the range of a stopped particle by the use of calculated cell size, available in tabular form for protons and pions /43, 44/, and hence the scattering parameter of the unknown particle is determined. The mass of the unknown particle is determined from the relation

$$\frac{M}{M_p} = \left(\frac{d_p}{d}\right)^{2.31} \tag{2.6.6}$$

where M and M_p are the masses of the unknown particle and proton respectively, and d and d_p are the corresponding noise corrected sagitta.

For a fragment of charge Z the following modified equation is used :

$$\frac{M}{M_p} = \left(\frac{d_p}{d}\right)^{2.31} Z^{-0.36} \tag{2.6.7}$$

2.6B3. Scattering and grain density measurements :

It has been shown /41, 45/ that some of the properties, like mass, of a particle can be determined by an inspection of grain-density and multiple Coulomb scattering observed in the tracks caused by the passage of these charged particles.

The ratio of the scattering parameters for two particles of unit charge producing the same grain density is inversely proportional to the ratio of their masses. Therefore, from the plots of grain density (or blob density) versus scattering parameters /45/ for two (or more) particles, the ratio(s) of the scattering parameters corresponding to same value of grain density may be obtained. From the mean of the ratios obtained for different values of grain density, knowing the mass of one of the particles, the mass of the other(s) can be found out.

2.7. DETERMINATION OF ENERGY AND VELOCITY FROM THE OBSERVED RANGE:

The energy of a particles can be obtained from the observed range by using cell size, available in tabular form for protons and pions /43, 44/, and hence the scattering parameter of the unknown particle is determined. The mass of the unknown particle is determined from the relation

$$\frac{M}{M_p} = \left(\frac{d_p}{d}\right)^{2.31} \quad (2.6.6)$$

where M and M_p are the masses of the unknown particle and proton respectively, and d and d_p are the corresponding noise corrected sagitta.

For a fragment of charge Z the following modified equation is used :

$$\frac{M}{M_p} = \left(\frac{d_p}{d}\right)^{2.31} Z^{-0.36} \quad (2.6.7)$$

2.6B3. **Scattering and grain density measurements :**

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2.7. DETERMINATION OF ENERGY AND VELOCITY FROM THE OBSERVED RANGE:

The energy of a particles can be obtained from the observed range by using the range energy relations /44, 46/. The relation between range R (in microns) and energy E (in MeV) of a heavy nucleus of charge Z (in unit of charge of a proton) and mass M (in unit of mass of a proton) is given /47/ by the relation.

$$E = 0.251\ Z^2 M^{0.419} R^{0.581} \qquad (2.7.1)$$

This relation, however, does not hold good at very low energy. In stead of it, the range energy data and curves /18, 48-51/ are more reliable.

In the present investigation the range energy curves and data published by Berkeley group /18/ for different particles and suggested extensions thereon, have been used for determining the energy of a particle from its observed range. For particles of charge upto 9, Wilkins curves /49/ - normalised to G-5 emulsion, are occasionally used. The range energy data of Heckman et al /50/ have often been used to estimate energies of heavy fragments upto mass number A 40. For slow and heavier particles of A greater than 30, the range momenta data of Lou et al /51/ are used.

The velocity β (velocity of light c as unity) of a charged particle at different points in the trajectory can be deduced from the range energy relations. For small values of β , the velocity can be deduced from the Newtonian expression for kinetic energy with an error less than about 3 per cent /52/. Thus

$$\beta \quad \left(\frac{2E}{M}\right)^{1/2} \qquad (2.7.2)$$

where both of E (the kinetic energy) and M (the mass of the particle) are expressed in MeV.

Figs. 2.1(a), (b), and (c) shows some of the range velocity curves derived from references /50/, /51/ and /18/ respectively.

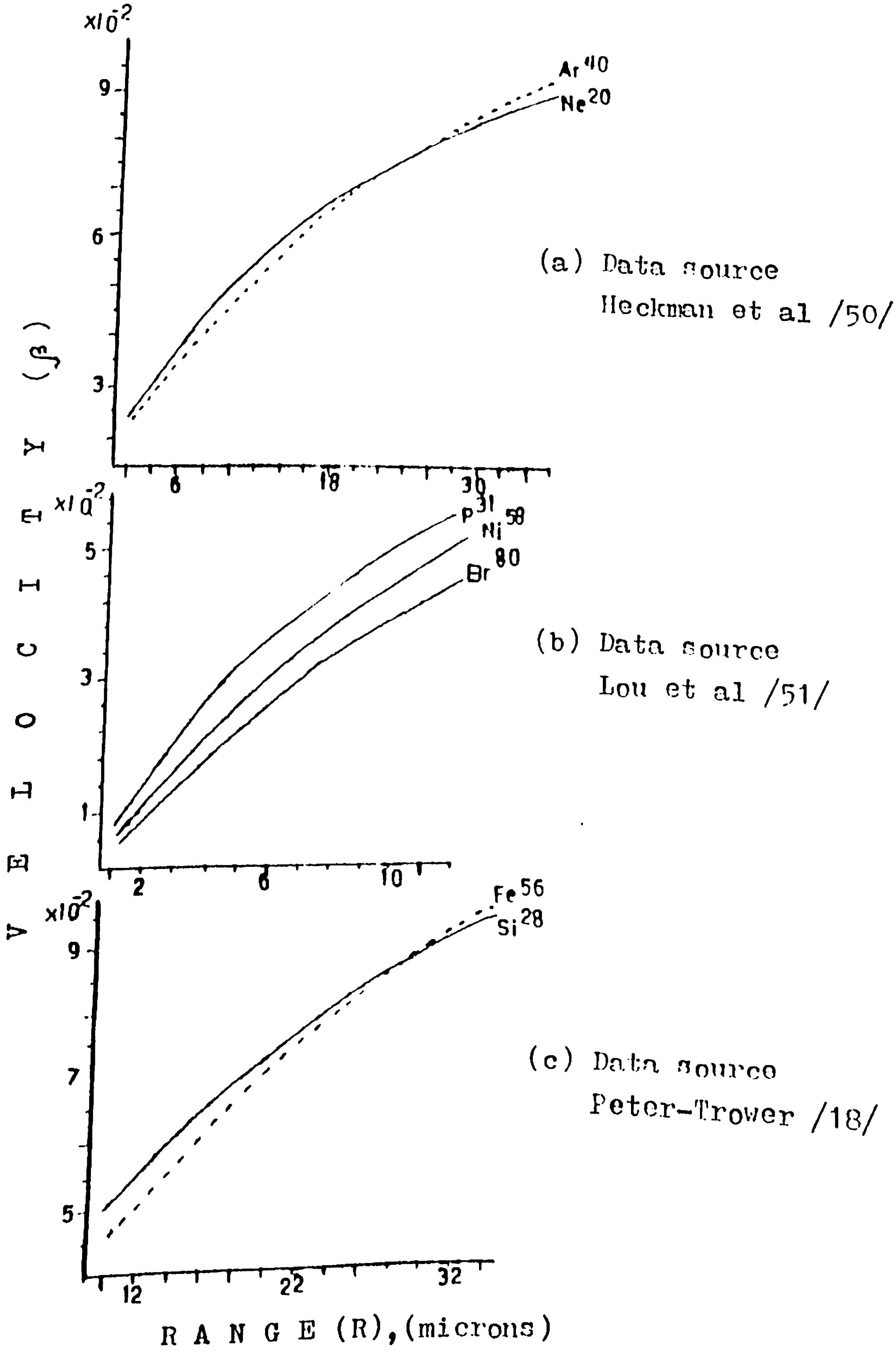

FIG. 2.1:- Some of the range-velocity curves.

2.8. SCANNING OF EMULSION PLATES :

Suitably cut emulsion pellicles are examined under high power microscope to scan for events of interest. There are two methods of scanning, viz (i) along the track i.e., line scanning, and (ii) volume or area scanning.

For along the track scanning, a particular track of the projectile (primary) is picked up at the point of entrance and followed through the pellicle(s). This method, though very slow, is almost unbiased in collection of various types of events.

In area scanning method, every piece of the emulsion pellicle is examined for the desired events. The events are generally recorded from the coordinates available on the glass surface of the pellicles.

Here, in this investigation, the area scanning method has been adopted.

2.9. CORRECTION FOR LOSS OF EVENTS :

The corrections necessary for some factors, which are responsible for the loss of events actually searched for, are discussed below.

2.9A. Scanning efficiency :

The area scanned data requires correction for observational biasness by estimating an efficiency factor for individual scanner. Assuming that the events missed are purely random, various types of efficiency factor can be calculated as follows :

To get the correct number of total events, the same sample is scanned by two observers A and B with efficiency F_A and F_B respectively. Let N be the total number of events present in the sample. Then

events observed by both A and B $= n_1 = NF_AF_B$

additional events observed by A alone $n_2 = NF_A - n_1$

$= NF_A (1-F_B)$

additional events observed by B alone $= n_3 = NF_B(1-F_A)$

Thus

$$F_A = \frac{n_1}{(n_1 + n_3)} \qquad (2.8.1)$$

$$F_B = \frac{n_1}{(n_1 + n_2)}$$

and

$$N = \frac{(n_1 + n_2)(n_1 + n_3)}{n_1} \qquad (2.8.2)$$

The total efficiency F, with which the area is scanned by the two independent observers, is given by

$$F = F_A + F_B - F_A F_B$$

In practise the scanners tend to miss similar type of events, specially events with small number of prongs. For a particular scanner, however, the efficiency is assumed to be constant though may slightly be affected by prolonged working with the microscope. The variations of scanning efficiency with the number of heavily ionizing prongs N_h (as defined in section 3.3), as obtained in this investigation, have been presented in Fig. 2.2. The average efficiency of scanning, for each of the two stacks, has been found to be about 97 percent.

2.9B. Loss of events due to dip angle limitations :

While working with a microscope, it has been observed that the tracks of very short range lying almost perpendicular to the surface of emulsion i.e., lying

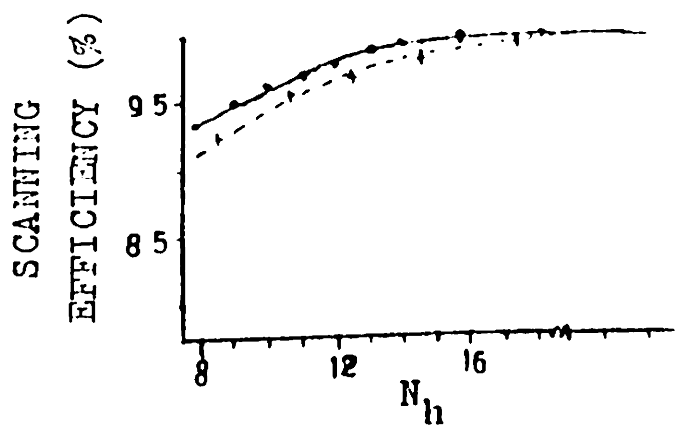

FIG. 2.2:- N_h-scanning efficiency plot.

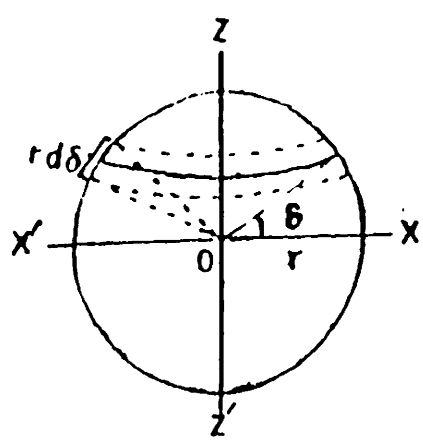

FIG 2.3:- Sphere of visualisation (for volume correction).

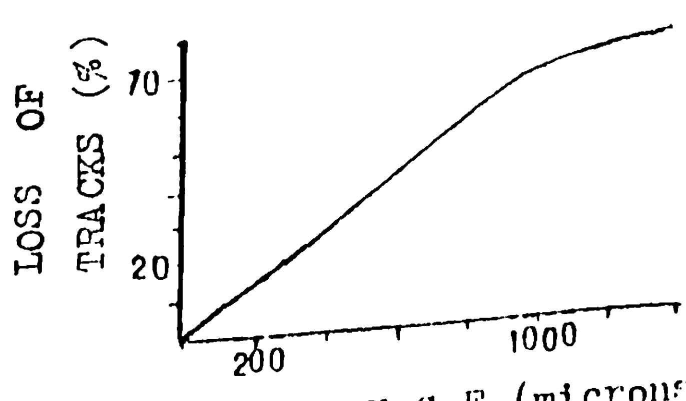

FIG. 2.4:- Fractional loss of tracks with range.

additional events observed by A alone $= n_2 = NF_A - n_1$

$= NF_A(1-F_B)$

additional events observed by B alone $= n_3 = NF_B(1-F_A)$

Thus

$$F_A = \frac{n_1}{(n_1 + n_3)} \tag{2.8.1}$$

$$F_B = \frac{n_1}{(n_1 + n_2)}$$

and

$$N = \frac{(n_1 + n_2)(n_1 + n_3)}{n_1} \tag{2.8.2}$$

The total efficiency F, with which the area is scanned by the two independent observers, is given by

$$F = F_A + F_B - F_A F_B$$

In practise the scanners tend to miss similar type of events, specially events with small number of prongs. For a particular scanner, however, the efficiency is assumed to be constant though may slightly be affected by prolonged working with the microscope. The variations of scanning efficiency with the number of heavily ionizing prongs N_h (as defined in section 3.3), as obtained in this investigation, have been presented in Fig. 2.2. The average efficiency of scanning, for each of the two stacks, has been found to be about 97 percent.

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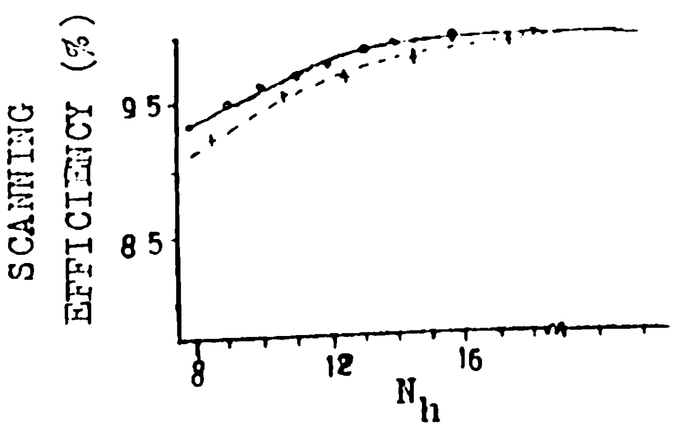

FIG. 2.2:- N_h-scanning efficiency plot.

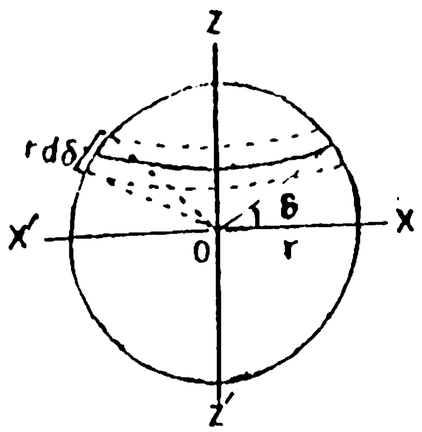

FIG 2.3:- Sphere of visualisation (for volume correction).

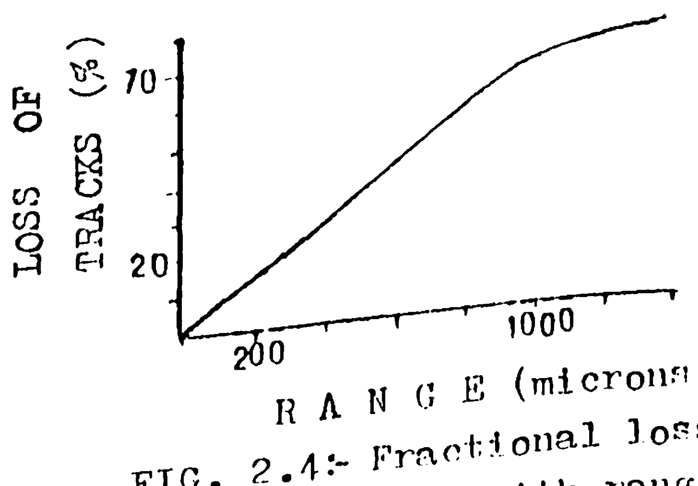

FIG. 2.4:- Fractional loss of tracks with range.

along the axis of vision, cannot be distinguished from blobs. Further, the core of steep tracks cannot be visualized without ambiguity due to shrinkage of emulsion along the said axis. Thus often it becomes near impossible to identify tracks (due to events) lying with a large dip angle. These impose limitations and necessiate restrictions on observation of steep (inclined) tracks.

For correction of frequency of events due to dip angle limitations and restrictions, the following geometrical consideration is adopted :

Fig. 2.3 shows a sectional (vertical) diagram of a sphere of radius r, the centre of which is taken to correspond the location of the disintegrating target nucleus. The elementary surface of thickness $rd\delta$ and area $2\pi r^2 \cos\delta \, d\delta$ subtends a solid angle $2\pi\cos\delta \cdot d\delta$ at the centre. By limiting the dip angle upto δ for observation, one examines tracks from a dip angle $-\delta$ (angle OZ′ axis) to $+\delta$ (along OZ axis). The fraction of solid angle so observed becomes equal to $\sin\delta$. For a frequency of N_1 observed events, indentified by a minimum number of n isotropically emitted tracks, the corrected number N becomes

$$N = \frac{N_1}{\text{Sin}^n \delta} \tag{2.8.3}$$

From the principle of addition vectors /53/, for a disintegrating nucleus moving with an average forward velocity, one expects that the average number of particles emitted isotropically by it along the two diametrically opposite cones will be independent of the diameter choosen. Thus the relation (2.8.3) will be applicable for such systems also. This is evidenced by the near constancy of the F/B ratio /54/ of fragments, obtained from 2π and 4π measurements. (Further discussions are given in the Appendix).

2.9C. Loss of events due to tracks leaving the emulsion Sheets :

The loss of tracks due to the escape of particles from the emulsion pellicles has been estimated from geometrical considerations of each emulsion sheet. The percentage of loss of tracks of various range groups has been calculated by taking account of their origin and orientations with respect to the emulsion surfaces, the thickness of each of the superimposed emulsion pellicles being 600 microns. Then the average percentages for loss of the tracks were calculated. Such fractional losses of particles of varying ranges have been plotted in Fig. 2.4.

Ascribing proper statistical weight to each track one may, in principle, correct for both energy and angular distribution of the emitted particles. Ofcourse, this can be done in the part of the distribution where statistics is large. Corrections introduced in this way in the part of the distribution where the statistics is poor, is likely to increase fluctuations strongly.

Moreover, this investigation is carried out leaving aside 25 microns of processed emulsion from the either surfaces of the pellicles. This, together with the dip angle restrictions, provides information that no correction is necessary for loss of events due to loss of tracks of range 69 microns. In the present investigation it will be seen that the vast majority of the tracks of our interest have ranges less than 69 microns. Therefore, in the present investigation, this correction is considered to be essential only for understanding the nature of loss of tracks from emulsion pellicles.

Thus in the present investigation, unless otherwise specified, a corrected frequency and cross-section will imply that correction in respect of scanning and dip angle restrictions are considered for their evaluation.

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CHAPTER III

THE GENERAL CHARACTERISTICS OF DISINTEGRATION STARS

3.1. INTRODUCTION-FORMATION OF STARS :

A nucleus under normal condition is an assembly of nucleons where the nucleons do retain a substantial part of their identity as nucleons, with whatever meson clouds they have /1/ and by whatever constituents they be formed /2/, relatively unchanged by the presence of other nucleons /1, 3/. But always a highly excited complex nucleus disintegrates by emitting particles and fragments; a substantial number of which are charged and can ionize the medium they pass through. They may also be studied from the photographic records.

Such disintegrations produced by cosmic rays were first studied by using cloud chambers which produce only a few events over a long period of operation. Observations on cosmic ray events (1937) in photographic emulsion marks the beginning of a series of investigations on various aspects of nuclear disintegrations produced by cosmic rays and machine accelarated particles.

Constituents of a common nuclear emulsion can be broadly classified into two groups; the lighter group containing hydrogen, carbon, nitrogen and oxygen; and the heavier group containing mainly silver and bromine. A silver or bromine nucleus may be assumed to have about a hundred nucleons, spherical in form with a diameter of about 4 to 5 nucleons. The characteristics of disintegration of these nuclei produced by particles of specific energy will depend on the impact parameter and also on the number of nucleons participating in the initial collisions. The collisions may roughly be devided into two classes; (i) peripherial and (2) central. In the central penetration the nuclear thickness for heavier nuclei is assumed to be about 4 to 5 nucleons while for peripherial, it is about 1 to 3 nucleons. The types of collisions are approximately equally frequent /4/.

When a high energy particle (projectile) interacts with a target nucleus several pions, both charged and uncharged, are created within a very short time (about 10^{-23} sec.). The particles so produced, commonly known as shower particles also, traverse the nucleus in a short time (within about 10^{-22} sec.) tending to collimate strongly in the direction of the incident particle. The two "cascade-type" theories for their production are (i) plural theory /5/ and (ii) multiple theory /6/. According to the plural theory the incident particles makes a series of collisions with individual nucleons creating a single meson in each encounter. Accordingly, a space and time separated shower of mesons is expected after several encounters. According to the multiple theory several mesons are created in the first encounter which is so highly inelastic that the primary has often insufficient energy to generate further mesons in the subsequent impacts. In addition to these, there are models for describing the particle production by the double step mechanism processes /7/ where in the first step one or more compound systems are assumed to be produced. In the second step they decay into final state particles.

The quark models are also sometimes adopted to discuss the passage of the high energy incident projectile (say hadron) as well as the particle production process under the following assumption :

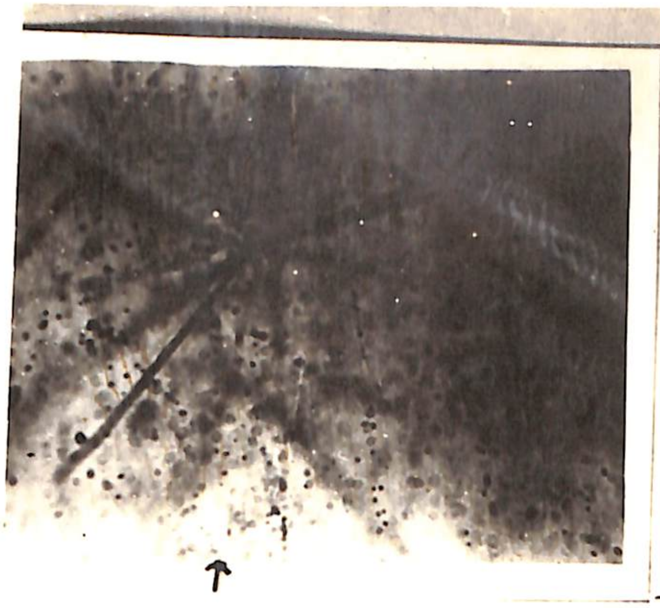
As the Lorentz contracted hadron (which may have a disc like shape) passes through the nucleus, after collision with the first nucleon forms a complicated system of quarks and gluons. While propagating further through the nucleus, the system (as well as the rest of the nucleus) gets more excited. After leaving the nucleus it disintegrates mostly into pions /8, 9/.

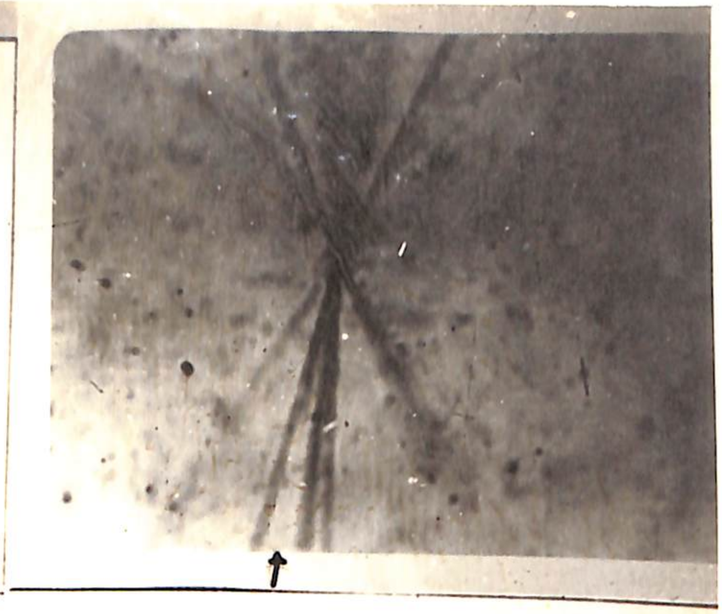
One of the most interesting consequences of interaction of a high energy projectile with the target nucleus is that the target nucleus first gets excited and subsequently gets rid of the excitation energy during de-excitation. Nuclear particles and fragments are very frequently emitted during such high energy excitation and de-excitation processes.

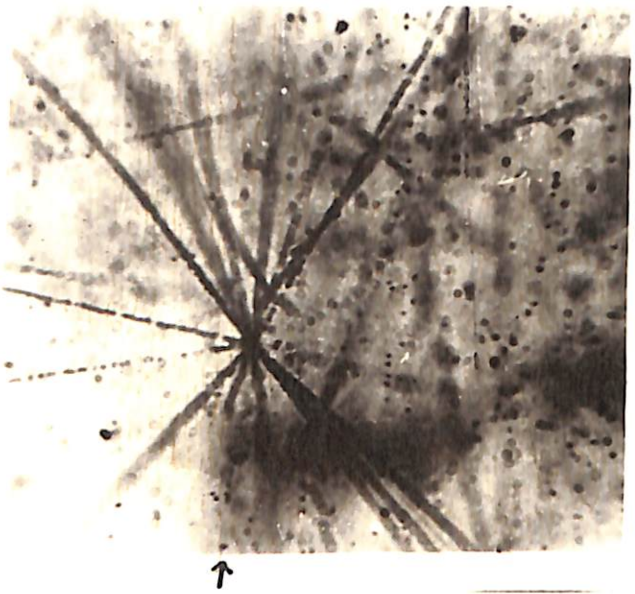
In photographic records (as in nuclear emulsion) the tracks formed due to ionisation of the medium through which the produced charged particles as well as the emitted charged target particles and fragments pass, appear to be emitted from a common point - the location of the target nucleus. Due to the characteristic appearance, the structure so formed is known as the "star". Plate No. 1 shows a few microphotographs of some of the disintegration stars.

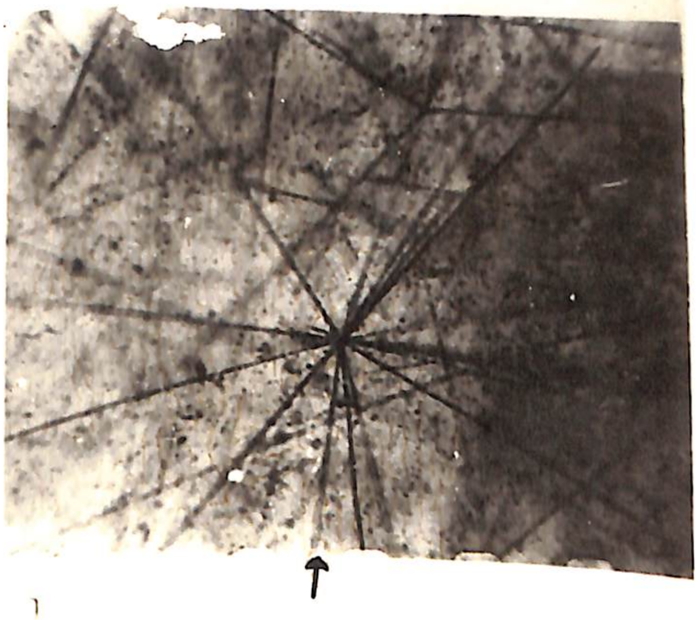
3.2. EXCITATION AND DE-EXCITATION OF THE TARGET NUCLEUS (CASCADE - EVAPORATION MODEL) :

According to the cascade-evaporation model of interaction /10/ the recoiling nucleons, often of lower velocity than the incident one, make further collision(s) with other nucleons. The recoiling particles from them interact with some more. The process continues until the available energy is rapidly shared with other nucleons in the nucleus. In this process of intranuclear cascade, some of those recoiling nucleons having kinetic energy large enough as compared to the binding energy per nucleon, commonly escape without making more than one or two collisions. These particles, emitted soon after the instant of impact,are less collimated with respect to the primary particle and produce grey tracks. For those of lower energy the nucleus is much more opaque and will generally be trapped within the nucleus only after a few collisions. The nucleus, thus excited to a high degree because of the nucleonic cascade, emits









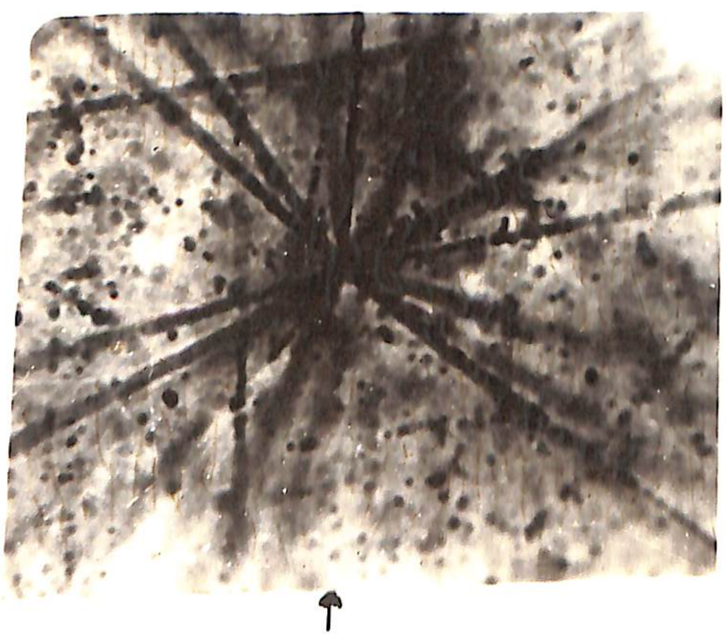


PLATE No. 1 :
Microphotographs of
disintegration stars
(beam direction
→ indicated)

individual nucleons and heavier fragments in a slower process viz., the nuclear evaporation, after an interval of time which may be termed as life time.

It is generally taken that the life time of an excited nuclear system, on the average, may be about 10^{-17} sec. /5, 11/; which, however, may change depending on the amount of energy deposited **to** the target nucleus /12-15/. Fission decay time of Uranium and Tungsten exposed to about a hundred MeV heavy ion beams have been estimated /15, 16/ to be about 10^{-17} to 10^{-18} sec. There are evidences on observation of thermalised systems excited to a nuclear temperature of about 5 to 6 MeV /17/, corresponding to which the life time may be as low as 10^{-21} sec. /13, 14/. Thus the distinction between knock-on and evaporation phases of the reaction probably becomes fuzzy at high excitation energies - rather, at about 1 GeV excitation energy there is likely to be a smooth transition as far as both time scale and energy of the particles concerned, from emission by pure knock-on (cascade) to an evaporation mechanism /18, 19/, if any other mechanism like "explosive decay" /20/ does not predominate.

The nuclear evaporation process :

The mechanism of emission of slow particles from a highly excited nucleus may be compared to the evaporation from a heated liquid drop. For a nucleus, however,

(i) the (number of) nucleons in it are fewer than the (number of) molecules in the liquid drop and consequently the emission of a single particle results in considerable lowering of excitation energy and hence its nuclear temperature.

(ii) The ratio of surface area to volume for a nucleus is much larger than that for a droplet of liquid and hence thermal excitation in the form of surface as well as volume waves becomes important.

Further, (iii) the emission of a charged particle is complicated by the effect of Coulomb barrier.

The statistical treatment of the evaporated particles was first suggested by Bohr and Kalckar /21/. Later Weisskopf /22/ derived an expression for the probability of emission of neutron from a large nucleus, with energy of the order of binding energy per nucleon. Considering Coulomb barrier as V, the probability of emission of a charged particle with energy between E and E+dE becomes

$$P(E)dE = \left(\frac{E - V}{T^2}\right) e^{-\left(\frac{E-V}{T}\right)} dE \qquad (3.1.1)$$

where T = nuclear temperature and V the Coulomb barrier, which becomes zero for uncharged particles like neutrons.

Considering the nucleus as formed out of a degenarate Fermi-gas without interactions between nucleons and taking the cooling down of the nucleus during evaporation into account, Begge /23/ obtained the total excitation energy of a nucleus having A nucleons as

$$U = KAT^2 \qquad (3.2.2)$$

where $K = \frac{\pi}{4G}$, G being the kinetic energy of the highest occupied states in the unexcited nucleus (Fermi energy). The value of K of the nuclear species may depend on factors like nuclear temperature, nuclear spin, deformation etc. /24/, various values ranging from 1/7 to 1/25 are in use /13, 24, 25/. However, a value of K approximately equal to 0.1 /26/, is quite useful to get the average description /27, 28/.

The average energy loss dU of the nucleus when dA nucleons are evaporated is obtained by using the relation

$$\frac{dU}{dA} = 2T + E_o \tag{3.2.3}$$

where T = instanteneous nuclear temperature

E_o = binding energy per nucleon for uncharged particles but for charged particles it is the sum of binding energy and effective barrier height.

By taking into consideration the correlation between neutron and proton emission and also the effect of thermal expansion of the nucleus, Le Couteur /29/ obtained the probability of emission of six different types of particles, viz, n^1, H^1, H^2, H^3, He^3 and He^4. Fujimoto and Yamaguchi /30/ neglected the thermal expansion of the nucleus in a similar calculation which takes into account the correlation among neutrons, protons and alpha particles only.

The production of singly and multiply charged nuclear fragments in the reaction between energetic projectiles (from particles to heavy ions) and nuclei is creating a great deal of interest. Various models /31/ have been used to explain the experimental observations on heavy particle production and emission. Monte Carlo methods /32/ have also been applied. Detailed calculations on the basis of such methods have been made in the attempts to explain the emission of different particles by different processes including that of evaporation.

The average energy carried away by the heavily ionizing particles during the cascade evaporation process may be estimated by the empirical relation of Powell et al /4/, i.e.,

$$E = (124\ N_h + 30)\ \mathrm{MeV} \tag{3.2.4}$$

which is valid for stars produced by primaries of energy greater than 1 GeV.

The average excitation energy just before the beginning of the process of evaporation may also be estimated /4/ by using the empirical relation

$$U = 42 (N_b + 1) \text{ MeV} \tag{3.2.5}$$

which is valid only when the initial excitation energy is more than 100 MeV.

3.3. EXPERIMENTAL PROCEDURE AND SELECTION CRITERIA :

Two emulsion stacks, one exposed to 1.8 GeV/c K^- beams (flux $\sim 2\times10^5$ K^- per sq. cm.) and the other to 20 GeV/c p beams (flux $\sim 5\times10^4$ p per sq.cm.) respectively, have been used for the investigations involving disintegration of silver and bromine nuclei. The emulsion sheets are area scanned within the selected volume under low magnification with 10x objective and 15x eye-piece. Care has been taken to exclude events lying in the peripherial regions, i.e., about 5 mm from each edge and about 25 microns from glass and air surfaces of the emulsion pellicles. Discussions on the study (general) of tracks associated with the disintegration stars and also the selection of Ag, Br events have been given bellow.

The tracks associated with the disintegration stars in nuclear emulsion are classified into three catagories. They are : (i) Thin or shower tracks, (ii) grey tracks, and (iii) black tracks. Shower tracks are identified from the rest by ionisation measurements. The grey tracks and the black tracks are separated from each other either by ionisation measurements or by measurement of the ranges of the tracks /33, 34/ or by a combination of the two.

During ionisation measurements the effect of development of emulsion on the observed grain density (g) is eliminated by normalizing g w.r.t. the grain density of the track of a singly charged particle moving in the same emulsion at a velocity which may be greater than 0.995c (platue grain density g_p as in e.g. /33, 35/) or 0.95c (minimum grain density g_{min} as in e.g./36/). g_{min} is normally about 11% less than g_p/4/. The assumed limits for separation of black and grey tracks in different experiments show a variation of proton energy from about 25 MeV /e.g., 33/ to about 35 MeV /4, page 414/.

In this experiment, unless otherwise specified, the classification /36/ of the tracks are as shown in table 3.1.

Table 3.1 : Classification of shower, grey and black tracks :

Specification	Shower tracks	Grey tracks	Black tracks
g/g_{min}	$\lesssim 1.4$	1.4 - 10.0	>10.0
Particle velocity (β = v/c) in units of c	>0.70	0.25 - 0.70	<0.25
Energy associated with the particle E_{kin} (MeV) (of proton)	>400 ($P_c \gtrsim 140$ MeV/c)	30 - 400	<30
Particles associated with the tracks	Pions, fast recoil (knock-on) protons.	Protons ($\sim$80%) due to cascade, pions.	low energy p,d, α and other fragments.
Probable mode of production	fast cascade	slow cascade	Mostly from thermalisation of observed energy.

The multiplicities of shower, grey and black tracks are conventionally denoted by N_s, N_g and N_b. The number of havily ionizing tracks,briefly, heavy tracks N_h of a star is given by $N_h = N_g + N_b$.

The particles producing shower, grey and black tracks in emulsion due to nuclear disintegrations are supposed to be resulting from three distinct mechanisms. It is generally accepted that most of the black tracks are due to evaporation of particles from the excited nucleus. Most of the protons emitted in the evaporation process have energies less than a limiting value of about 30 MeV. More energetic protons originate in cascade process. Thin or shower tracks are produced by protons of kinetic energy greater than 400 MeV and pions of momentum above 140 MeV/c.

Most of the particles producing heavy tracks are due to protons, deuterons, tritions, alpha-particles and heavier fragments, and majority of shower particles are due to pions /37/. The number of protons producing shower tracks is observed to be very nearly equal to the number of pions of relatively low energy producing grey tracks /4/. Thus the value of N_s for a disintegration is a good estimate of the charged pions produced. For high primary energy, the ratio of the number of charged mesons to the total number of mesons is taken to be 2/3. The average number of neutrons emitted during the disintegration is slightly higher than the average number of protons.

Experimental evidence reveal that the particle production process does not influence the nucleon emission process at any projectile energy /38/. This fact is supported by the absence of direct relation between pions and the nuclear excitation produced /4/; also, there is no relation between emission of heavy fragments and meson showers /39/.

N_h- the number of heavily ionizing tracks which is a measure of emitted charged nucleons and nuclear fragments also, provides the most useful criterion for selection of Ag, Br events from disintegration centres in nuclear emulsion. In some of the investigations /e.g. 40-44/ Ag, Br events are selected by adopting the criterion $N_h > 6$, while in some others /35, 45, 46/ the Ag, Br events are selected from the stars of lower N_h by adopting additional criterion like that for the range of short tracks. However, such identification by adopting additional criterion may lead to substantial distortion of characteristics of interaction /47/; for example, Ag, Br stars with low N_h may not have recognisable tracks due to recoils. $N_h > 8$ has been adopted as the criterion for unique identification of Ag, Br events in some of the investigations /48, 49/. From the criterion for selection of Ag, Br events in a large number of investigations /eg. 50-52/, also supported by cosmic ray investigations in cloud chambers /53, 54/, it becomes evident that the disintegration stars with $N_h > 7$ are only due to reaction with Ag, Br nuclei (may be due to moderately central and central collisions), while those with $N_h > 7$ are interactions with light nuclei, hydrogen and peripherial collisions.

Thus the stars are selected and recorded under criterion $N_h > 7$ from the selected volume of emulsion in order to exclude disintegration stars arising out of lighter elements of emulsion. The number of stars obtained under this criterion is expected to be nearly 50 p.c. of all interactions and most of the disintegrations may be due to central collisions /55, also 56/ with heavier group of emulsion nuclei. The interactions with silver and bromine nuclei may be estimated from the knowledge of the composition of emulsion and inelastic cross-sections /57/ to be in the ratio 1.2 to 1.

3.4. RESULTS AND DISCUSSIONS :

3.4A. Interaction Cross-section :

Out of a selected volume of about 123.3 c.c. of emulsion from the first (K^-) stack a total of 60,000 disintegration stars and from the second (p) stack out of a selected volume of about 16.32 c.c. of emulsion a total of 5,000 disintegration stars, each with $N_h > 7$, have been recorded. The observed reaction cross-section of K^- and p with complex nuclei (Ag and Br) estimated from these observations are ~118 mb and ~296 mb respectively.

For the study of characteristics of stars produced during the disintegration of Ag and Br nuclei and also for correction due to loss of events during scanning, a total of about 3.45 c.c. of emulsion from the K^- stack and 1.625 c.c. from the p stack were selected at random from different positions of the respective stacks and scrutinized further by a second observer.

The details are presented in table 3.2.

Table 3.2 : Interaction cross-section :

Beam	No. of stars		Approx. Cross-section (mb)	
	Observed	Corrected	Observed	Corrected
1.8 GeV/c K^-	1683	1732	118	121
20 GeV/c p	497	513	296	305

As expected, these values are larger in comparision with the reaction cross-sections for K^--p ~20 mb, K^--d ~45 mb, p-p ~30 mb, p-d ~65 mb /58, 59/ in the similar energy range.

3.4B. Star size distribution :

The N_h - distribution, N_b- distributions, and N_g - distribution, of (a) 1732 stars from K^- - Ag, Br interaction, and (b) 513 stars from p-Ag, Br interactions are presented in Figs. 3.1 (a), (b); 3.2 (a), (b); and 3.3 (a), (b) respectively. The mean prong multiplicities are presented in table 3.3 and compared with the results of other experiments.

The average excitation energies of the target nuclei, estimated using the relation (3.2.5), are about 425 MeV for K^- -Ag, Br interactions and about 480 MeV for p-Ag, Br interactions respectively.

Table 3.3 : Track multiplicities of stars :

Beam	$\bar{N}_h$	$\bar{N}_b$	$\bar{N}_g$	$\langle N_g/N_h \rangle$ (p.c.)	Selection criteria	Ref.
0.66 GeV p	6.46	5.33±0.18	1.13	21	$N_h > 2$	/60/
1.8 GeV/c K^-	13.19±0.04	9.66±0.03	3.58±0.01	27	$N_h > 7$	/61/
3.0 GeV/c p	12.22±0.23	8.00±0.20	4.22±0.12	34.51±1.18	$N_h > 7$	/34/
20.0 GeV p	17.4±0.5	12.3±0.3	5.1±0.2	29	$N_h > 7$	/62/
22.5 GeV p	15.65±0.34	9.64±0.21	6.01±0.20	38.40±1.00	$N_h > 7$	/63/
1.8 GeV/c K^-	12.62±0.10	9.17±0.08	3.46±0.04	27.41±0.40	$N_h > 7$	P.W.*
20 GeV/c p	15.39±0.27	10.52±0.19	4.88±0.15	31.68±0.73	$N_h > 7$	

* P.W. = Present work.

Table 3.3 shows that the results of this investigation are consistant with those of others. As is generally expected /4/ for high energy interactions with projectile energy greater than 1 GeV, the value of N_g/N_h does not differ greatly from 0.3.

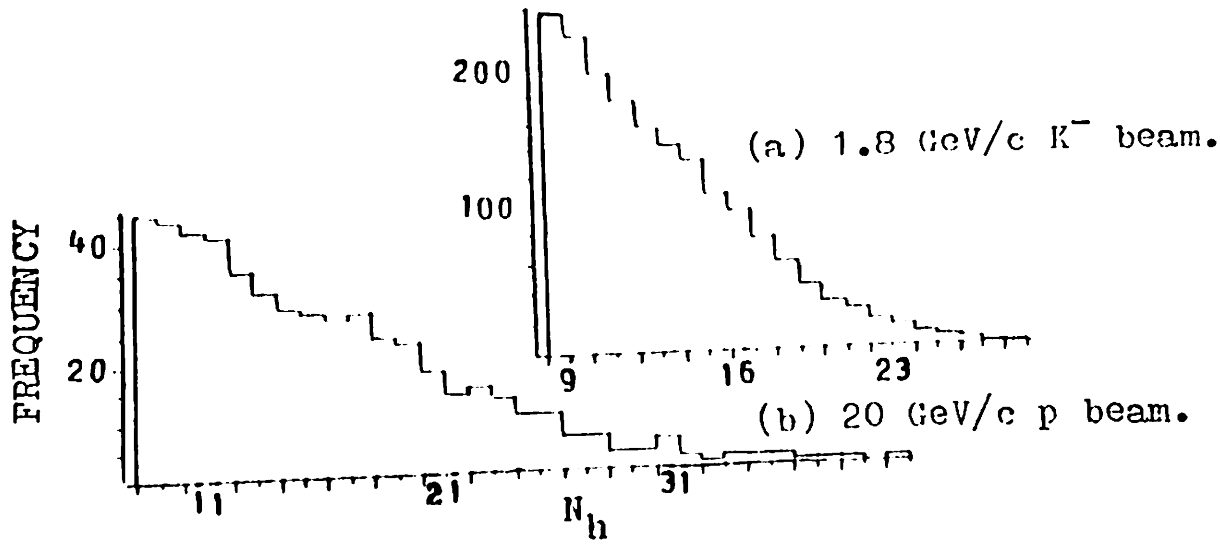


FIG. 3.1:- N_h distribution.

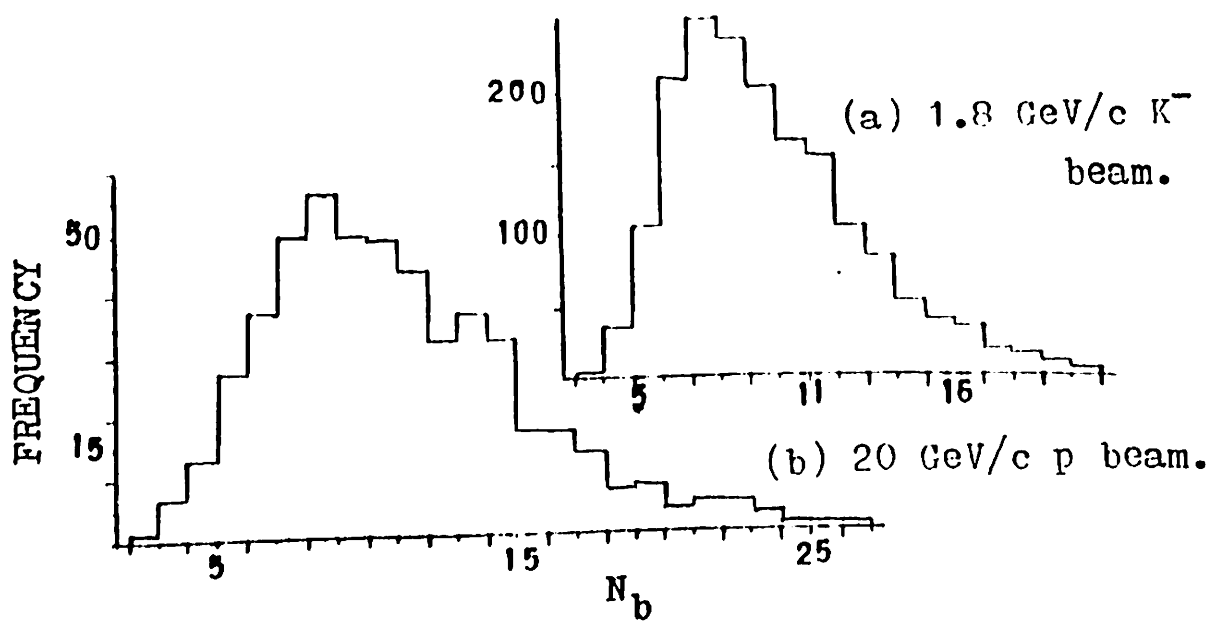


FIG. 3.2:- N_b distribution.

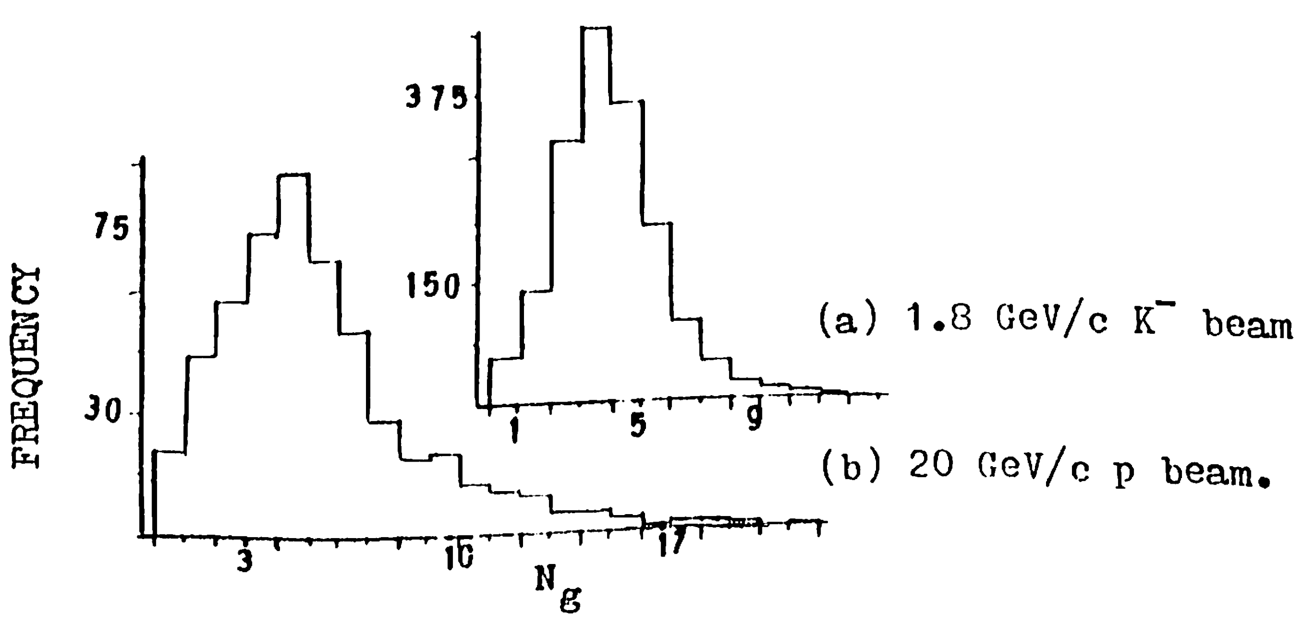


FIG. 3.3:- N_g distribution.

3.4B1. Complete disintegration (large scale spallation) :

Normally the disintegration of an excited nucleus proceeds through evaporation process during which the particles are emitted one after another by maintaining a thermodynamic equilibrium. The excited nucleus gradually cools down as it goes on losing energy during the process of evaporation. However, when the excitation energy of the bombarded nucleus is very high - may be of the order of total binding energy of the nucleus or even higher than that, the disintegration may be much quicker. The disintegration may also proceed without maintaining a state of thermodynamic equilibrium /20, 44, 50, 62, 64-67/. As the heavy fragments are not expected to result from such disintegrations, they may be the instances of vaporisation also.

Disintegrations producing stars of $N_h > 27$ may be due to such complete disintegrations of Ag, Br nuclei/41, 52/. The fraction of observed stars as has been obtained in this investigation are tabulated and compared with some of the results of other investigations in table 3.4.

Table 3.4 : Complete disintegration - the observed fraction (per cent) :

Beam	Observed fraction (per cent) $\left(\frac{N_h > 27}{N_h > 7}\right)\%$	Ref.
6.2 GeV p	3.39 ± 0.66	/63/
20.5 GeV p	5.15 ± 1.67	/68/
22.5 GeV p	5.65 ± 1.30	/63/
27.0 GeV p	6.37 ± 1.82	/68/
Nucleus (cosmic rays)	17.9 ± 3.1	/52/
20.0 GeV/c p	4.48 ± 0.96	P.W.

Table 3.4 shows that the results of the present investigation are consistant with the other investigations. Such disintegrations may not constitute more than about 6 p.c. of the Ag, Br interactions considered herein at a projectile (particle) energy about 20 GeV.

3.4C. Correlation :

To represent the dependence of (I) the values of $\langle N_b \rangle$, the average value of N_b for specific values of N_g; and (II) the values of $\langle N_h \rangle$, the average value of N_h for specific values of N_g for (a) K^- -Ag, Br interactions and (b) p-Ag, Br interactions respectively, the least square fit graphs are presented in Figs. 3.4 (a) and 3.4 (b). The corresponding relations are :

(a) for 1.8 GeV/c K^- -Ag, Br interactions

(I) $\langle N_b \rangle = 0.35\ N_g + 8.44$

(II) $\langle N_h \rangle = 1.34\ N_g + 8.48$

(b) for 20 GeV/c p-Ag, Br interactions (3.4.1)

(I) $\langle N_b \rangle = 0.33\ N_g + 9.09$

(II) $\langle N_h \rangle = 1.32\ N_g + 9.14$

This shows that, on the average for stars with $N_h > 7$, there is an increase in N_b with the increase of N_g as may be observed from the results of other investigations also /33, 69, 70/.

The least square linear fits, at lower N_g values in particular, do not appear to be good. This may be due to selection of Ag, Br events with $N_h > 7$ which exclude events with low N_b values that are likely to be associated with low N_g values also. The significance

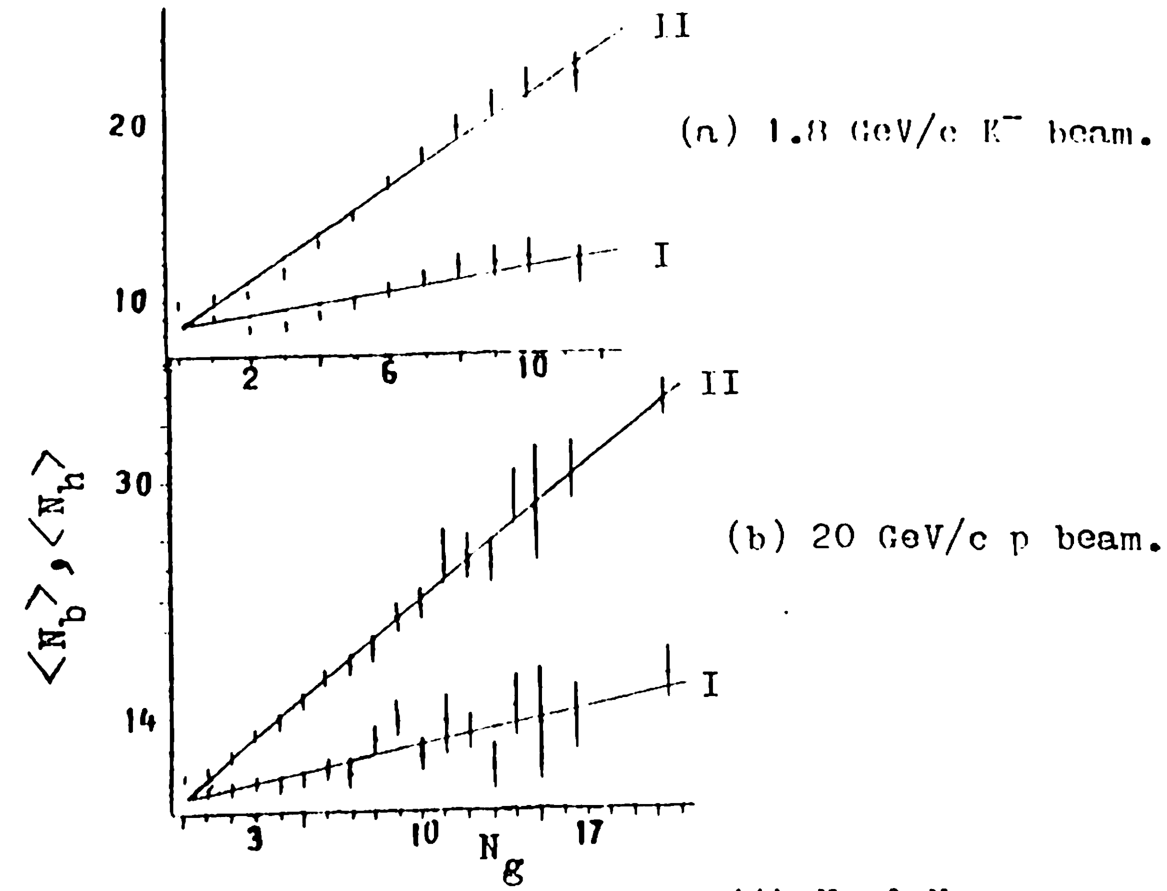


FIG.3.4:- Relation of N_g with N_b & N_h.

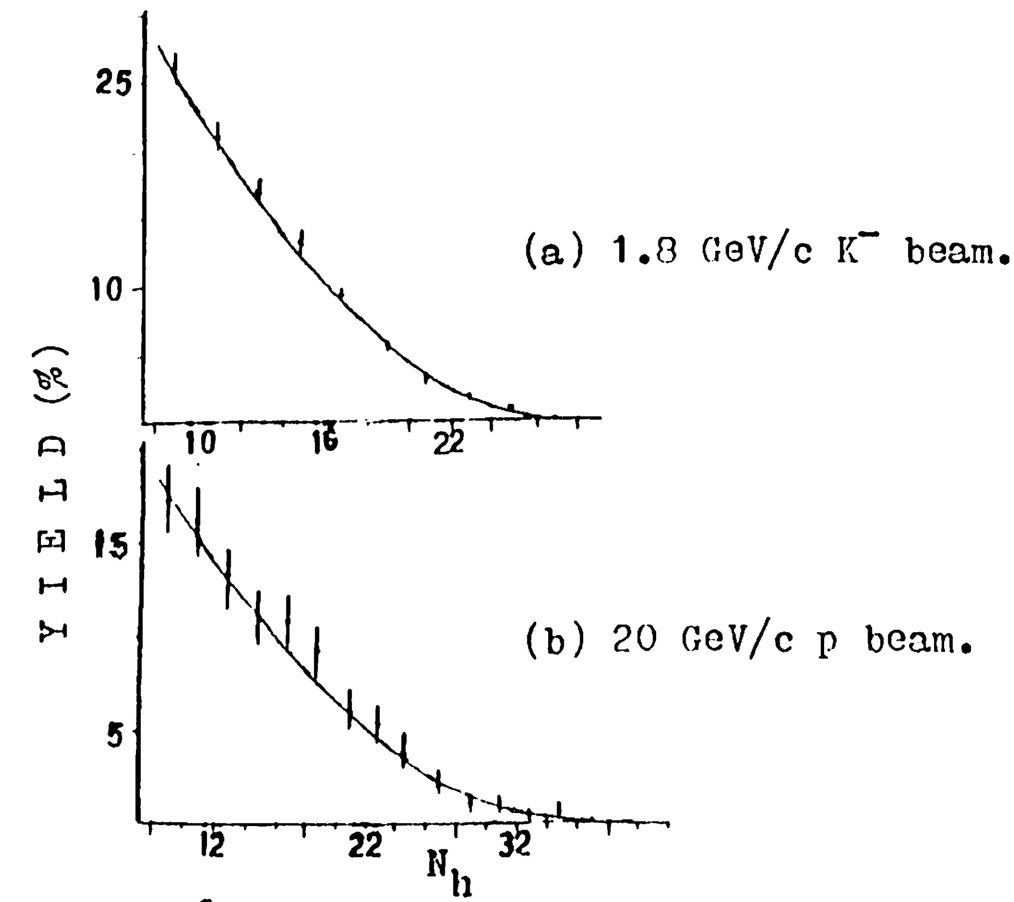


FIG.3.5:- Yield-N_h plot.

of the correlation between N_b and N_g may, however, be studied by using correlation table /71/ and by computing the 95% confidence intervals /72/. The results of this investigation are compared with those obtained from the results (for $N_h > 7$ only) of other investigations in table 3.5.

Table 3.5 : Comparison of N_b-N_g correlation :

Beam	Correlation co-eff. r	95% conf. interval of r	Slope of N_g-N_b graph from r	Slope of N_g-N_b graph from graph using data	data source (Ref.)
3 GeV/c p	+0.01	0.01 ± 0.12	+0.01	+0.23	/34/
6.2 GeV P	+0.35	0.35 ± 0.06	+0.49	+0.33	/63/
22.5 GeV P	+0.37	0.37 ± 0.09	+0.39	+0.34	/63/
1.8 GeV/c K^-	+0.21	0.21 ± 0.04	+0.38	+0.35	P.W.
20.0 GeV/c p	+0.27	0.27 ± 0.08	+0.34	+0.33	P.W.

Table 3.5 shows that the correlation between N_b and N_g obtained in the present investigation is significant. Though the correlation co-efficient computed from the data of 274 stars from ref. /34/ does not seem to be significant (may be the consequence of inadequate data also), the slope of the N_g-N_b graph obtained directly from the data for a least square fit straight line shows an increase in N_b with N_g within the range of N_h under consideration. Thus the results of this investigation are consistant with those of other works.

3.4D: The yield :

Taking statistical errors into account (indicated by vertical lines), the distributions of stars have been plotted as functions of N_h in Figs. 3.5 (a) and 3.5 (b) for K^- -Ag, Br and p-Ag, Br interactions respectively. The solid curves, drawn to guide the eyes only, show that the frequencies of interactions i.e., the yield may decrease exponentially /63/ with the increase in N_h.

3.4E. Estimation of charge and mass :

From the predictions of evaporation theory, Key et al /73/ has estimated the frequency of emission of different types of particles as shown in table 3.6.

Table 3.6 : Expected values for evaporated nuclear fragments :

Emitted nucleus	Percentage of evaporated particles	Relative frequency per charged particle 'f'	Assumed momenta P(MeV/c)	Assumed energy E(MeV)	No. of particles expected to be emitted	Expected to be carried away: Total charge Z	Total mass A
1	2	3	4	5	6	7	8
n^1	36.2	0.567	75	3	5.2	-	6
H^1	24.3	0.381	123	8	3.5	4	4
H^2	10.7	0.168	173	8	1.5	2	4
H^3	7.0	0.110	213	8	1.0	1	3
He^4	18.4	0.288	346	16	2.6	5	10
$\langle Be^8 \rangle$	3.4	0.053	650	28	0.6	2	5

The average momentum per observed evaporated particle is taken to be about

$$\bar{P} \quad (\Sigma P^2 f)^{1/2}$$

$$275 \text{ MeV/c.}$$

The values shown in coulomns 6-8 have been calculated for types of stars with N_h = 12.62. For convenience, the emission of fragments from Li^6 to B^{11} has been represented by an average fragment $\langle Be^8 \rangle$, the energy of which is estimated from the observed mean energy of Li^8 adjusted for Coulomb barrier effects. The relative frequencies of emission of different fragments in such disintegrations are in confromity with the experimental findings also /28, 67, 74, 75/.

The average charge(Z) and mass(A) carried away from the target nucleus (average of Ag and Br nuclei) during cascade-evaporation part of nuclear disintegration may be assumed to be about 17 and 37 (units) respectively. This being the statistical average of all the events, the charge and mass of the residual nucleus (left after cascade-evaporation) may be expected to be 24+6 and 57+14 (units) respectively. Thus the mean residual nucleus may be expected to be in the vicinity of $_{25}Mn^{55}$.

3.5 REMARKS :

The results discussed above are in good agreement with those of other works /4, 33, 34, 60-63, 68/. Inspite of a few limitations /39, 76, 77/, the characteristics of the nuclear disintegrations discussed so far indicate the overall validity of the cascade-evaporation model /11, 78-80/. Thus it may be assumed that in most of the occasions of interactions of the high energy projectiles with the targets like silver and bromine nuclei, the projectiles knock some of the nucleons in the target. These in turn knock-out a number of nucleons from the target nucleus so long the process of excitation continues. The target acquires energy and gets heated. In the subsequent process of de-excitation, most of the energy from the heated target nucleus is carried aways by the evaporated nucleons and light clusters.

After de-excitation, often a residue with reduced charge and mass may be emitted. They may travel recognisable distance in photonuclear emulsion. The disintegrating target nucleus may also emit two or more fragments by way of fission or multifragmentation. Most of the tracks in emulsion produced by the heavy nuclides emitted during the processes are short. In the subsequent chapters brief discussions on the emission of such fragments are presented.

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CHAPTER IV

SPALLATION

4.1. INTRODUCTION :

A spallation reaction is an inelastic reaction between a complex nucleus and its collision partner in which the available energy exceeds the interaction energy between nucleons in the nucleus. Spallation reactions will obviously take place whenever a flux of high energy projectiles efficiently collide with some relatively stationary matter provided that one of them or both contains complex nuclei /1/. A large cross-section of the emitted heavy fragments is beleived to be due to spallation.

From the systematic features /2/ of momentum and energy transfer in ion induced nuclear reactions /3/ it may be observed that the compound nucleus model /4-6/, so successful at lower energies (upto about 20 MeV/nucleon), gradually fails to describe the process as the incident energy goes on increasing. The spallation reactions, occurring at higher energies, are often described in terms of a two-step model-called "cascade-evaporation /7/" and later "abrasion-ablation /8/". However, in some sense the two-step model(s) is the idea of a "compound nucleus" reaction extended to high energies.

The incident projectile while interacting with target nuclei imparts forward momentum to it and removes some of the nucleons from it is an act of depositing and distributing energy (cascade stage) inside the target. The target nuclei, thus excited to a varying degree, get rid of most of their excitation energy by successive emission of nucleons and nuclides (evaporation stage) leaving behind residues of various charge and mass /9-13/ - called spallation residues. It has been shown that after emission of the penultimate nucleon, in general, the excitation energy of the residual nucleus lies between 0.5 MeV and 3.5 MeV /12/. The nucleus, however, begins emission of gamma-rays if the energy is below 7 MeV and thus ultimately gets de-excited by emitting gamma-rays.

Studies relating to spallation have been made by adopting various experimental methods such as study of tracks in nuclear emulsion /14-19/ and solid state nuclear track detectors /20-23/, counting of radioactive spallation products /24/, mass spectrometric determination of relatively stable species /25/, determination of mass, charge, angular distribution and energy of the product species by the use of scattering chambers and counter arrays /26-29/, and determination of mass, charge and other properties of the product species by the use of mass-separators /30, 31/. Often experiments are designed to measure cross-sections /32-42/ and calculations /43-52/ are destined to interpotate, predict and/or compare cross-sections. The interpolations are often done from a general equation /43/ which may contain six to ten adjustable parameters /31, 41, 42/. A number of measurements on other factors such as excitation function, recoil properties, energy released, and dependence on projectile energy have also been done /53-64/. Studies, like those on the mass yield curve /39/, neutron-proton ratios /45, 61/, recoil properties /59, 65/, and/or track multiplicities of the heavy fragments /14, 19, 21, 66/, are often made in order to differantiate the spallation products from the rest.

The range distribution of tracks produced by particles emitted due to disintegration of Ag, Br nuclei in photonuclear emulsion shows a minimum in the interval 10 microns to 50 microns. It has been shown that most of the short track of range within 10 microns are due to heavy residues which recoil as a consequence of ejection of particles and fragments from the disintegrating nucleus and are essentially spallation products /14, 15, 67-70/.

Energetic heavy fragments ($Z \gtrsim 10$), not more than one in some of the disintegrations, occasionally produce tracks which extend beyond 10 microns in nuclear emulsion /71, 72/. They may originate in the process(es) other than that for the recoiling residues /67, 72, 73/. Also, considerations in the light of "local hot spots", "terbulant effects associated with meson showers" and "surface oscillations" /73-77/ do not seem to provide adequate understanding on their production /10, 68, 73/. The appearance and implications of the "shock-waves" /78-81/ in this respect are very much in dark. Thus though there are ambiguities in respect of their production, as the multiplicity of the heavy fragment is 1, the fragments are considered as the spallation products in the subsequent discussions. Plate Nos. 2 and 3 show some of the microphotographs of the spallation events.

It has been observed that on occasions relatively longer range of a spallation residue has been considered as an act of statistical fluctuation to produce adequate momentum by emitted particles and fragments on the recoiling residue /82-85/. Also, angular correlation between spallation products and other emitted fragment(s) with $Z \geqslant 3$ have been obtained in some of the experiments /67, 71/.

Here, an attempt has been made to study the emission of single heavy fragments associated with the disintegration centres. Some of the characteristics like mass, charge, velocity and angular distributions are also studied to derive information regarding their emission.

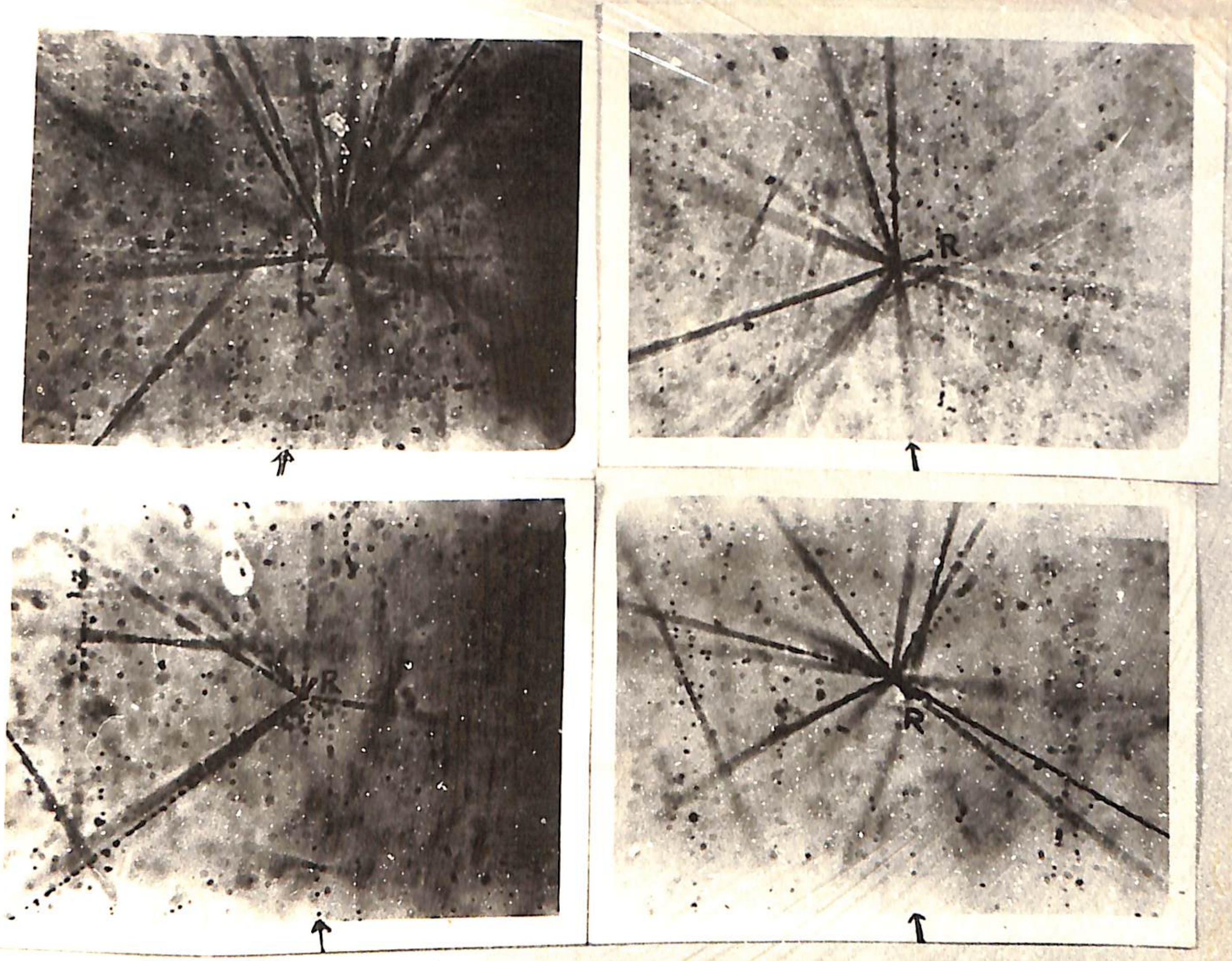

PLATE No. 2

Microphotographs of RR events.
R represents recoiling
residues,arrow head
for beam direction.

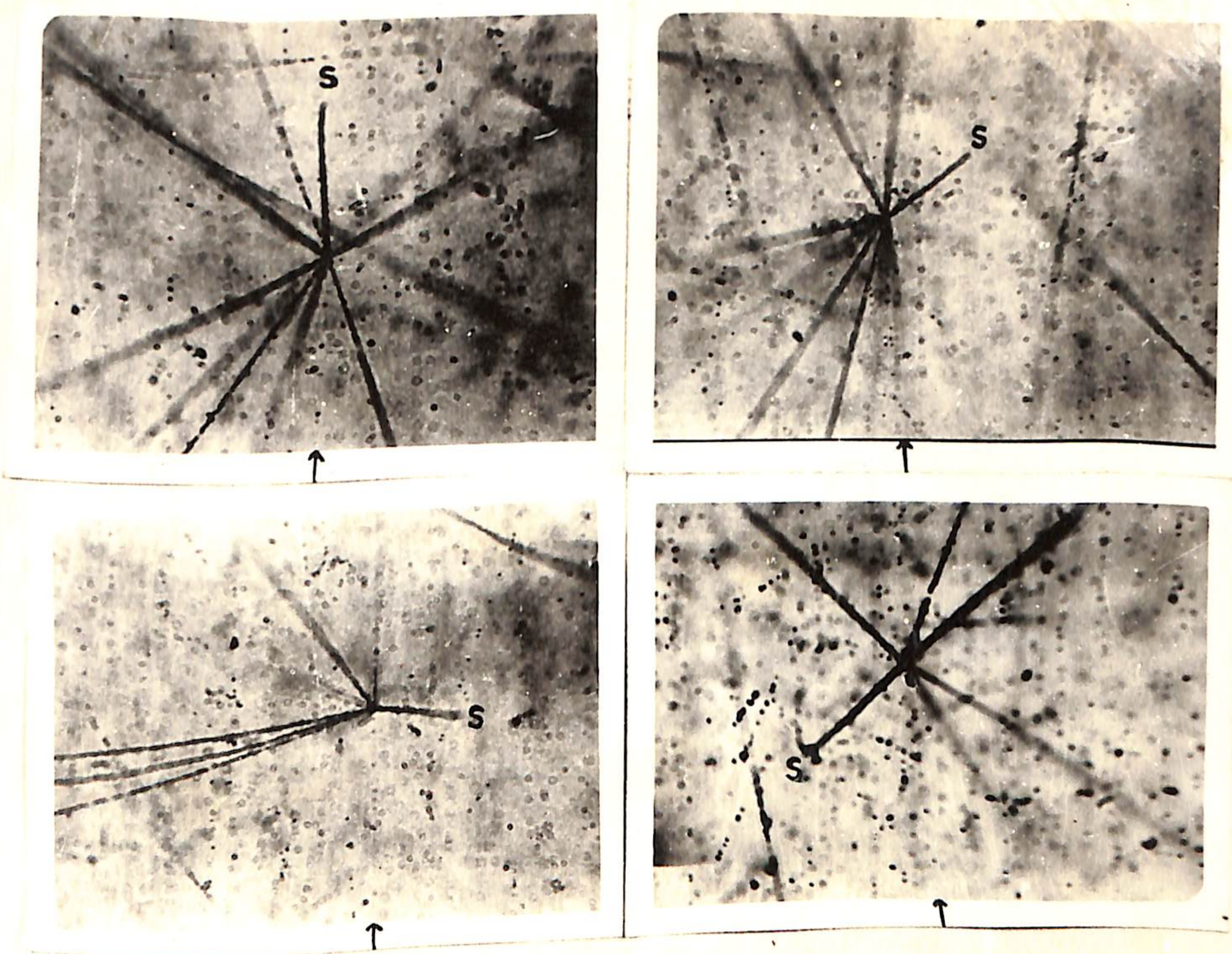

PLATE No. 3

Microphotographs of ST events. S represents the spallation products, arrow head for beam direction.

4.2. EXPERIMENTAL PROCEDURE AND SELECTION CRITERIA :

Disintegration stars, obtained by area scanning of volumes of emulsion selected from the stacks exposed to 1.8 GeV/c K^- and 20 GeV/c p beams, are scrutinized under a total magnification of 1875x (100x-oil immersion objective) to detect the presence of spallation products which produce short, dense tracks. These heavy, slowly moving spallation products, not more than one in a disintegration star, produce characteristic tracks in nuclear emulsion /86/ by which their separation from lighter particles, protons and light fragments are possible. Measurements on range, angle and dip, and also ionisation measurements for tracks associated with the stars are done as usual. The actual ranges and space angle w.r.t. primary beam direction are obtained. Charges and masses of the products are estimated statistically /87/.

To accept only the genuine events the following criteria are adopted :

(i) The tracks due to the spallation products should be with a continuous, dense black core. They should be almost straight and free from Coulomb scattering.

(ii) The tracks due to the spallation products recoiling after particle evaporation should have range in the interval 2 microns to 10 microns. The lower range limit is adopted to avoid the probability of inclusion of blobs etc. The upper range limit is adopted as these recoiling residues are expected not to travel more than 10 microns in emulsion even due to fluctuations associated with particle evaporation. Only practically flat tracks are accepted for identification as they provide the best visual access to the profile characteristics of the tracks. Spallation products so selected are called "Recoiling Residues" briefly, "RR".

(iii) The emission of spallation products of range above 10 microns in nuclear emulsion, may also involve processes other than that for RR. Such products are identified upto a range not exceeding 35 microns. The upper range limit corresponds to an energy which is higher by about an order of magnitude than the energy expected for an average RR. The tracks should show tapering towards the end. The selection is made only out of those tracks whose dip angles do not exceed 30° in the unprocessed emulsion as they provide very good access to the profile characteristics. The spallation products so selected are called "Short Tracks", briefly, "ST".

4.3. RESULTS AND DISCUSSIONS :

4.3A. For RR events :

4.3A1. Production frequency and cross-section :

Result of the investigation in respect of production frequency and cross-section of RR are presented in table 4.1.

Table 4.1 : Freq. and cross-section of RR :

Beam	Emulsion used (approx.) (c.c.)	Stars scrutinized	No. of RR	Corrected Freq. (p.c.)	Corrected Cross-sec. (mb)
1.8 GeV/c K^-	41.1	20,000	1431	35.7±5.2	43.2±6.3
20 GeV/c p	16.32	5,000	414	43.0±6.5	131.1±19.9

The results so obtained are compared with some of the results of other emulsion works in table 4.2.

Table 4.2 : Comparison of Frequency and cross-section of RR (emulsion works).

Beam	Freq. (p.c.)	Cross-section (mb)	Ref.
1.0 GeV p	13.1 ± 1.8*	131 ± 18	/88/
2.0 GeV p	36.7 ± 4.7*	367 ± 47	/88/
2.9 GeV $\bar{p}$	-	840	/89/
3.0 GeV p	36.0 ± 4.7*	360 ± 47	/88/
20.0 GeV p	46.1 ± 2.2[+]	-	/84/
24.0 GeV/c p	45 ± 3	-	/83/
Cosmic Rays	47.2 ± 1.6[+]	-	/15/
1.8 GeV/c K^-	35.7±5.2	43.2 ± 6.3	P.W.
20.0 GeV/c p	43.0 ± 6.5	131.1 ± 19.9	

* Derived from data; + upper limit only.

Table 4.2 shows that the results of this investigation are consistant with those of others. Further, from the table it may be observed that the frequency of emission of RR does not increase sharply with the projectile (proton) energy beyond about 2 to 3 GeV. This comes closely with the observation" in proton induced reactions at sufficiently high energies the cross-section of large fragments are approximately energy independent /90/."

The particulars of the distributions for track multiplicities and their mean values obtained in this investigation are presented in table 4.3 (section 4.3A2).

4.3A2. **Star size distribution :**

Some details derived from the measurements relating to the star size distributions of RR events are as follows :

Table 4.3 : Track multiplicities of stars with RR.

Beam	Direction of RR	No. of stars	N_h distribution Fig No.	N_h distribution Mean	N_b distribution Fig. No.	N_b distribution Mean	N_g distribution Fig. No.	N_g distribution Mean
1.8 GeV/c K^-	Forward	836	4.1 (a)*	12.00 ±0.11	4.2 (a)*	8.72 ±0.09	4.3 (a)*	3.27 ±0.05
	Backward	528	4.1 (a)+	11.88 ±0.15	4.2 (a)+	8.56 ±0.12	4.3 (a)+	3.28 ±0.07
	Total	1431	4.1 (b)*	11.90 ±0.08	4.2 (b)*	8.64 ±0.07	4.3 (b)*	3.26 ±0.04
20 GeV/c p	Total	414	4.1 (c)*	13.41 ±0.20	-	-	-	-

* Histograms represented by continuous lines.

\+ Histograms represented by discrete lines.

The results in table 4.2 do not show a significant differance among the observed mean multiplicities when the stars are classified as per the direction of ejection of RR w.r.t. primary beam.

The average excitation energies /91/ of the target nuclei producing RR are approximately 400 MeV and 430 MeV respectively for 1.8 GeV/c K^- and 20.0 GeV/c p interactions.

4.3A3 **Correlation :**

The straight lines marked I and II in Fig. 4.4 represent the variation of the average values of N_b and N_h with respect to N_g for stars with RR.

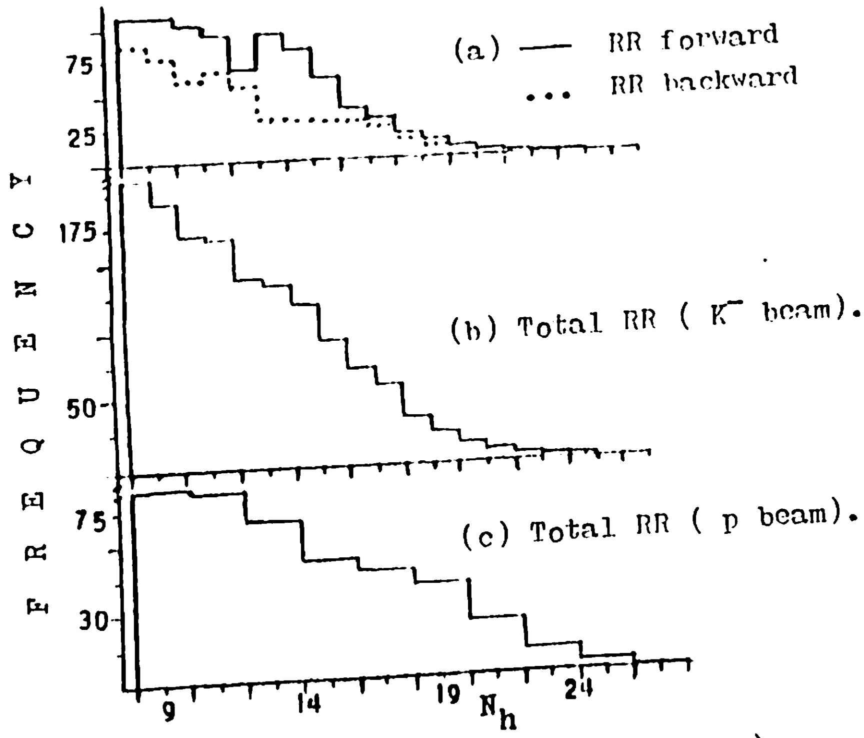

FIG. 4.1:- N_h distribution (RR events).

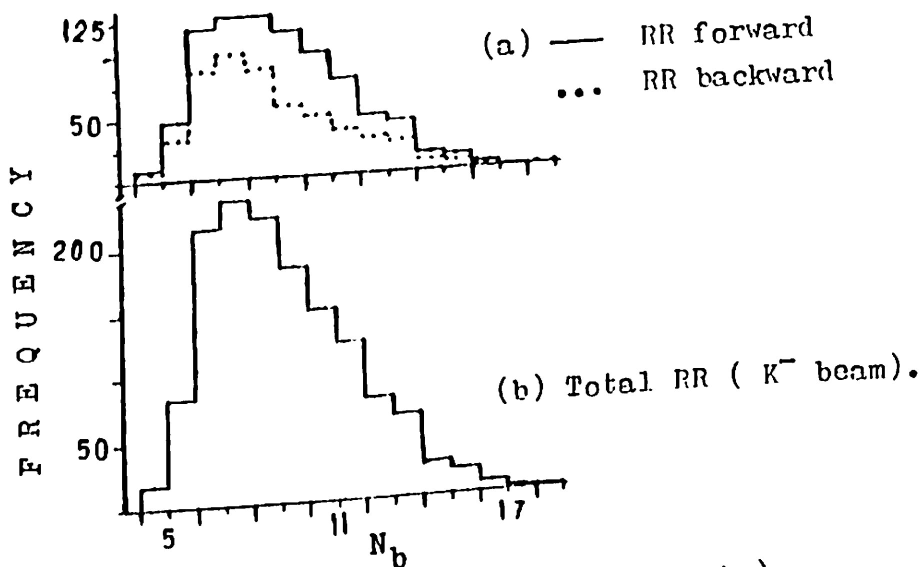

FIG. 4.2:- N_b distribution (RR events).

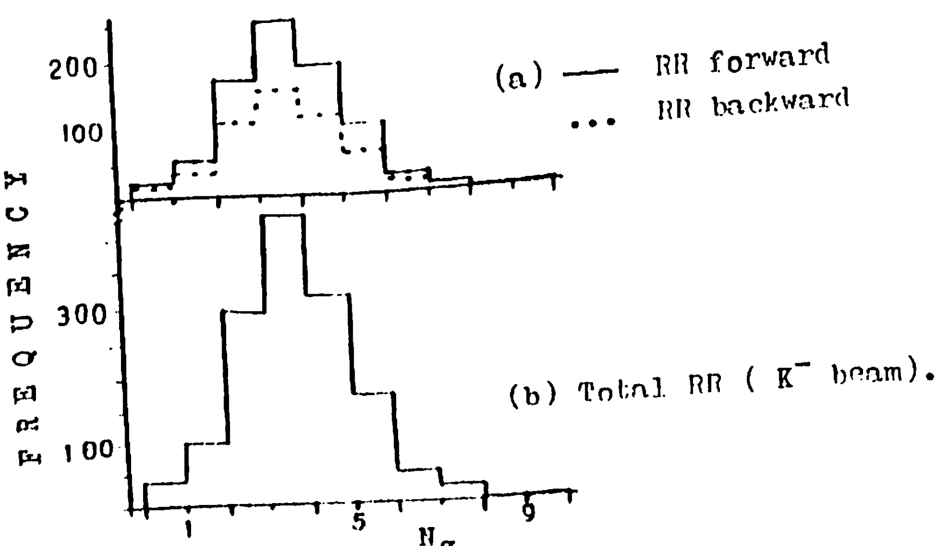

FIG. 4.3:- N_g distribution (RR events).

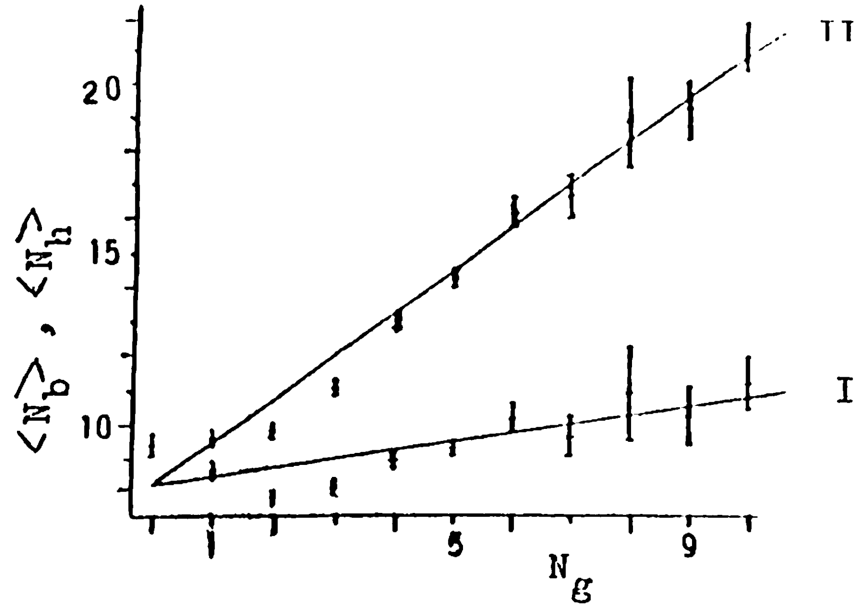

FIG. 4.4:- Relation of N_g with N_b and N_h (RR events).

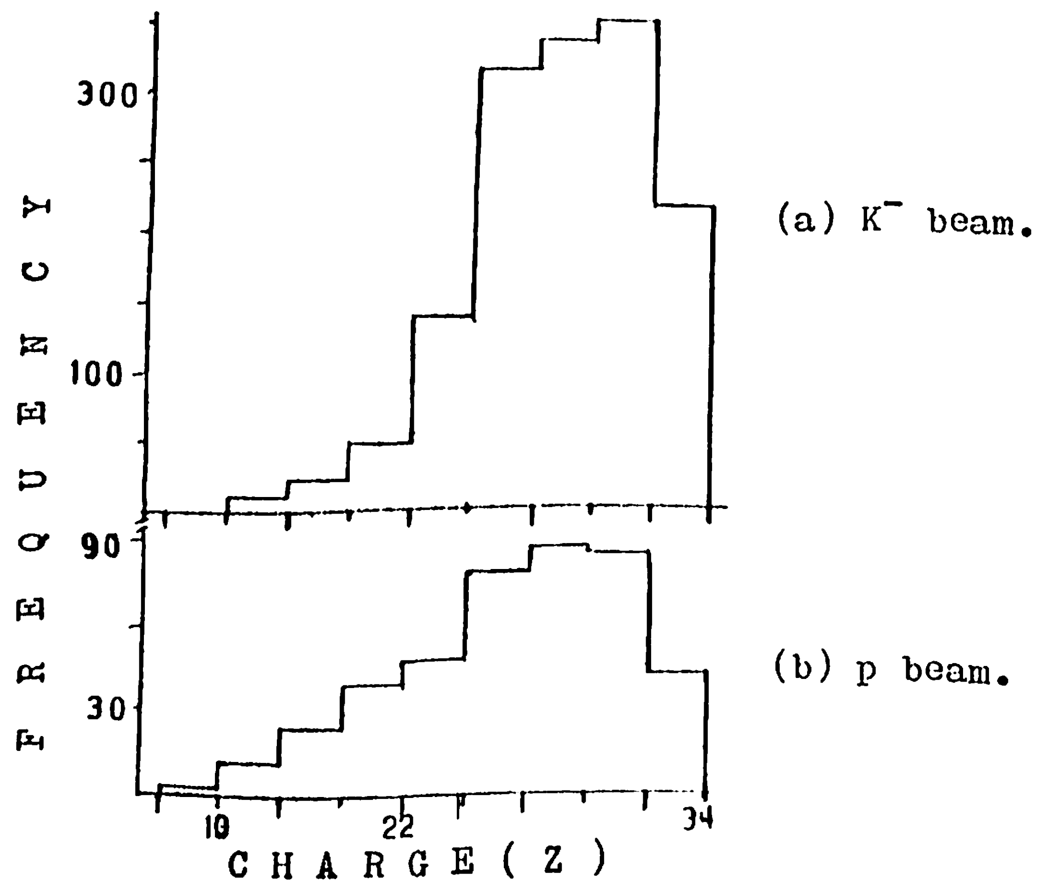

FIG. 4.5:- Charge distribution of RR.

The linear least square fits may be represented by the equations

(I) $\langle N_b \rangle = 0.27\ N_g + 8.26$

(II) $\langle N_h \rangle = 1.27\ N_g + 8.26$

Also, the correlation coefficients (represented by 'r') between N_b and N_g, their confidence intervals (CI), and the slopes of the computed and experimental N_g -N_b graphs are given in table 4.4.

Table 4.4 : N_b -N_g correlation for stars with RR.

Direction of RR w.r.t. primary	r	95% CI of r	Slope of N_g-N_b graph From r	From data (above)	Remarks
Forward	+0.15	0.15±0.08	0.25	-	Correlations are significant, and may not depend on the direction of ejection of RR.
Backward	+0.23	0.23±0.09	0.40	-	
Total	+0.19	0.19±0.05	0.34	0.27	

As N_b is a measure of the excitation energy /91/ of the pre-evaporation nucleus and as excitation energy is proportional to the number of nucleons removed /66/ (N_g gives a measure for it), the correlation between N_b and N_g may be assumed to be caused by the excitation energy.

4.3A4 Charge, mass and momentum of RR.

Relevant details of the estimation of charge and mass of RR obtained in this investigation are similar to those for the residual mass as has been shown in section 3.4E. They are consistant with ref./87/. Table 4.5 shows some of the results obtained in this investigation. Since in nuclear emulsion the interactions in silver nuclei and in bromine nuclei cannot be identified individually, the average charge and mass of both of the target nuclei have been taken for consideration. However, the expected values for charge and mass of Ag and Br residues are also presented in table 4.5 along with the average values obtained.

Table 4.5 : Charge and Mass of RR.

Beam	Particulars	Fig. No.	Width from	Width to	Expected mean value for Ag.	Expected mean value for Br.	Average value (approx.)
1.8 GeV/c K^-	Charge (Z)	4.5(a)	11	32	33	21	27
	Mass (A)	4.6(a)	20	75	75	47	61
20.0 GeV/c p	Charge (Z)	4.5(b)	8	34	31	19	25
	Mass (A)	4.6(b)	16	75	71	43	57

On the average, the mean of the RR from the disintegrations of Ag, Br nuclei due to the impact of 1.8 GeV/c K^- may be in the vicinity of $_{28}Ni^{58}$ and that for 20 Gev/c p interactions may be in the vicinity of $_{25}Mn^{55}$ respectively.

The evaporated particles, each having an average momentum of about 275 MeV/c (section 3.4E), impart random recoil momenta to the residual nucleus. The resultant of N random momenta $\bar{P}_r$, each of magnitude P, has a most probable value /92/ given by

$$\bar{P}_r = P\,(2N/3)^{1/2}$$

Thus the average momentum of RR in 1.8 GeV/c K^- interactions is about 620 MeV/c while that for 20 GeV/c p interactions is about 683 MeV/c.

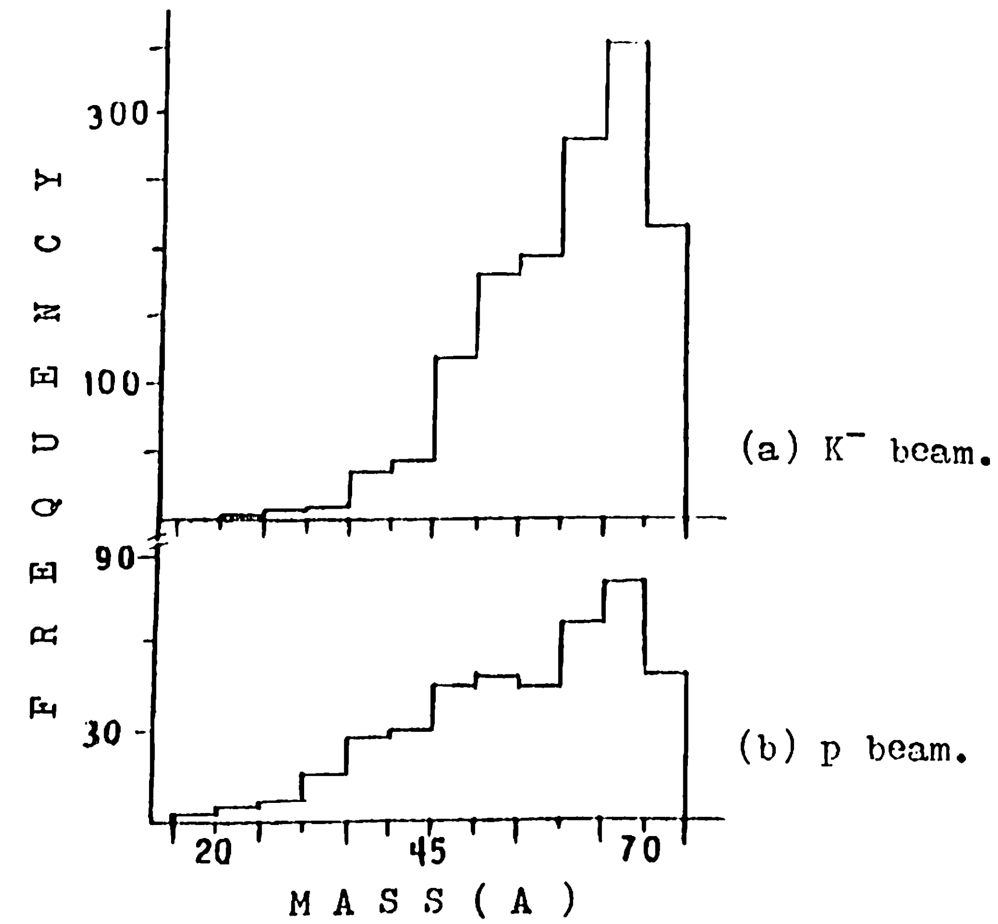

FIG. 4.6:- Mass distribution of RR.

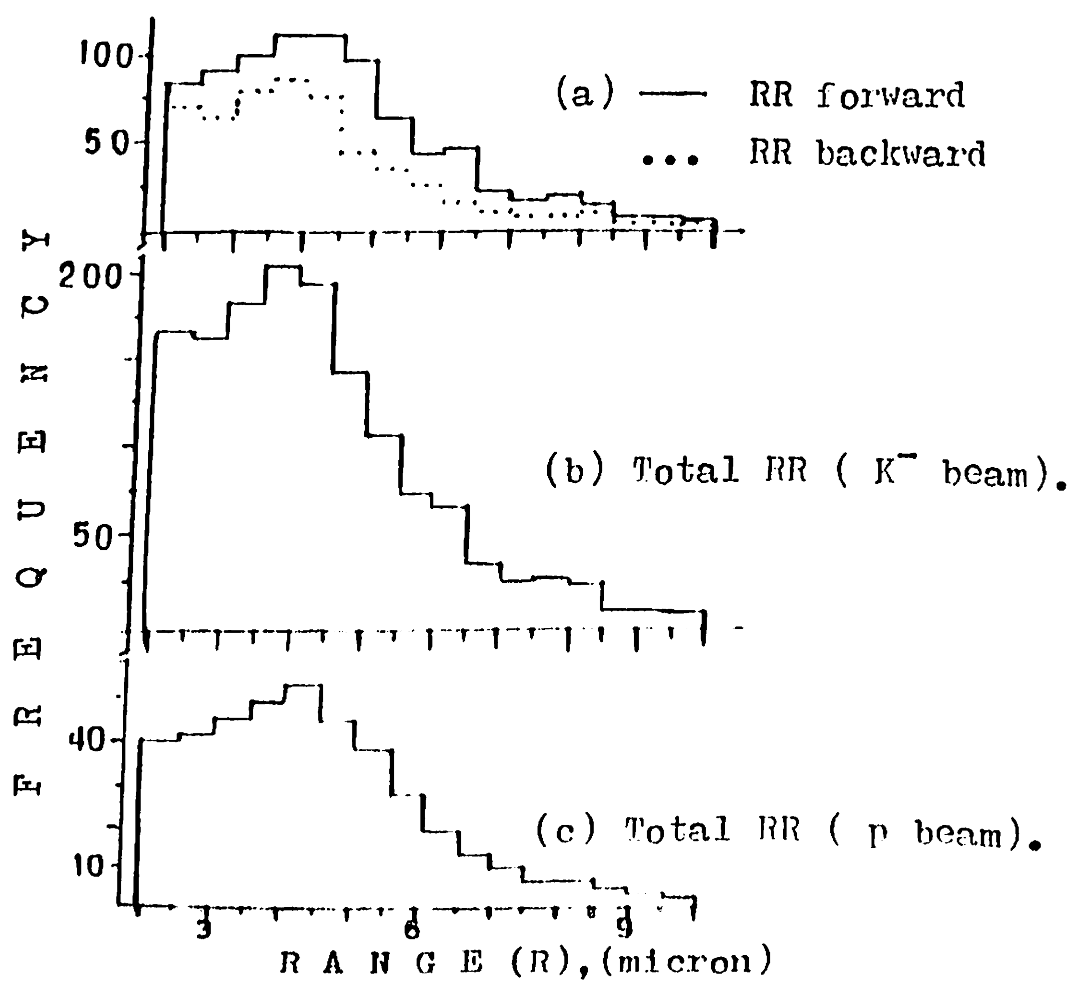

FIG. 4.7:- Range distribution of RR.

Provided that the distribution of recoil momentum imparted by the evaporated particles are isotropic with respect to RR and the statistical fluctuations are not very large, and also that the RR derive momentum only from evaporated particles, one may expect that the average range of RR in 1.8 GeV/c K^- interactions and in 20 GeV/c p interactions to be about 2.28 microns to be about 2.13 microns and in 20 GeV/c p interactions to be about 2.28 microns respectively.

4.3A5 **Range :**

The results of range measurements are summerized in table 4.6, the mean ranges are compared with some of the other investigations also.

Table 4.6 : Ranges of RR :

Beam	Direction of RR w.r.t. primary	Distribution (Fig. No.)	Mean Range (microns)	Ref.
2.9 GeV $\bar{p}$	Total	-	4.5±0.1	/89/
3 GeV p	Total	-	4.2±0.1	/89/
17.2 GeV/c π^-	Total	-	4.9±0.1	/85/
20 GeV p	Total	-	4.8±0.1	/84/
1.8 GeV/c K^-	Forward	4.7 (a)*	4.43±0.06	P.W.
	Backward	4.7 (a)$^+$	4.09±0.07	
	Total	4.7 (b)*	4.28±0.04	
20 GeV/c p	Total	4.7 (c)*	4.51±0.08	

* histogram represented by continuous lines

* histogram represented by discrete lines.

The results are consistant with those of earlier works. However, the corresponding momentum /93/ of about 1180 MeV/c (energy about 13 MeV) and 1215 MeV/c (energy about 14.5 MeV) for RR i.e., for nuclei like Ni and Mn, are a little higher than to be obtained from considerations of isotropic evaporation of particles alone.

It appears that the RR may get energy from other sources also and thus the range distribution will have more width than that expected from pure isotropic evaporation. Fig. 4.8, which shows that the observed range limits are almost independent of N_h, is in agreement with it. However, Fig 4.8 does not provide any other details of the distribution like most probable range and mean range.

A careful observation of earlier works shows that there may be an increasing tendency of the mean range of RR with the increase of energy of the projectile /89, 94/ and also with the increase of N_h/ 71/.

In Fig. 4.9 (a), (b), (c) the average values of R for different N_g, N_b and N_h values. The straight lines, drawn in the respective Figs., may be represented by the least square fit equations :

$$\langle R \rangle = 0.31\, N_g + 3.23 \quad \text{(Fig 4.9 (a))}$$

$$\langle R \rangle = 0.21\, N_b + 2.60 \quad \text{(Fig 4.9 (b))}$$

and $$\langle R \rangle = 0.18\, N_h + 2.16 \quad \text{(Fig 4.9 (c))}$$

Thus it becomes evident that the residue recoils with momentum which has contributions from both cascade and evaporation stages. The mass carried away during the two-step process has also an impact on the observed increase in range.

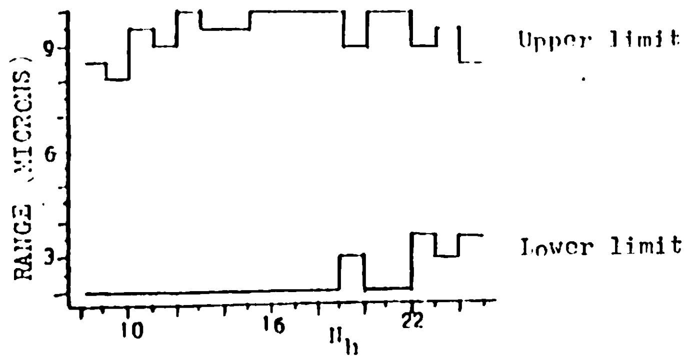

FIG. 4.8:- N_h-range limit plot for RR.

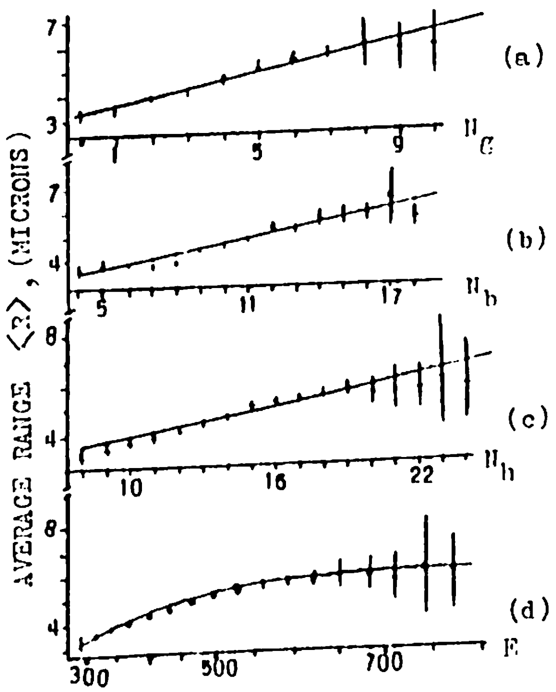

FIG. 4.9:- Variation of ⟨R⟩ of RR.

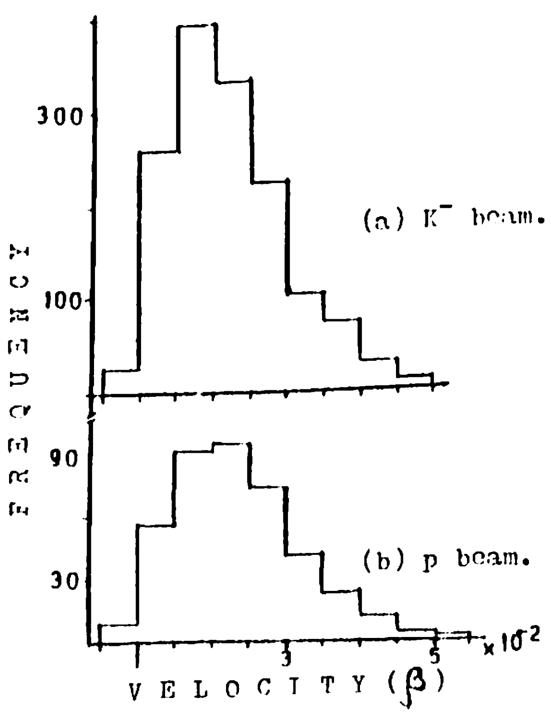

FIG. 4.10:- Velocity distribution of RR.

As N_g, N_b and N_h are correlated with each other, for higher values of these track multiplicities one may expect the ejection of a lighter RR with higher momentum. But though the graphs indicate an increase of the average value of R, the rise is not as cumilitive as may be expected from the above considerations. Also, the Monte-Carlo results /95/ show that the range distribution of spallation hyperfragments cannot be well explained by considering the contributions of momenta only from the impact of primary, cascade stage and the stage of particle evaporation.

As the excitation energy is correlated to the number of nucleons removed /66, 96/ and the number of evaporated particles depend on the excitation energy /91/, there may be a relation between the excitation energy of the target nucleus and kinetic energy of the RR. Further, as $R \propto E_K^{1.724}$ where E_K is the kinetic energy of RR /91/, and if E_K is proportional to the excitation energy E, one may expect that R may be proportional to $E^{1.724}$. But as the RR will be lighter at higher excitation energy, by considering that $M^{0.724}/Z^2$ is higher for lighter nuclei one may expect a faster rise of average R than the linear one. Fig. 4.9(d), showing relationship between $E^{1.724}$ and R (solid line is drawn to guide the eye only), does not conform with the expectation. Thus it may be expected that the fraction of energy available to the target nucleus for ejections of RR may decrease with the increase of excitation energy, particularly at higher excitation energies.

4.3A6. Velocity distribution :

The velocity distributions of RR are found out by using the range velocity curves (as in section 2.7) obtained from of Lou et al /93/ and Heckman et al /97/. The results are summerised in table 4.7.

Table 4.7 : Velocity of RR :

Beam	Fig. No	Width (in c)		Mean velocity approx. (in c)	Range expected from mean velocity (in microns)
		from	to		
1.8 GeV/c K^-	4.10 (a)	0.005	0.05	0.022	4.25
20 GeV/c p	4.10 (b)	0.005	0.055	0.024	4.47

The results are consistant with those of range distributions. As expected, the values of velocities are a little higher than those obtained by considering only the random momenta due to particle evaporation.

4.3A7 **Angular distribution :**

Some of the results obtained from the angular measurements are shown in table 4.8; the observed forward to backward ratios i.e. F/B ratios, as is usually defined from the directions of incident projectile, have been compared with those of some of the other investigations also.

Table 4.8 : Angular distributions and F/B ratios of RR :

Beam	Fig. No.	F/B ratio	Ref.
2.9 GeV $\bar{p}$	-	1.3±0.2	/89/
3.0 GeV p	-	1.8±0.2	/89/
3.5 GeV/c π^-	-	1.56±0.09	/85/
17.2 GeV/c π^-	-	1.56±0.09	/85/
25.0 GeV/c p	-	1.8 ±0.4	/71/
1.8 GeV/c K^-	4.11 (a)	1.58±0.09	P.W.
20.0 GeV/c p	4.11 (b)	1.50±0.16	P.W.

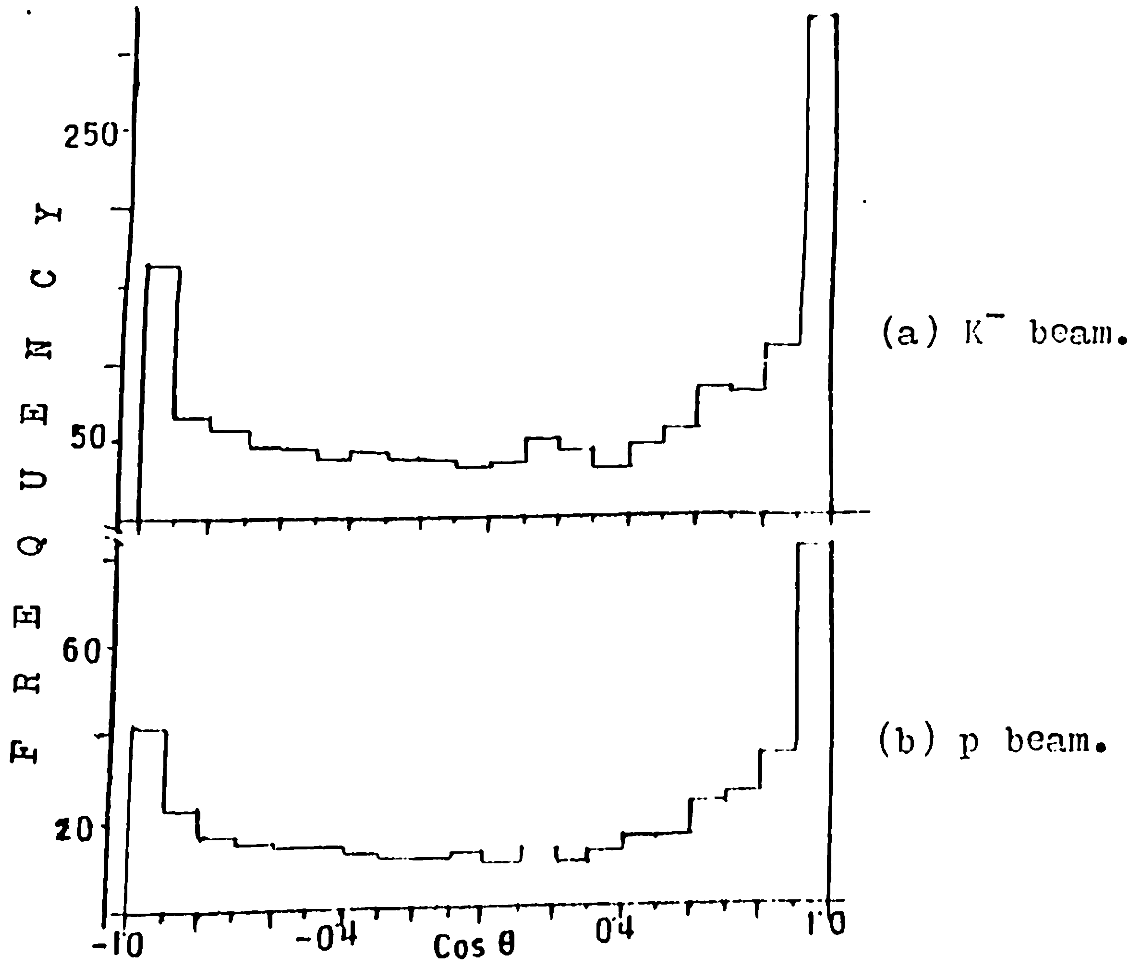

FIG. 4.11:- Angular distribution of RR.

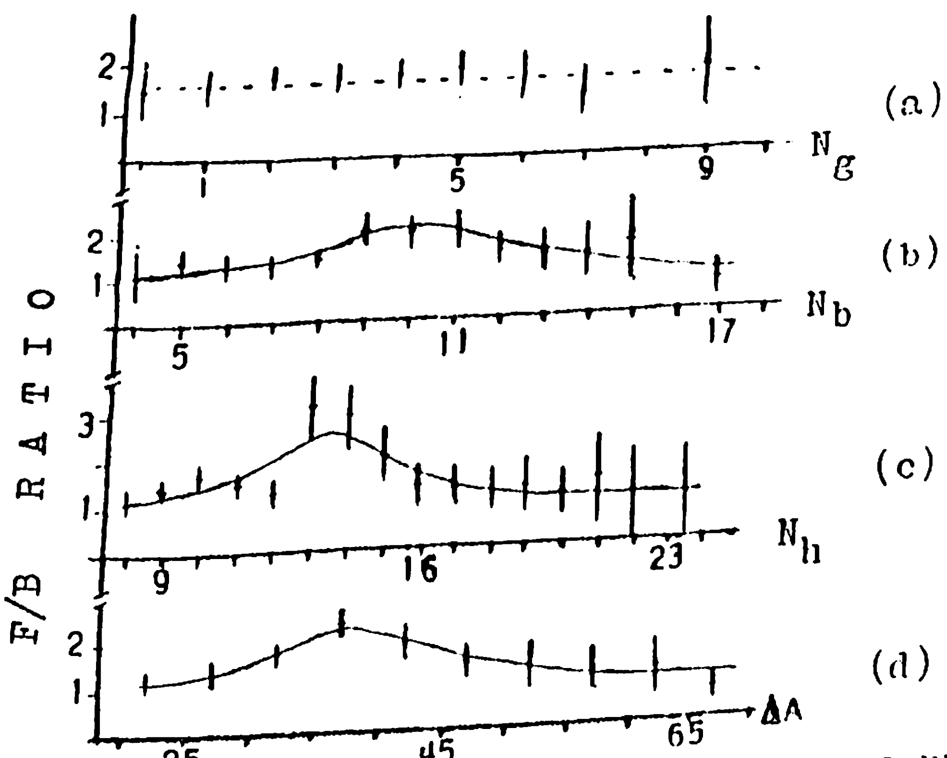

FIG. 4.12:- Variation of F/B ratio of RR.

The results are consistant with those of other experiments. The distributions are consistant for isotropic emission of RR from moving systems.

The average velocities of the moving systems, computed as per two velocity vector model /92, 98/, are compared with the results of some of the other investigations in table 4.9.

Table 4.9 : Forward velocity (RR events) :

Beam	Target	Forward velocity (in c)	Detector	Ref.
0.66 GeV p	AgBr	0.003	Emulsion	/69, 99/
1-3 GeV p	AgBr	0.007	Emulsion	/98/
25 GeV/c p	AgBr	0.004±0.002	Emulsion	/71/
30-350 GeV/c	Xe	0.002	Counter	/100/
	Kr	0.007	Counter	/100/
1.8 GeV/c K^-	AgBr	0.005	Emulsion	P.W.
20 GeV/c p	AgBr	0.005	Emulsion	

The forward velocity of the moving system as estimated from the considerations of particle evaporation alone for the projectiles used in this investigation is slightly lower in magnitude. However, from table 4.9 it may be observed that the average forward velocities of the moving systems lie within about 10^{-3}c to 10^{-2}c. Thus the results are consistant with other investigations.

While investigating the variation of F/B ratio of the target residues of Ta^{181} irradiated with 8.0 GeV Ne^{20}, Loveland et al /101/ observed that the F/B ratio increases rapidly with mass loss from the target nucleus until about 40 nucleons have been lost. With further mass loss the F/B values of the target residues decrease until one reaches the lightest products. Also, it has been observed that the forward momentum transferred by protons to heavy targets peaks at about 2 GeV and then decreases for higher beam energy /102/. Such energy dependence is shown by a number of target fragments most of which are residues /24, 103/. The variation of F/B with N_g, N_b, N_h and the number of nucleous removed (Δ A) for K^- -AgBr interactions are presented in Figs. 4.12 (a), (b), (c) and (d) respectively. In Figs. 4.12 (c) and (d), the F/B ratios in the intervals corresponding to $N_h \simeq$ 13-14 and $\Delta A \simeq$ 35 to 40 nucleons show peaks. Thus the F/B values of RR are likely to be related with the energy transferred and also with the number of nucleons (mass) removed. But there is no peak in Fig. 4.12(a), and in Fig. 4.12(b) there is only a trend for formation of peak in the interval of $N_b \simeq$ 9-11. Thus the effects of cascade and evaporation stages have not been observed separately in respect of formation of peaks in the F/B ratio curves.

In Fig 4.13, the angular distribution of RR in the interval N_h = 13 and 14 is compared with that of all the residues taken together. Though the frequencies of RR at the either ends of the distribution are different, the distribution are consistant for emission of residues from moving systems with different average velocity. The velocity of the moving system from which the residues in the interval N_h = 13 and 14 are emitted, is relatively higher ($\sim$0.01c).

It follows that the forward momentum imparted to the target nucleus by the primary remains prominent with the moving, disintegrating systems until it

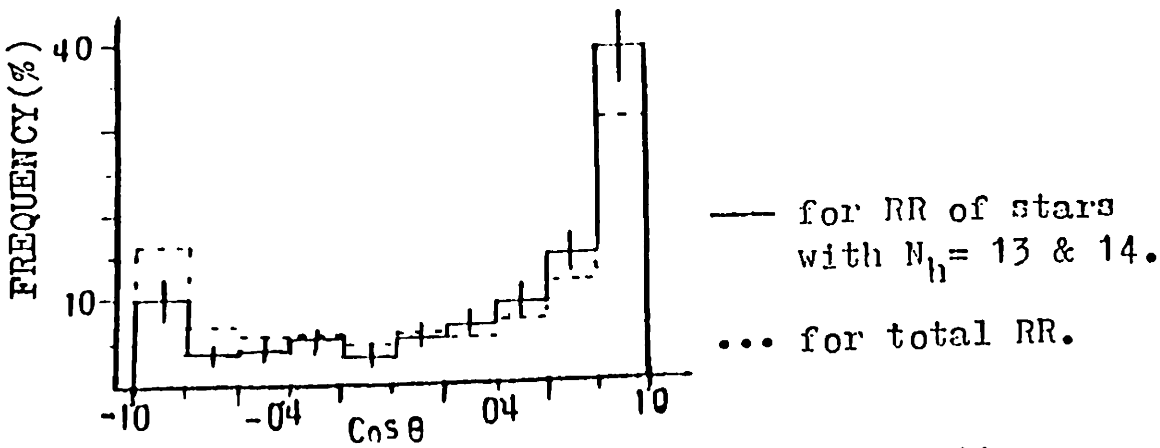

FIG. 4.13:- Comparison of Angular distributions.

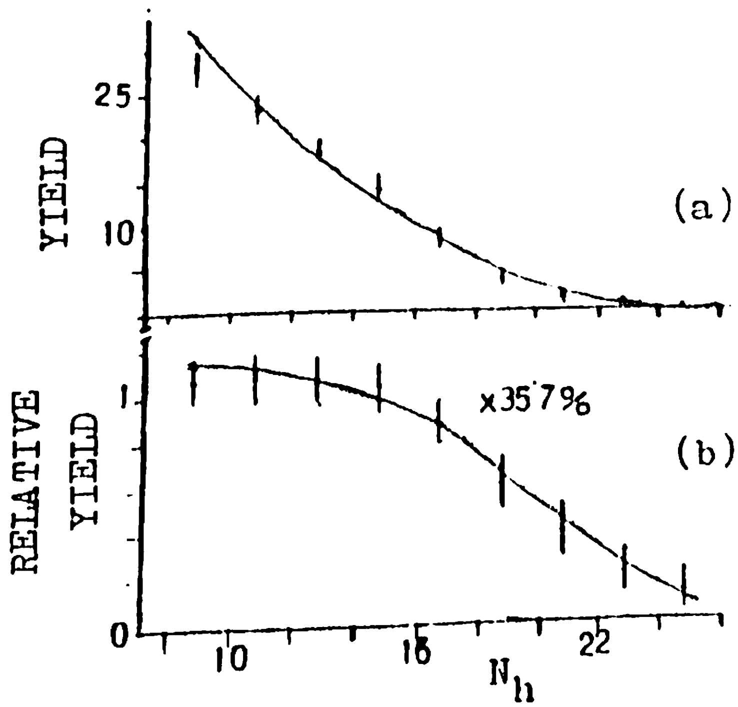

FIG. 4.14:- Yield-N_h plot (RR events).

loses a few nucleons (say about 40) from it, then starts decreasing. However the magnitude of forward momentum transferred, has also an important role. During initiation of intranuclear cascade, the forward momentum transferred to the target nucleus remains at its maximum. Though, along with a decrease in energy (associated with the target nucleus) during ejection of target particles and fragments the average forward momentum may also decrease, it is the recoil momentum which is chiefly responsible for the changes in the direction of ejection of RR.

From the survey of 100 out of 1431 RR stars, the F/B ratio of the black tracks w.r.t. RR is found to be 0.73 ± 0.05 which is in conformity with the other investigations /104/. This indicates that a substantial fraction of the momentum of RR comes from particle evaporation. Also, such a collimation is one of the causes of obtaining higher momentum of RR than expected from random evaporation of particles.

4.3A8 The yield :

The variation in the yield (percent) of RR with N_h is shown in Fig 4.14 (a). The solid curve, drawn to guide the eye only, shows that the yield of RR is likely to decrease exponentially with the increase of N_h.

The variation of relative yield (defined as a fraction of interaction at a particular N_h value of the stars with RR) with the value of N_h is plotted and shown in Fig. 4.14 (b). It seems to conform with the observation /39/ that the spallation products comprise nuclides mainly within about 40 units of target mass and their formation cross-section decrease sharply with the decrease of mass of the products.

4.3B For ST events :

4.3B1 Production frequency and cross-section :

The results in respect of production frequency and cross-section are presented in table 4.10.

Table 4.10 : Frequency and Cross-section of ST :

Beam	Emulsion used (c.c.) (approx.)	Stars Scrutinized	No. of ST	Corrected Freq. (p.c.)	Corrected C.S. (mb)
1.9 GeV/c K^-	123.3	60,000	227	0.76±0.05	0.92±0.06
20 GeV/c p	16.32	5,000	31	1.24±0.22	3.18±0.68

4.3B2 Star size distribution :

Results in respect of the multiplicities of tracks associated with the stars which contain ST, have been shown in table 4.11.

Table 4.11 : Track multiplicities of stars with ST :

Beam	S T Classi-fication.	No. of events	N_h distiribution Fig, No.	N_h Mean	N_b distribution Fig. No.	N_b Mean	N_g distribution Fig. No.	N_g Mean
1.8 GeV/c K^-	R < 20 μm	162	4.15(a)*	13.07 ±0.26	4.16(a)*	9.57 ±0.22	4.17(a)*	3.49 ±0.13
	R ⩾ 20 μm	65	4.15(a)$^+$	13.86 ±0.47	4.16(a)$^+$	10.17 ±0.37	4.17(a)$^+$	3.69 ±0.23
	Forward	123	4.15(b)*	12.96 ±0.32	4.16(b)*	9.38 ±0.26	4.17(b)*	3.58 ±0.15
	Backward	84	4.15(b)$^+$	13.93 ±0.36	4.16(b)$^+$	10.23 ±0.31	4.17(b)$^+$	3.70 ±0.19
	Total	227	4.15(c)*	13.30 ±0.23	4.16(c)*	9.74 ±0.19	4.17(c)*	3.55 ±0.12
20.0 GeV/c p	Total	31	4.15(d)*	15.92 ±0.73	-	-	-	-

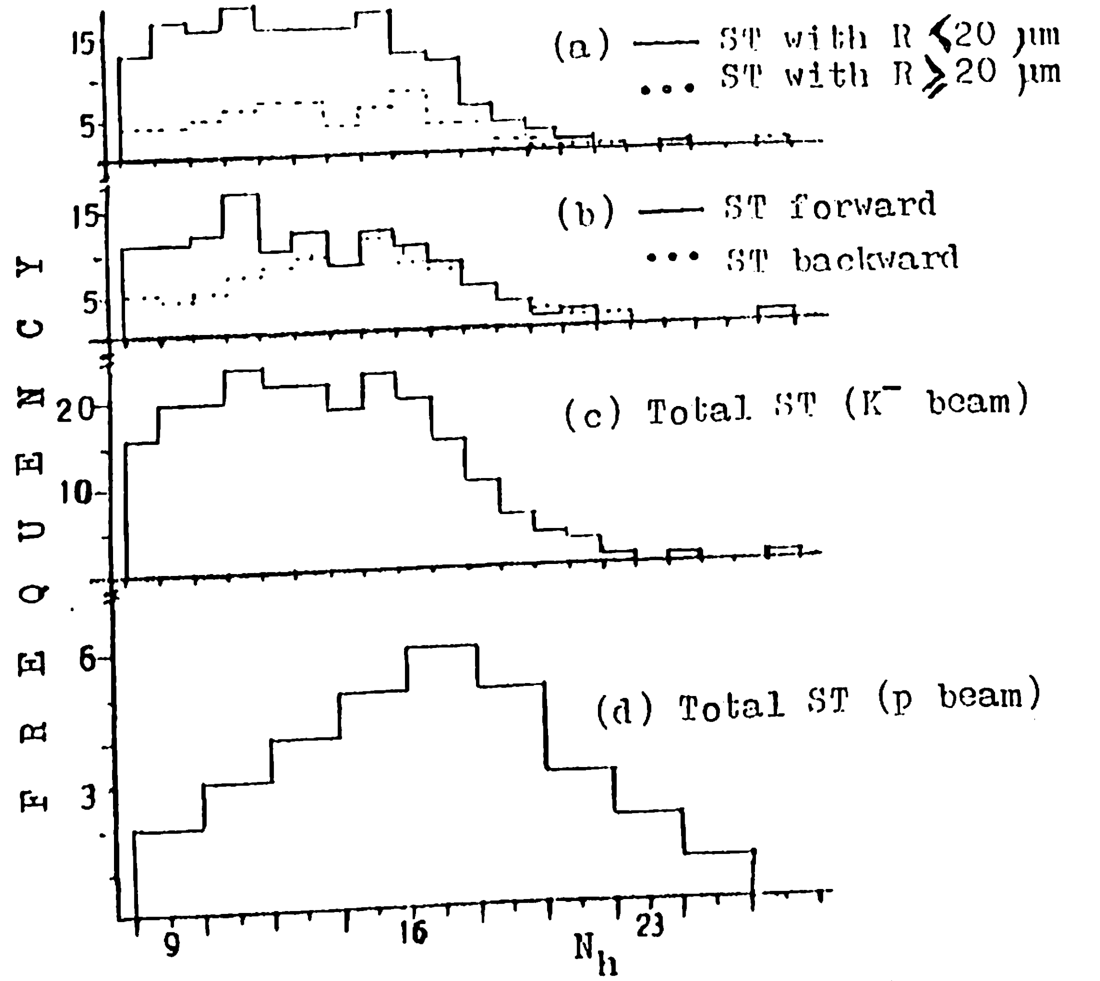

FIG. 4.15:- N_h distribution (ST events).

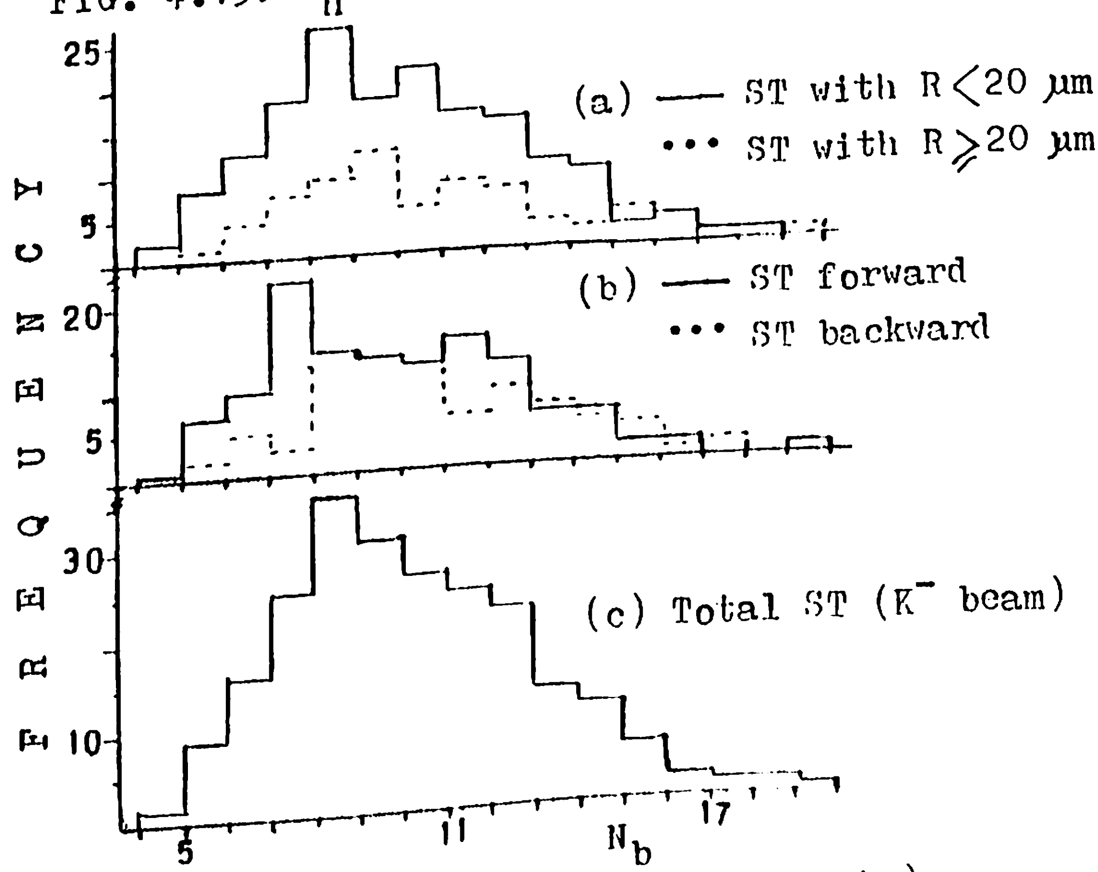

FIG. 4.16:- N_b distribution (ST events).

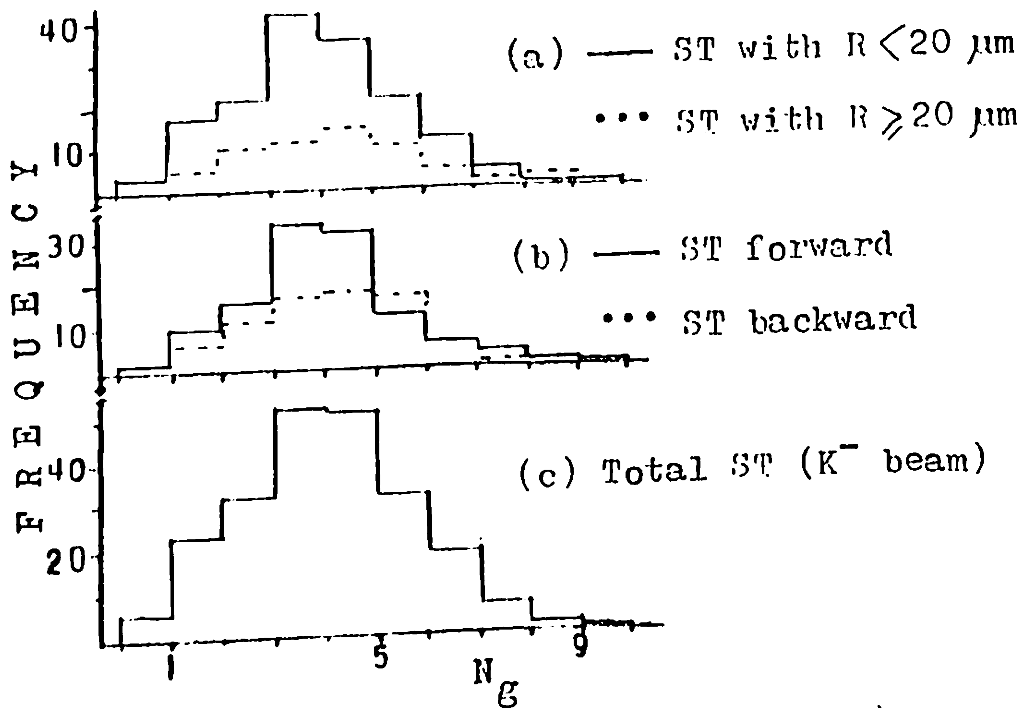

FIG. 4.17:- N_g distribution (ST events).

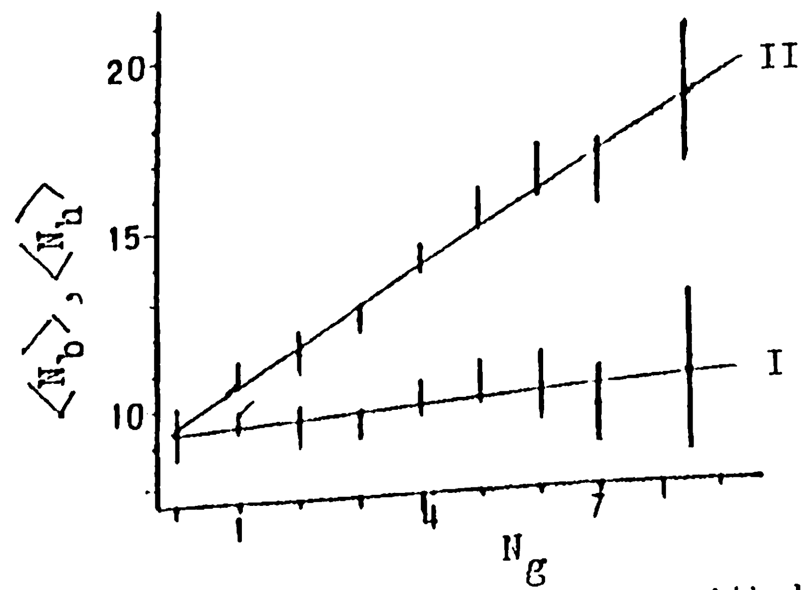

FIG. 4.18:- Relation of N_g with N_b & N_h (ST events).

where, * histograms are represented by continuous lines.

\+ histograms are represented by discrete lines.

The average excitation energy /91/ of the target nuclei producing ST are approximately 450 MeV and 500 MeV respectively for 1.8 GeV/c K^- and 20 GeV/c p interactions.

4.3B3 **Correlation :**

The straight lines marked I and II in Fig 4.18 represents the variation of $\langle N_b \rangle$ and $\langle N_h \rangle$ with N_g for stars with ST; the corresponding least square fits may be represented by

(I) $\langle N_b \rangle = 0.09\, N_g + 9.43$

(II) $\langle N_h \rangle = 1.06\, N_g + 9.48$

Also, the correlation co-efficient "r", 95% confidence interval (CI) of r and slope of N_g -N_b graphs are given in table 4.12.

Table 4.12 : N_b -N_g correlation for stars with ST :

ST Classification.	r	95% CI of r	Slope of N_g -N_b graphs: From r	Slope of N_g -N_b graphs: From data (above)	Remarks
R $<$ 20 μm	+0.05	0.05±0.16	+0.09	-	N_b-N_g Correlations are not significant.
R $\geq$ 20 μm	+0.13	0.13±0.25	+0.21	-	
Forward	+0.13	0.13±0.28	+0.23	-	
Backward	-0.02	0.02±0.22	-0.03	-	
Total	+0.08	0.08±0.13	+0.14	0.09	

The absence of correlation between N_b and N_g is often taken as an indication that the disintegration may proceed through a process other than cascade-evaporation. Also, it has been observed that when the energy deposited to the nucleus (target) is very high and track multiplicities becomes large, processes like multibody break-up of the nucleus may occur or the system may also become unstable; N_b becomes independent of N_g/105/. But, in general even for the events of high multiplicities, it has been observed that charge and mass lost by the target nucleus during the disintegration can be represented by the average probabilities /106/.

4.3B4 Expected charge and mass :

The charge and mass of ST have been estimated as per the evaporation probabilities considered in the light of the section 3.4E, section 4.3A4, section 4.3B3 and consistant with ref./87/. The particulars are presented in table 4.13.

Table 4.13 : Charge and mass of ST (evaporation considerations) :

Beam	Particulars	Fig. No.	Width From	Width To	Expected average value
1.8 GeV/c K^-	Charge (Z)	4.19(a)	7	34	25
	Mass (A)	4.20(a)	11	75	56
20 GeV/c p	Charge (Z)	4.19(b)	11	34	21
	Mass (A)	4.20(b)	21	75	49

Thus the average ST from 1.8 GeV/c K^- and 20 GeV/c p interactions are expected to be in the vicinity of $_{25}Mn^{55}$ and $_{22}Ti^{48}$ respectively. The mean

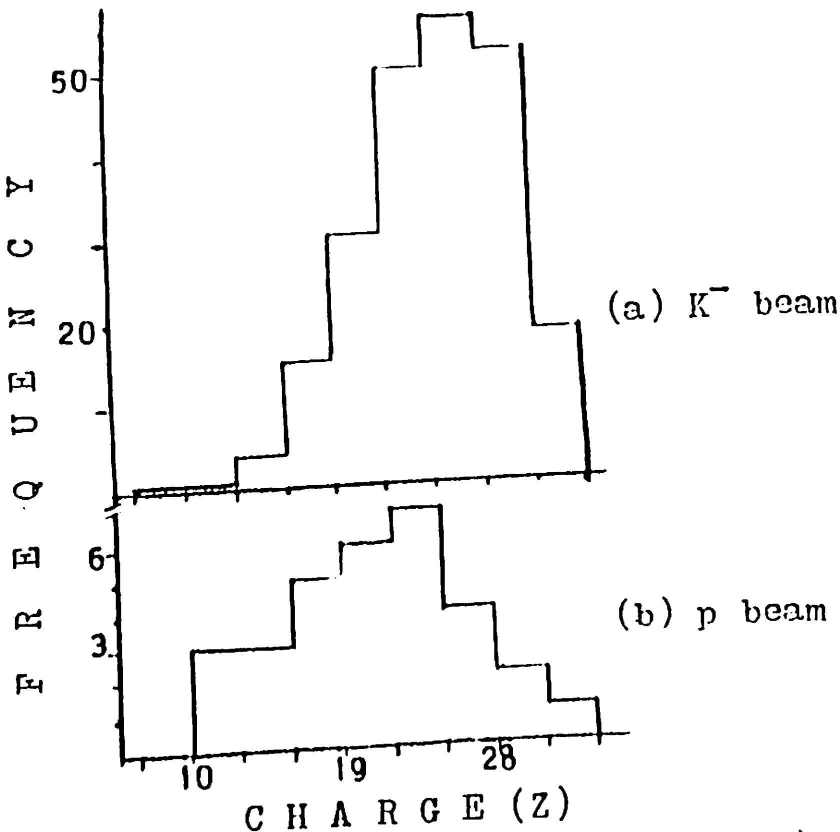

FIG. 4.19:- Charge distribution (ST).

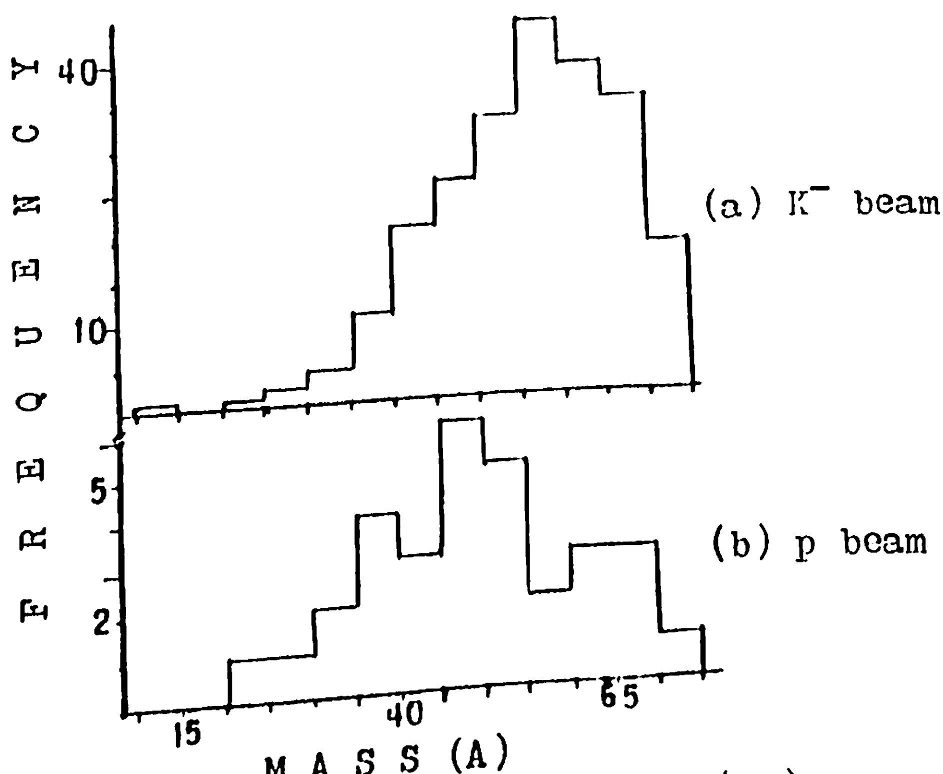

FIG. 4.20:- Mass distribution (ST).

momentum imparted by the evaporated particles are expected to be above 665 MeV/c and 744 MeV/c respectively.

4.3B5 **Range :**

Results from range measurements of ST, summerized in table 4.14, are as follows :

Table 4.14: Ranges of ST :

Beam	ST Classification	Fig No.	Mean Range (in microns)
1.8 GeV/c K^-	Forward	4.21 (a)*	16.79±0.53
	Backward	4.21 (a)+	17.02±0.66
	Total	4.21 (b)*	16.98±0.40
20 GeV/c p	Total	4.21 (c)*	15.90±0.97

* histogram represented by continuous lines.

\+ histogram represented by discrete lines.

Table 4.14 does not show a significant difference among the mean ranges of ST depending on their direction of emission w.r.t. primary.

The observed range limits of ST at different N_h values, represented in Fig 4.22, shows that ST may have any value of range within the observed limits.

The variation of the average value of R with N_h has been shown in Fig 4.23. The least square fit may be represented by

$$\langle R \rangle = 0.10\, N_h + 15.65$$

Within limits of experimental error, no correlation between N_h and R can be observed.

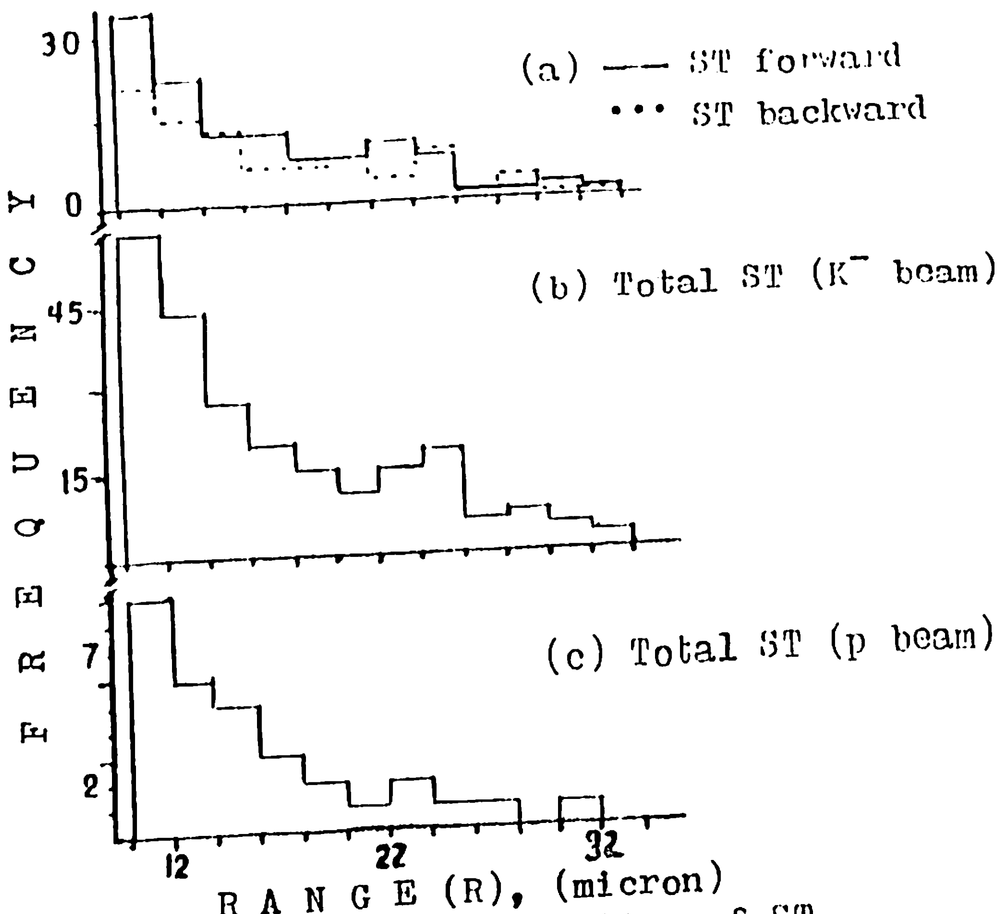

FIG. 4.21:- Range distribution of ST.

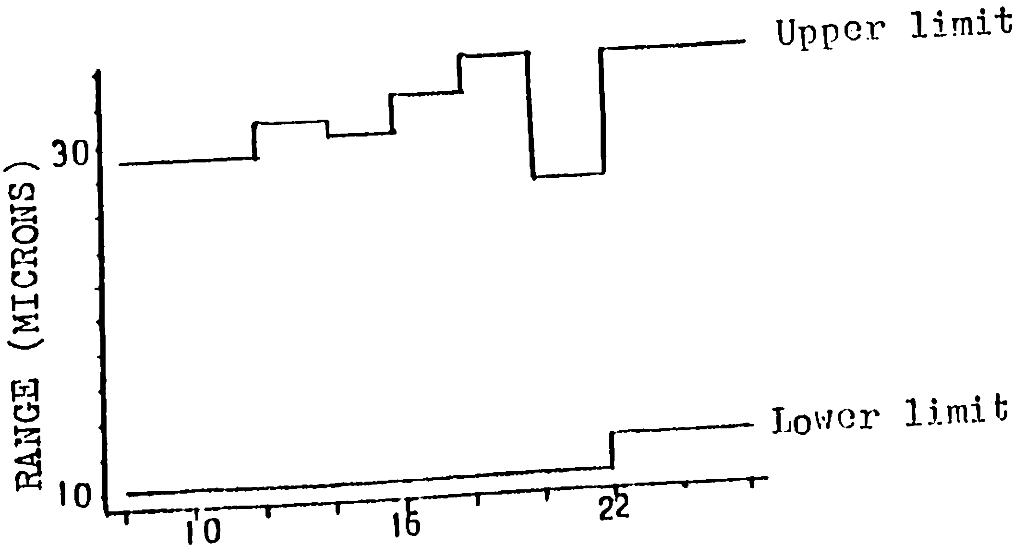

FIG. 4.22:- N_h-range limit plot for ST.

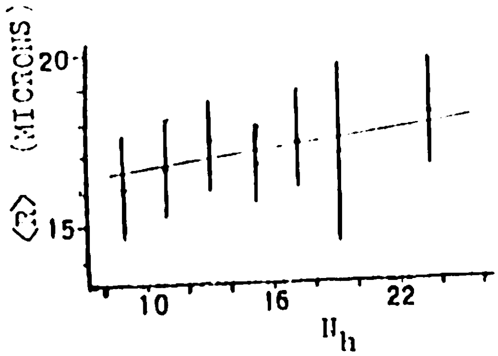

FIG. 4.23:- $\langle R \rangle - N_h$ plot for ST.

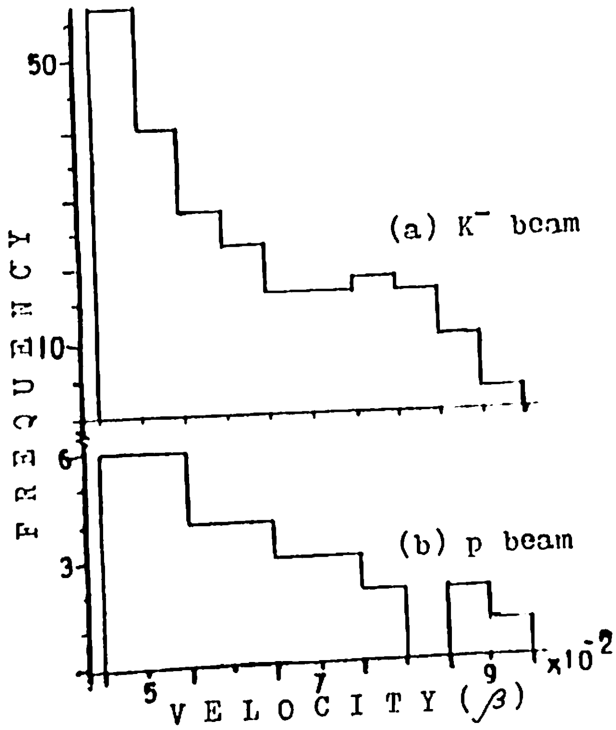

FIG. 4.24:-Velocity distribution of ST.

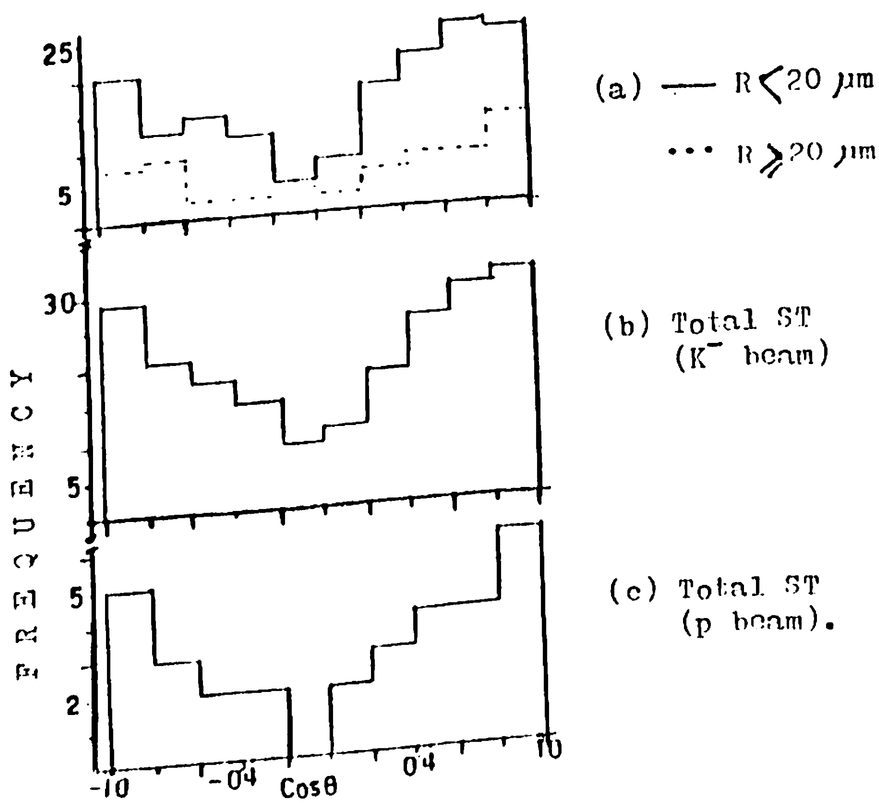

FIG. 4.25:- Angular distribution of ST.

4.3B6. Velocity distributions :

From the range-velocity curves (as in section 2.7) the velocity distributions of ST are found out; the results are summerized in table 4.15

Table 4.15 : Velocity of ST :

Beam	Fig No.	Width (in c) From	Width (in c) To	Mean velocity (in c) approx.	Expected range (microns) from mean velocity
1.8 GeV/c K^-	4.24 (a)	0.045	0.095	0.062	16.6
20 GeV/c p	4.24 (b)	0.045	0.095	0.062	16.4

The velocities expected from evaporation considerations are about 0.013c and 0.017c respectively.

4.3B7. Angular distributions :

Some of the results obtained from angular measurements on ST have been shown in table 4.16.

Table 4.16 : Angular distributions and F/B ratios of ST.

Beam	Classification	Fig. No.	F/B ratio
1.8 GeV/c K^-	$R < 20$ μm	4.25(a)*	1.44±0.24
	$R \geqslant 20$ μm	4.25(a)⁺	1.52±0.41
	Total	4.25(b)*	1.46±0.21
20 GeV/c p	Total	4.25(c)*	1.42±0.53

* histogram represented by continuous lines.

\+ histogram represented by discrete lines.

The average forward velocities of the systems from which the ST are ejected, are found to be about 0.012c and 0.011c respectively. The velocities of the moving systems for ejections of the products receiving momentum only from particle evaporation but with an angular distribution alike the one as observed herein, are about 0.002c and 0.003c. Thus the forward velocities of the moving systems as obtained from evaporation considerations are much lower than those observed herein.

Within limits of experimental error the Fig 4.26, drawn to represent the variation of F/B ratio of ST with N_h, provides no conclusive information in respect of forward peaking of ST.

The average F/B ratio of the black tracks w.r.t. ST in the 227 events found to be 0.53±0.04, indicates that the black track producing particles are preferantially emitted in a direction opposite to the direction of ejection of ST. Consequently the black track producing particles provide considerable momentum towards ejection of ST by directional effects also. Further, such a collimation of the black tracks in a direction opposite to ST, singifies that the short track producing particles under consideration are essentially heavy fragments of the target /104, 107/.

4.3B8. **The Yield .**

The variation of "the percentage of total ST events (yield)" and "the fraction (percent) of reaction emitting ST at various N_h values of the stars (relative yield)" with the change of N_h values of the stars are represented in Figs 4.27(a) and 4.27(b) respectively. The Figs. show that the ST prefers its emission at relatively higher N_h values (degree of break-up) than that for RR.

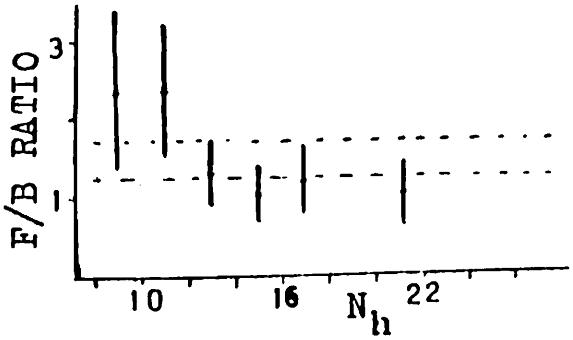

FIG. 4.26:- F/B ratio-N_h plot for ST.

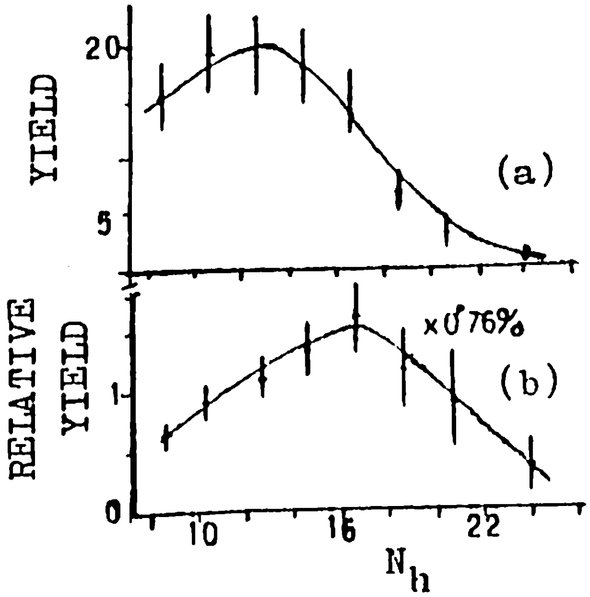

FIG. 4.27:- Yield-N_h plot (ST events).

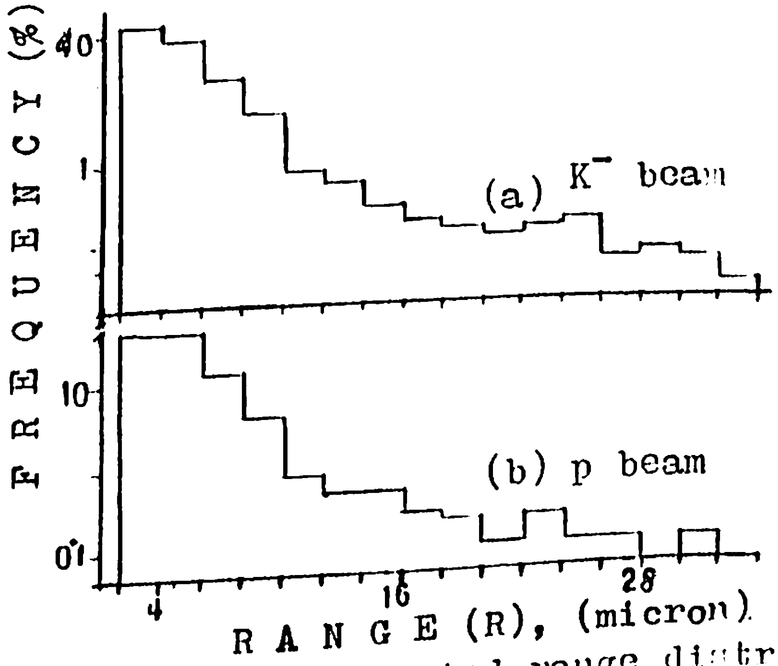

FIG. 4.28:-Integrated range distribution of spallation products.

4.4. SPALLATION PRODUCTS :

There are a number of nuclear disintegrations in each of which only one heavy fragment having high charge and mass (without any other fragment of comparable charge and mass) is obtained. Often such products are termed as spallation products.

The emission of some of the spallation products may be reasonably understood from the cascade-evarporation theory. They are termed as evaporation residues also. The RR's considered herein, are constituted mostly by the products of the kind. Kinetic energies associated with them are relatively low.

More energetic heavy fragments (only one from a disintegration) are also emitted in some of the nuclear disintegrations. They may either be emitted in a fragmentation process /72/, or due to a fast anisotropic process /67/; above all they may be of different origin /73/. The ST's considered herein, may be products of this kind.

However, as the number of heavy fragments associated with a disintegration star in one, the RR's and ST's have been classified as spallation products.

Some of the observed characteristics of RR and ST, and also stars with which they are associated, which probably differ for each type are presented in table 4.17.

Table 4.17 : Some of the observed characteristics.

Classification	$\bar{N}_h$	Excitation energy (MeV) approx.	95% CI of r	Average forward velocity of moving system (in c)
For RR	11.90 ± 0.08	400	0.19 ± 0.05	0.005
For ST	13.30 ± 0.23	450	0.08 ± 0.13	0.012

Table 4.17 shows that ST events are likely to occur at relatively higher excitation energy, there may not be any correlation between the number of black and grey tracks of the corresponding disintegration stars and forward velocity of the moving system ejecting ST is relatively higher. For RR events the average excitation energy is relatively lower the correlation between heavy track multiplicities is significant and the average forward velocity of the moving system ejecting RR is lower.

Further, the observed momentum of ST cannot be understood by considering only the evaporation probabilities. This may either be due to the over estimation of their mass or due to energy obtained by other mechanism or due to a combination of these probabilities. It may be pointed out that such fragments associated with lamda-hyperons have mass(A) in the region from 20 to 40 /72/.

The particulars of the integrated range distribution of the spallation products are presented in table 4.18 and the mean ranges are also compared with that obtained in other investigation.

Table 4.18 : Ranges of spallation products :

Beam	Fig No.	Mean range (in microns)	Ref.
25 GeV/c p	-	5.3 ± 0.4	/71/
1.8 GeV/v K^-	4.28(a)	4.62 ± 0.03	P.W.
20 GeV/c p	4.28(b)	4.89 ± 0.06	P.W.

The frequency of emission of the spallation products obtained in the present investigation are compared with those of the others in table 4.19.

Table 4.19 : Frequency of emission of spallation products :

Beam	Emission frequency (per cent) approx.	Ref.
24 GeV/c p	46 ± 4	/83/
25 GeV/c p	46 ± 8	/71/
1.8 GeV/c K^-	36.5 ± 5.3	P.W.
20 GeV/c p	44.2 ± 6.5	P.W.

The results obtained in this investigation are consistant with those of other investigations.

The cross-section of spallation products obtained in some of the investigations are presented in table 4.20.

Table 4.20 : Cross-section of spallation products.

Beam	Target	Cross-section (mb)	detector	Ref.
0.225 GeV Ar^{40}	Pd^{110}	665±70	ΔE-E Telescope	/27/
0.6 GeV p	Ag	5	Mica	/102/
1.0 GeV p	Ag	13	Mica	/102/
2.0 GeV p	Ag	58	Mica	/102/
3.0 GeV p	Ag	53	Mica	
7.0 GeV p	Ag	69+8	Mica	/108/
		64+13	Macrofol-N	/108/
		77+11	Macrofol-E	/108/
		92+12	Diacel	
		120	Mica	/102/
29 GeV p	Ag	150	Mica	/22 /
29 GeV N^{14}	Ag			
1.8 GeV/c K^-	Ag Br	44.1+6.3	Emulsion	P.W.
20.0 GeV/c p	Ag Br	134.9+19.9	Emulsion	P.W.

Khan et al /108/ by comparing their results obtained by using mica detector with those of Hudis et al /102/ opined that the cross-section of spallation products increases with the increase of beam energy at least upto 13 GeV of protons. It was opined by Hudis et al /102/ that their 4π mica detector recorded only energetc ($E \gtrsim 10$ MeV) heavy fragments ($Z \gtrsim 15$). Thus the opinion of Khan et al may be valid only for such energetic heavy spallation products. The investigations in emulsion, however, show that the cross section of the products may increase only very slowly beyond about 2 to 3 GeV of proton beam energy.

4.5 REMARKS :

The spallation products of Ag, Br nuclei as considered herein, are beleived to be emitted with an average charge and mass around those of Ni or Mn. However, the individual products may have mass(A) varying from 16 to 75. Also, the vast majority of these products have mass above 20. The frequency of the emitted products seems to decrease rather exponentially as one goes towards lighter products. The low energy products (RR) are mostly evaporation residues which may be assumed to be emitted isotropically from a moving system. Most of the high energy spallation products (ST), contributing marginally to the observed cross-section for spallation, are also likely to be of mass greater than 20; and may be assumed to be emitted rather isotropically from a moving system in a relatively faster process.

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CHAPTER V

FISSION

5.1. INTRODUCTION :

One of the important mechanisms of emission of heavy fragments from silver and bromine nuclei is the nuclear fission. The nuclear fission /1/ is a process by which a single nucleus undergoes a cataclysmic rearrangement into two nuclei of comparable mass. Following the state of confusion /2/ arising in the early attempts to synthesise transurénic elements /3/ and the subsequent identification of the product nuclides /4/ which may be due to fission, Bohr and Wheeler /5/ succeeded in obtaining a good understanding /6, 7/ of the fission process on the basis of liquid drop model - the important feature being the interplay of the disruptive Coulomb repulsion and cohesive surface tension.

A great deal of the present knowledge comes from the extensive works done on the problem of fission of heavy elements. The largest amount of data has been obtained from careful study of spontaneous fission with sources such as Cf^{252} and from fission induced to fissile elements like U^{235} by thermal neutrons available in large fluxes with reactors /8, 9/. Such measurements are of fundamental importance for obtaining informations on properties of the scission point where the strongly elongated nucleus actually breaks-up into two fragments. Added interests to fission are comming from the observations like fission isomers /10, 11/, intermediate structure in sub-threshold fission /12, 13/, fast /14-16/ and prompt /17, 18/ fissions, delayed fission /18-21/ and the anomalous behaviour of fission cross-section at extreme sub-barrier energies /22/.

Charge(Z) and mass(A) are two important factors on which the stability of a nucleus against fission depends. The fission barrier height, calculated from a simple liquid drop model, rises to a maximum of about 52 MeV as A increases to about 90 and then falls gradually for heavier nuclei to disappear at high A /23/. The introduction of the region of "Super heavy elements" or "Super elements" /24/ by way of shell corrections /25, 26/ shifts limit for barrier disappearance to higher A. Also, the fission barrier is expected decrease for nuclides placed further and further away from the line of beta-stability /27/. In general for a rotating nucleus, the fission barrier height gets lowered with the increase in the angular momentum /28/. As such, at high angular momentum the nucleus tends to undergo fission /29/.

From a systematic study of fission induced by energetic (few hundred MeV) protons, Perfilov /30/ argued that the inelastic cross-section of elements with $Z \geqslant 94$ should be entirely determined by fission. The fission cross-section of targets like Uranium gradually decreases as the proton projectile energy is increased from about 600 MeV onwards /31, 32/; and binary fission events may even disappear /33, 34/ when the excitation energy deposited to the target nucleus exceeds about 1 GeV. Moreover, at high excitation energies fission does not occur as a predominant mechanism with formation of highly excited fragments, but rather is generally a low energy phenomenon occurring late in the de-excitation chain of the primary cascade residues /35-37/.

Going down the periodic table, for intermediate (medium) mass nuclei as the fission barrier is high and as the total fission products becomes a few MeV heavier than that of fissioning target, it becomes possible to induce fission only by energetic projectile capable of depositing at least about 60 MeV excitation energy to the target /38/. Consequently the excited "Prefission" target nuclei, composed of the parent nuclei and the various daughter nuclei formed by cascade-evaporation, during the process of de-excitation sometimes undergo fission by competing with the evaporation chain.

Various factors probably affect the shape of the mass distribution of fission fragments /39/. The prefission charge distribution /40, 41/, order-disorder motion /42/ and the nucleon exchange /43-45/ processes are some of the mechanisms proposed to explain the mass distribution.

The mass distribution of spontaneous and low energy fission of nuclei in the vicinity of Uranium is predominantly asymmetric /46-50/ caused primarily by the fragment shell effect /51-54/. The most probable split for very heavy nuclei (Z $\sim$ 100) is symmetric /55, 56/. At low energies the mass distributions for fission of nuclei in the vicinity of Radium have three peaks corresponding to both symmetric and asymmetric mass splits /57, 58/. It has been observed that shell effect plays an effective role for fission induced to Bi by 60 MeV protons /59/ and for targets like Uranium the shell effect persists appreciably upto an excitation energy of about 30 MeV/56/ but liquid drop behaviour dominates in W^{182} at an excitation energy of about 20 MeV above the fission barrier /60/. As the excitation energy increases, the probability for division into two equal fragments increases until at high excitation energies the experimental mass distribution for all nuclei becomes peaked about a division into two equal fragments /61, 62/. The transition is probably associated with the decrease of relative importance of single particle (shell) effects at high excitation energies /63, 64/ where nucleons are distributed randomly over a large number of single particle levels /65, 66/. Though there are a few diverse opinions /67, 68/, the nuclei lighter than Bi or Po may be taken to devide primarily into two approximately equal fragments /8, 35, 38, 61, 69-73/ during fission.

A number of workers /5, 74, 75/ have suggested that some of the prompt neutrons may be emitted at the time of scission. For spontaneous and low energy fission of heavy elements, the variation of neutron yield with such paramters of the fission process as the mass division, compound nuclear excitation energy and kinetic energy release, provides important insight to the partition of energy at scission /63, 76-80/.

The largest fraction of energy released in fission goes to the kinetic energy of the fragments - which may be a function of Z and A of the fissioning target nucleus /81, 82/. The prefission kinetic energy may be a governing factor /83, 84/. At very low incident energies, the total (translational) kinetic energy (TKE) has a minimum in the symmetric fission, reaches a maximum in the region of most probable fission and decreases with further increase of asymmetry /8/. As the incident energy is increased, the value of TKE in symmetric fission increases, also its value at the aforesaid most probable fission decreases /85, 86/. Though there is a sizable variation of TKE from event to event, there has been some investigations on the variation of mean TKE with excitation energy and angular momentum also /87-90/. Such variations may arise out of factors like shell and pairing effects /52/, deformation at scission /88/, nuclear surface tension /58/ and nuclear viscosity and friction /84, 91/. Also, some of the prescission rotational energy may appear as the kinetic energy of the separated fragments /92/. For targets lighter than Ra, the maximum TKE occurs for symmetric mass division and falls off with increasing mass asymmetry at a rate dependent on excitation energy and angular momentum.

Further, attempts to gather more and more informations on the process, the occurrence and the outcome of fission are being made by observing fusion-fission events and projectile fission fragments also /16, 93-98/.

During high energy disintegration of silver and bromine nuclei in emuslion, stars are sometimes found to contain a pair of short (within 25 microns), dense tracks presumably due to heavy nuclear fragments. The production of such heavily ionizing heavy nuclear fragments might be due to fission of the disintegrating nuclei /98-101/. Plate No. 4 shows the microphotographs of a few fission events.

The present investigation relates to the study of a pair of heavy fragments emitted from the disintegration nucleus which may result from a binary fission event. Some of the characteristics like charge, mass, velocity and angular distributions are also studied in order to gather informations regarding the emission of these fragments.

5.2. EXPERIMENTAL PROCEDURE AND SELECTION CRITERIA :

Each of the disintegration stars with $N_h > 7$, obtained by area scanning, were scrutinized under high magnification (1875x - oil immersion objective) carefully to detect the presence of a pair of short (range not exceeding 25 microns), dense tracks due to a fission event. To accept only the genuine events the following selection criteria are adopted :

(i) The tracks must have similar track characteristics (such as ionisation, end scattering, tapering and profile width).

(ii) They must be emitted in opposite hemispheres with respect to each other.

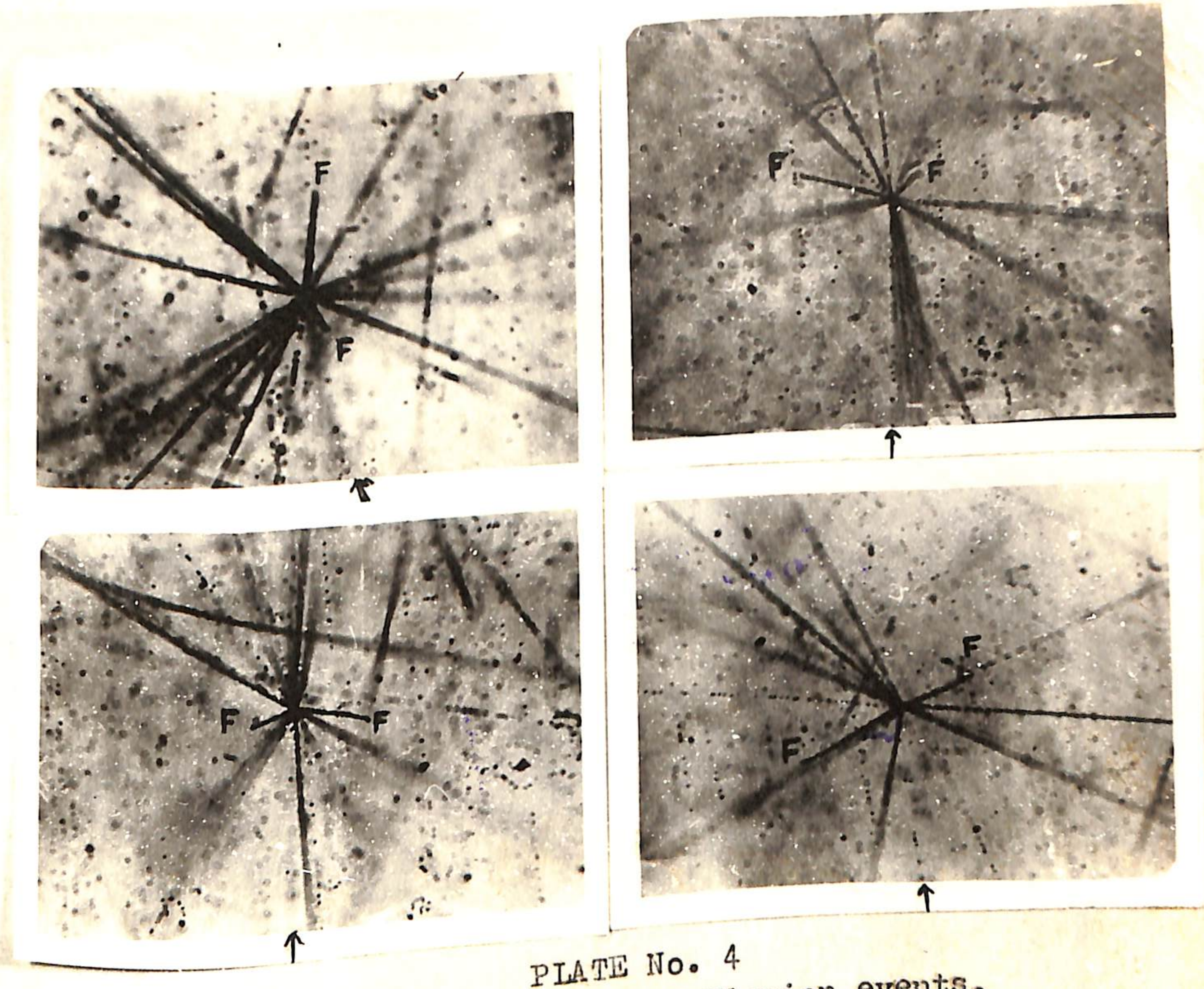

PLATE No. 4
Microphotographs of Fission events.
F represents the fragments,
arrow head for beam
direction.

(iii) The range ratio of the pair of tracks should not exceed 5.

(iv) The dip angle for the tracks under consideration should not exceed 45° in unprocessed emulsion in order to facilitate a check-up of the track profile.

5.3. RESULTS AND DISCUSSIONS :

5.3A. Frequency and cross-section :

The results in respect of frequency and cross-section of fission events are presented in table 5.1.

Table 5.1 : Frequency and cross-section of fission events :

Beam	Emulsion used (c. c.) (approx.)	Stars scrutinized	No. of fission events	Corrected	
				Freq. (p.c.)	C. - S. (mb)
1.8 GeV/C K^-	82.2	40,000	1208	6.04±0.18	7.31±0.22
20 GeV/c p	16.32	5,000	177	7.08+0.54	21.59+1.65

Some details derived out of the measurements from 640 events from 1.8 GeV/c K^- interactions and 177 events from 20.0 GeV/c p interactions with Ag, Br nuclei are presented in the following sections.

5.3B. Star size distribution :

The particulars of the distributions for track multiplicities and the mean multiplicities are given in table 5.2.

Table 5.2 : Track multiplicities of stars (fission events) :

Beam	No. of Stars	N_h distribution		N_b distribution		N_g distribution	
		Fig. No.	Mean	Fig. No.	Mean	Fig. No.	Mean
1.8 GeV/c K^-	640	5.1(a)	13.27±0.14	5.2	9.78±0.11	5.3	3.48±0.06
20 GeV/c p	177	5.1(b)	15.34±0.31	-	-	-	-

The average excitation energies obtained are about 450 MeV and about 485 MeV respectively for 1.8 GeV/c K^- and 20 GeV/c p interactions showing fission events.

5.3C. Correlation :

The straight lines marked I and II respectively show the variation of average values of N_b and N_h with N_g in Fig 5.4 for stars associated with fission events. The least square fits may be represented by the equations

$$\text{(I)} \quad \langle N_b \rangle = 0.32\, N_g + 8.82$$

$$\text{(II)} \quad \langle N_h \rangle = 1.31\, N_g + 8.91$$

The correlation, with co-efficient +0.30, is found to be significant; the corresponding value of 95% confidence interval is 0.30±0.07. The excitation energy deposited to the target nucleus may be the correlating factor.

5.3D. Charge and mass distributions :

The relevant details for the estimation of charge and mass of the prefission nuclei are similar to those for the residual mass as has been shown in section 3.4E. They are consistant with ref./102/. The particulars for the charge and mass

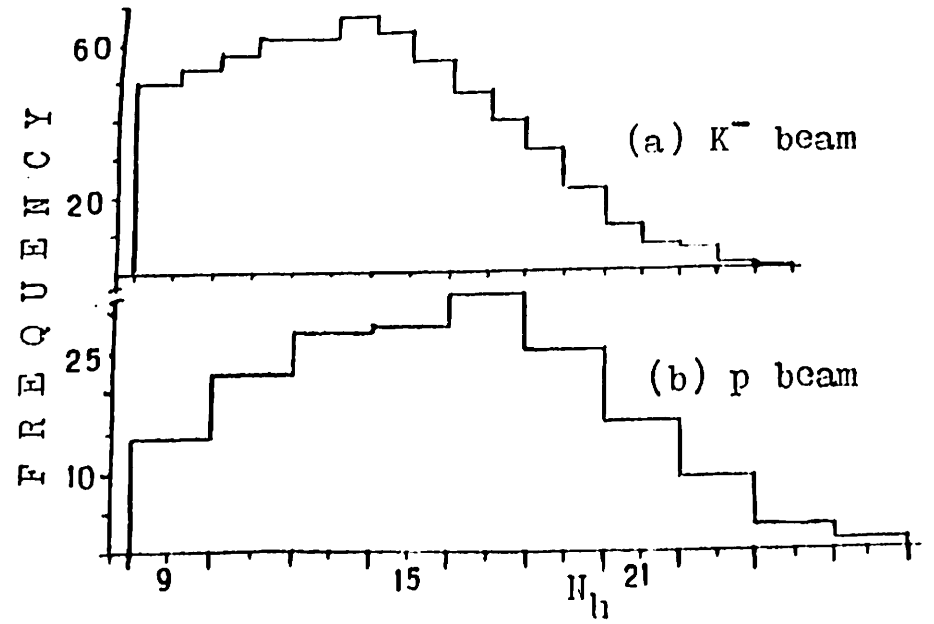

FIG. 5.1:- N_h distribution (fission events).

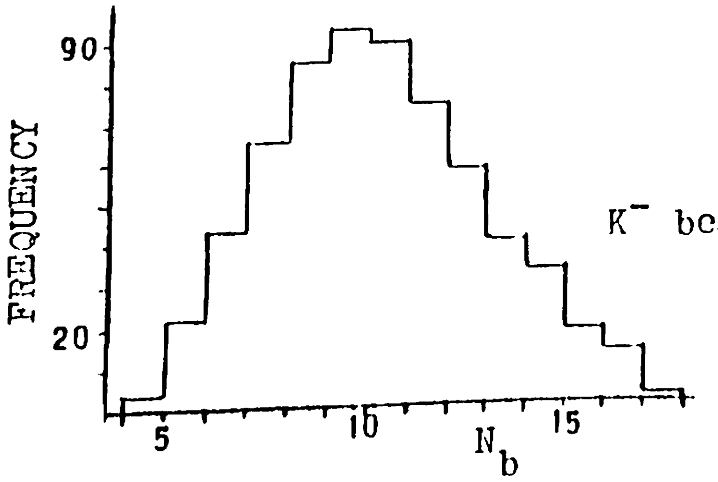

FIG. 5.2:- N_b distribution (fission events).

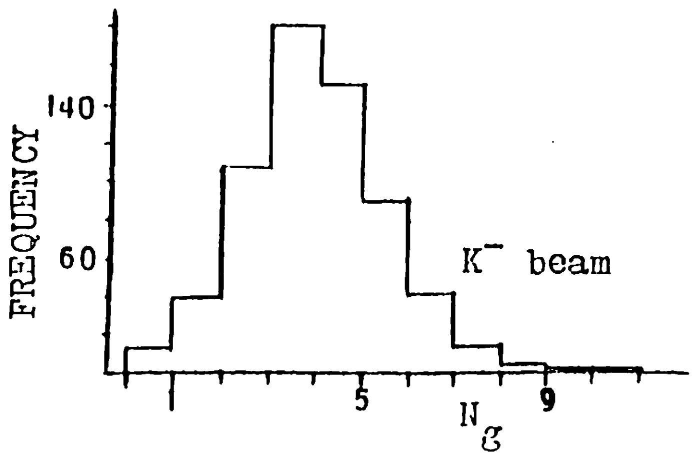

FIG. 5.3:- N_g distribution (fission events).

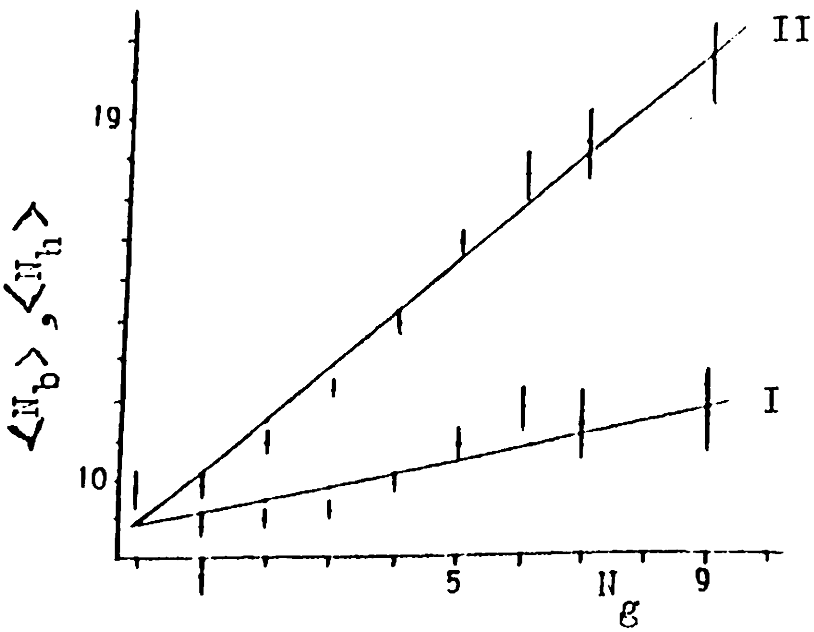

FIG. 5.4:- Relation of N_g with N_b & N_h. (fission events).

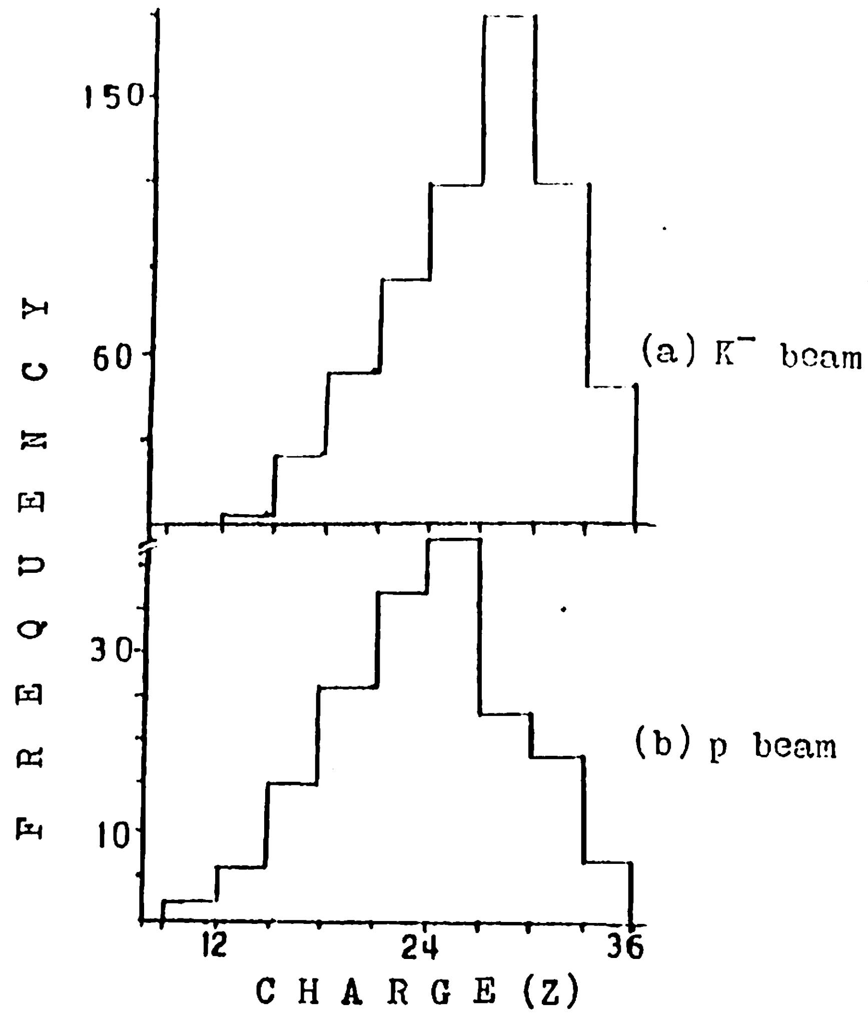

FIG. 5.5:- Prefission charge distribution.

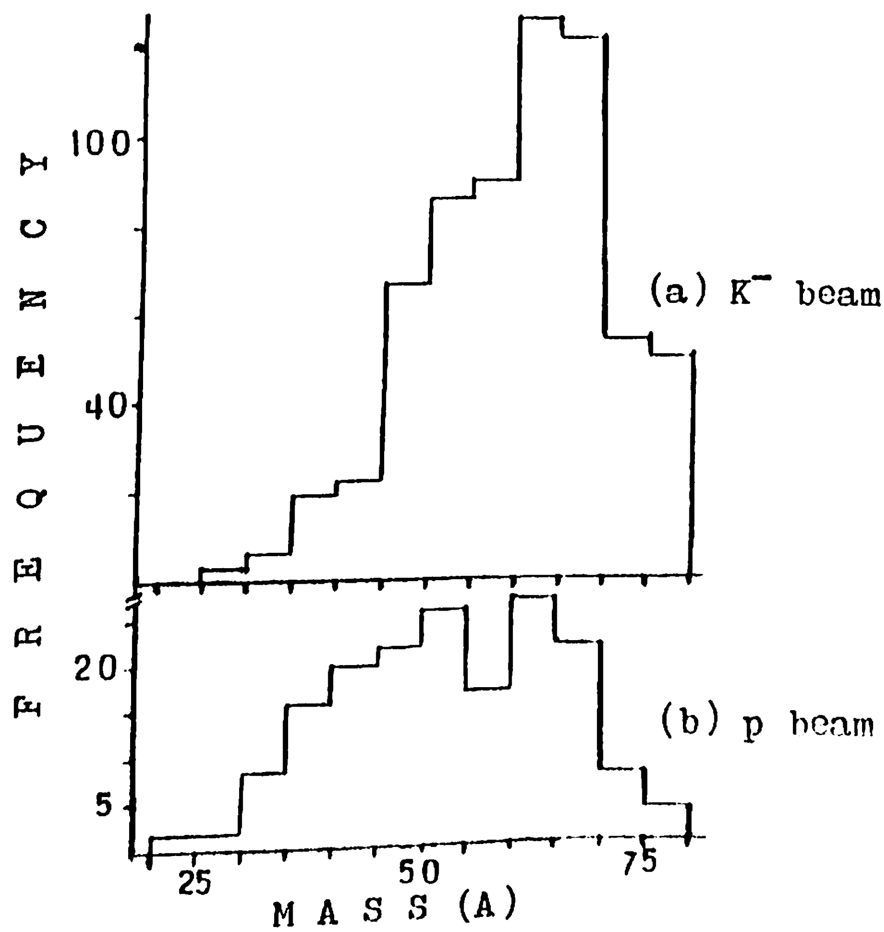

FIG. 5.6:- Prefission mass distribution.

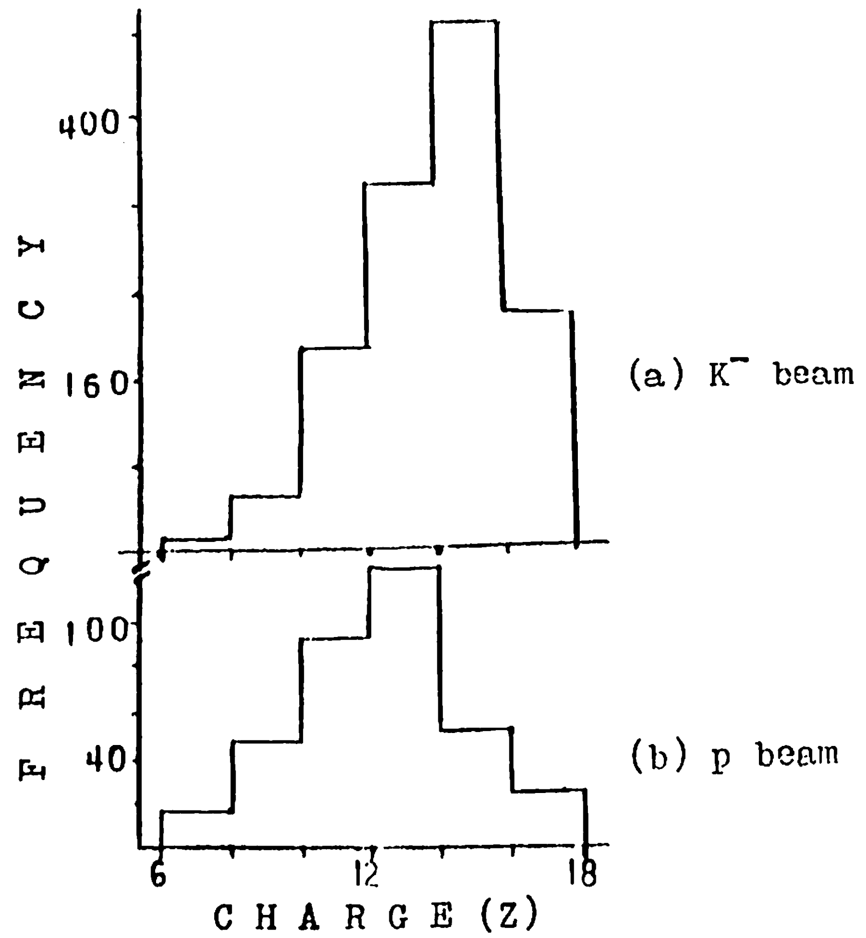

FIG. 5.7:- Charge distribution of fission fragments.

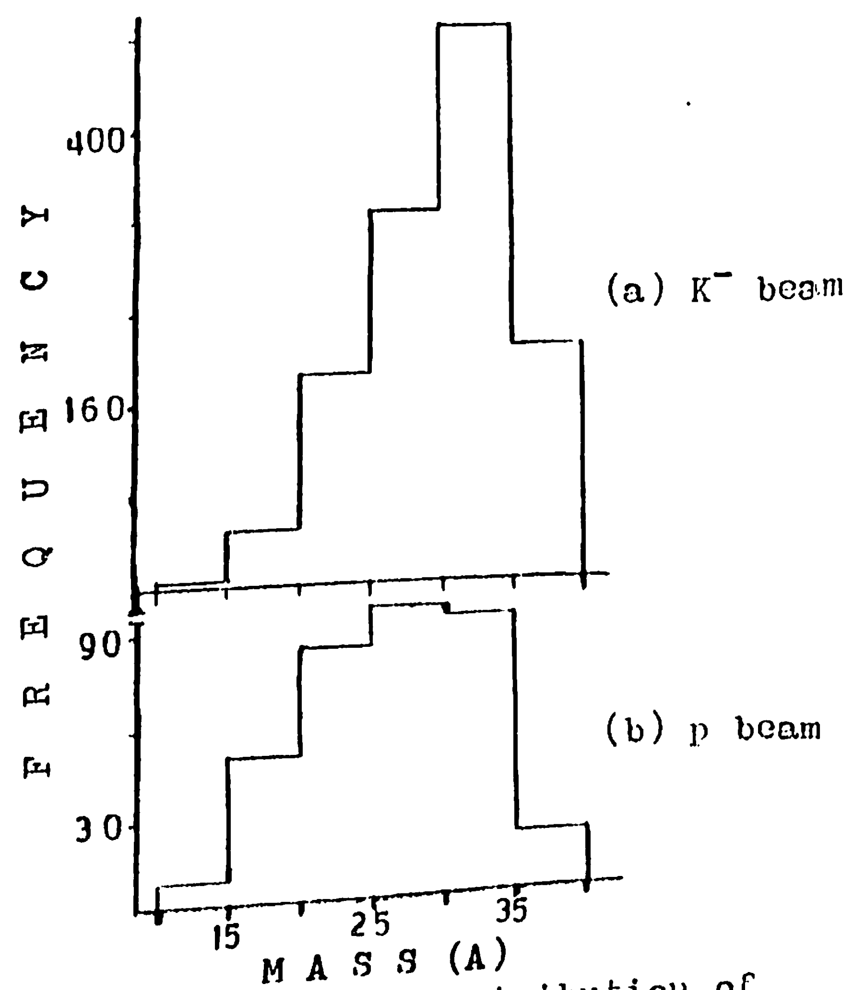

FIG. 5.8 :- Mass distribution of fission fragments.

distributions to correspond the prefission nuclei and also the fission fragments obtained by assuming symmetric division of the prefission nuclei, are given in table 5.3; also, the average values obtained from the distributions are presented in the table.

Table 5.3 : Charge and mass estimations (fission events) :

Beam	Particulars	Prefission nucleus Fig. No.	Prefission nucleus Width From	Prefission nucleus Width To	Prefission nucleus Mean (approx)	fission fragment Fig No.	fission fragment Width From	fission fragment Width To	fission fragment Mean (approx)
1.8 GeV/c K^-	Charge (Z)	5.5(a)	12	35	26	5.7(a)	6	17	14
	Mass (A)	5.6(a)	26	80	60	5.8(a)	11	40	30
20 GeV/c p	Charge (Z)	5.5(b)	9	35	24	5.7(b)	6	17	12
	Mass (A)	5.6 b)	21	80	54	5.8(b)	11	40	27

Thus the average prefission nuclei may lie in the vicinity of Ni^{58} and Cr^{52}; and the corresponding average fission fragments may lie in the vicinity of Si^{28} and Mg^{24} respectively.

Katcoff /103/ argued that the charges of the individual fission fragments should lie between 7 and 17; and masses should range from 15 to 35. The values obtained here are in excellent agreement with his estimations.

5.3E **Range of fission fragments :**

The details in respect of range distributions and mean values of ranges are given in table 5.4.

Table 5.4 : Range of fission fragments :

Beam	Fig. No.	Mean Range (in microns).
1.8 GeV/c K^-	5.9 (a)	9.82±0.10
20 GeV/c p	5.9 (b)	10.11±0.20

Fig. 5.10 which shows that the limiting range of any individual fission fragment does not depend on N_h, is in conformity with the earlier observations /104, 105/.

However, as shown in Fig. 5.11, the mean ranges of fission fragments associated with stars of different N_h values show a definite trend of its variation with N_h. From range-energy relations /106, 107/ it may be observed that at very high N_h, on the average, the TKE release from fission may rather decrease.

The mean TKE release from fission, estimated from the range-energy relations /106, 107/, is about 55 MeV. The values so estimated are compared with the results of some of the other investigations in table 5.5.

Table 5.5 : Mean TKE.

Beam	Target	TKE (MeV)	Ref.
124 MeV N^{14}	Ag	65-85	/108/
	Se	55-60	
	Br	30-45	
0.6 GeV p	Ag	62±4	/109/
1.8 GeV/c K^-	Ag, Br	55	P.W.
20 GeV/c p	Ag, Br	55	

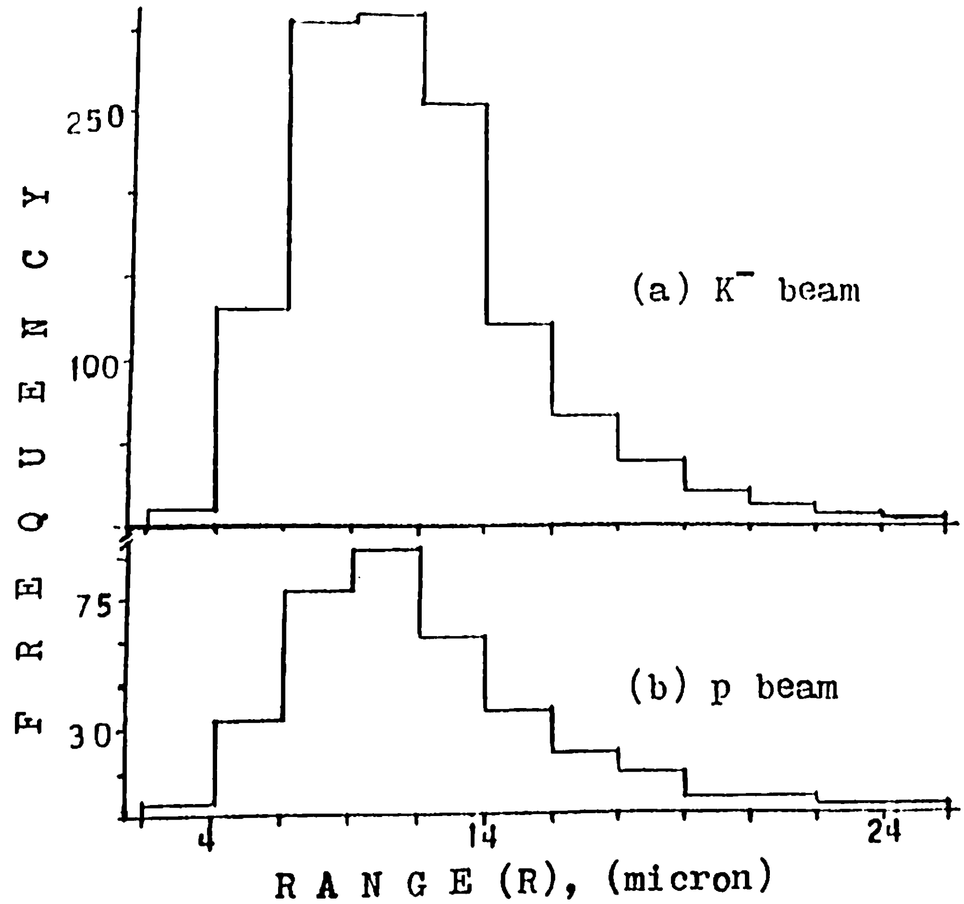

FIG. 5.9:- Range distribution of fission fragments.

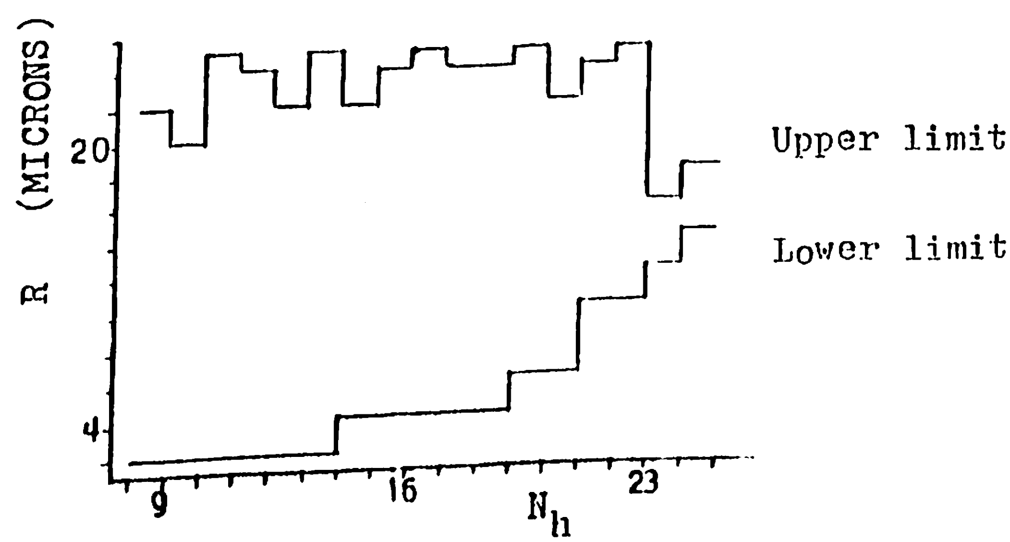

FIG. 5.10:- N_h-range limit plot for fission fragments.

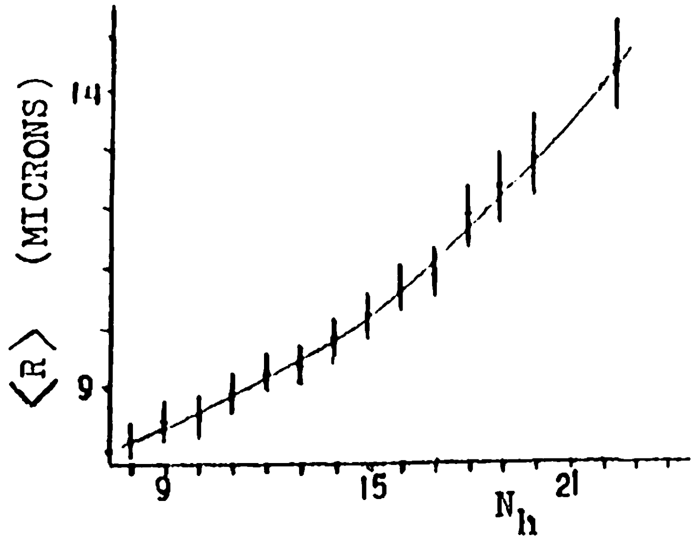

FIG. 5.11:- $\langle R \rangle$ - N_h plot for fission fragments.

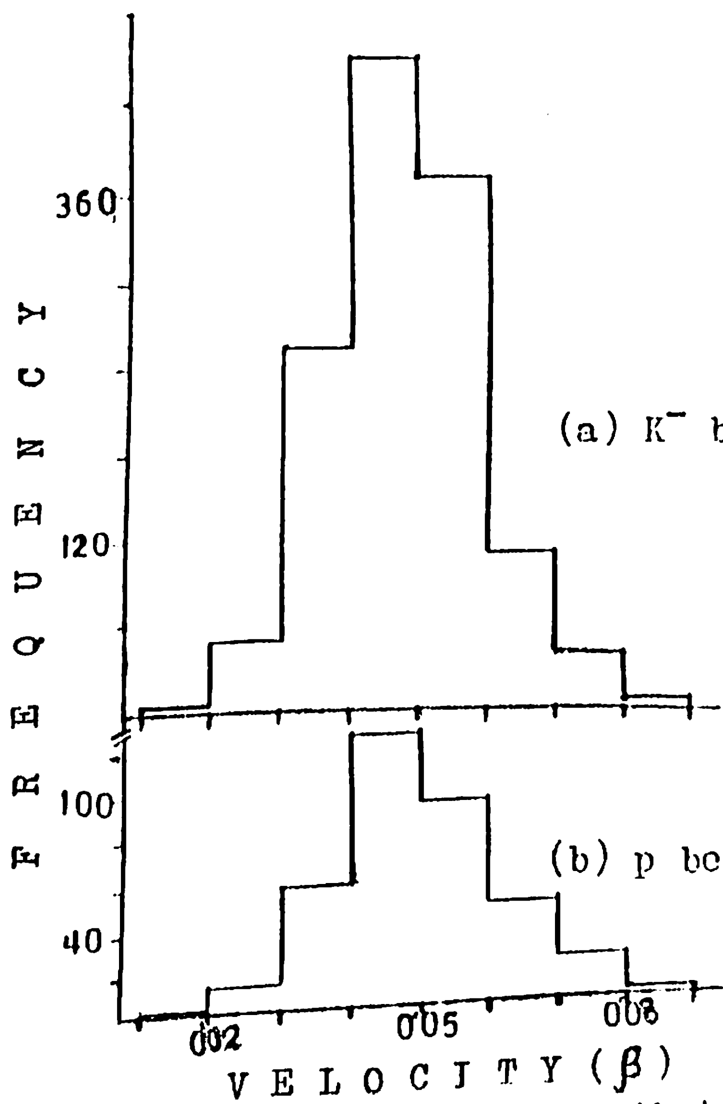

FIG. 5.12:- Velocity distribution of fission fragments.

Considering the average fission fragments (sec.5.3D) as charged spheres, the Coulomb energy for two touching fission fragments may be calculated by taking values of r_o (the radius constant) from Ref. /110, 111/. The values are nearly 42 MeV and 33 MeV respectively. This shows that the fragments acquire kinetic energy from other sources also. Various factors including the recoil momentum, excitation energy, angular momentum of the prefission nucleus and deformations contribute to the kinetic energy and also introduce a large variation of its value for individual fragments. Thus such factors are responsible for introducing a large width in the velocity distribution of fission fragments (section 5.3F).

5.3F **Velocity distribution :**

The velocities of the fission fragments are obtained from range velocity graphs (as in section 2.7) and the particulars relating to the distributions are shown in table 5.6.

Table 5.6 : Velocity distribution of fission fragments :

Beam	Velocity distribution				Estimated range (in microns)
	Fig. No.	Width (in c) From	Width (in c) To	Mean (in c) approx.	
1.8 GeV/c K^-	5.12(a)	0 01	0.09	0.048	9.6
20 GeV/c p	5.12(b)	0.01	0.09	0.050	10.1

The following are the possible causes of the observed width of the velocity distributions.

(i) **Coulomb width :**

The Coulomb energy for different fission fragments will depend on the charges of the various prefission nuclei formed during the competing cascade-evaporation process. This broadens the Coulomb velocity (V_C) distribution of the products. The width can be obtained only by estimating the charges of the individual fragments.

(ii) **Width due to recoil velocity :**

The prefission nuclei acquire a resultant recoil momentum and have velocity due to ejection of particles and fragments from the target nuclei by an extent similar to those of the corresponding RR. The velocity distribution of RR have widths as 0.005c to 0.05c and 0.005c to 0.055c with mean values of about 0.022c and 0.024c respectively (section 4.3A6). This affects the velocity distribution of the fission fragments to a great extent.

As the recoil velocity of the prefission nucleus V_R and the Coulomb velocity of the fission fragments V_C may assume any oriantation with respect to each other, on the extreme ends the resultants will be $V_C + V_R$ when they are parallel and $V_C - V_R$ when they are antiparallel. This shows that the recoil velocity may affect the velocity distribution of the fission fragments to a very large extent.

(iii) **Other factors contributing to the observed width :**

The initial impact of the primary has an aggregate effect to move the fissioning system in the forward direction. This adds to the width of the velocity distribution of the fission fragments.

The Coulomb energy is shared by the pair of fission fragments as per the law of conservation of momentum. Consequently any asymmetry in the charge or mass division is likely to add to the width of the velocity distribution.

The deformation energy at scission /35, 53/, angular momentum, excitation energy, probable evaporation of neutrons from fission fragments and nuclear properties like surface tension, viscosity of the prefission nucleus and mass to charge ratio of the fission fragments are a few likely causes which may add to the width of the velocity distribution of the fragments.

5.3G. Range ratios and velocity ratios :

For the symmetric fission of a nucleus at rest as the ranges of the fragments will be equal, the range ratio will be equal to unity. However, if the fission is asymmetric the lighter fragment due to its higher velocity will have higher range than that for the heavier fragment /99/ which results in a range ratio greater than unity.

The situation differs during high energy disintegrations where the prefission nucleus normally remains moving. As a result even for symmetric fission, except when V_C is perpendicular to V_R, the range ratio as well as the velocity ratio will be greater than unity. The maximum values of these ratios will be obtained when one of the fission fragments move parallel to V_R while the other moves oposite to it.

If the velocity of a prefission nucleus V_R is 0.022c and the velocity of the fragments due to Coulomb repulsion V_C is 0.048c, and if one of the fission fragments moves parallel to V_R while the other becomes antiparallel, then the velocity of the parallel fragment will be 0.07c and that of the antiparallel fragment will be

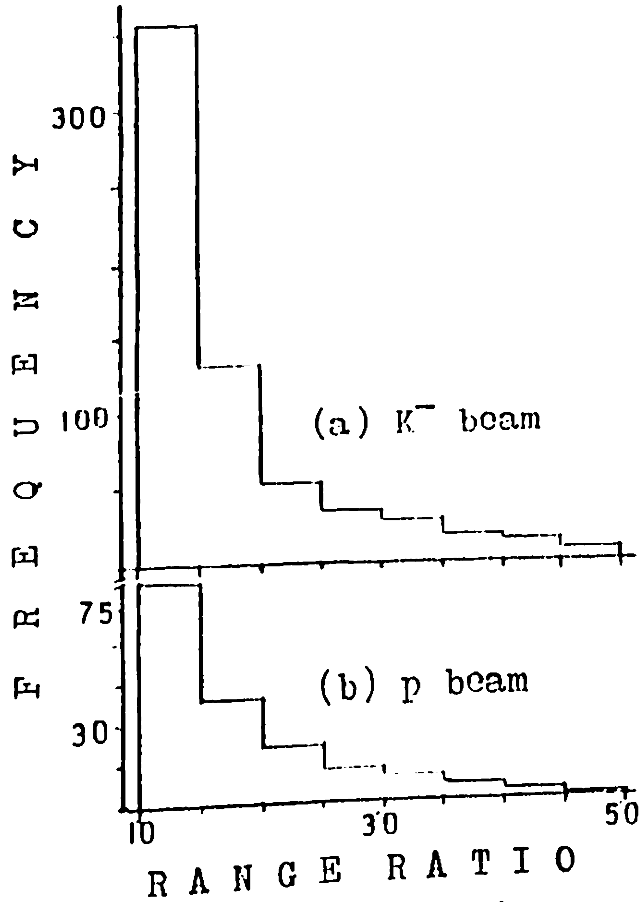

FIG. 5.13:- Range ratio distribution.

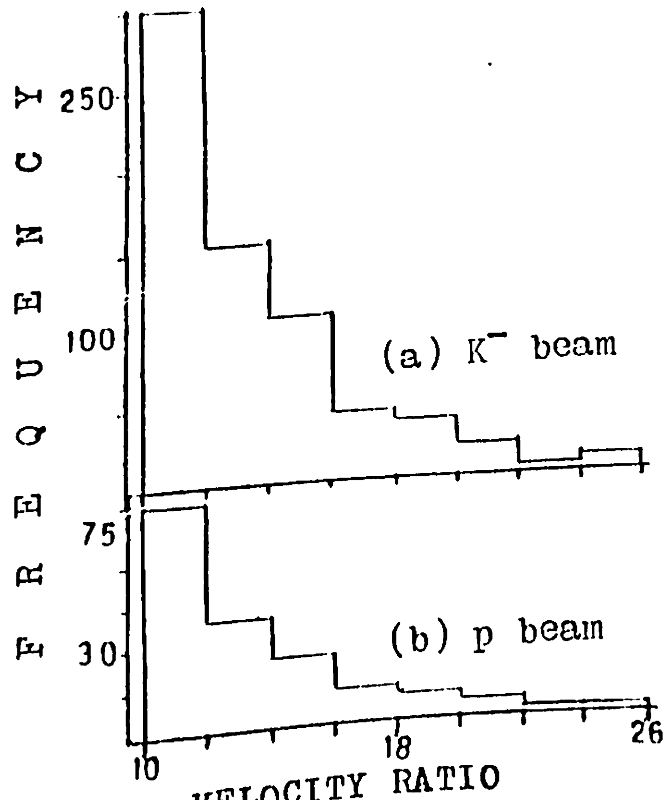

FIG. 5.14:- Velocity ratio distribution.

0.026c. For a Si^{28} fragment the corresponding ranges in emulsion are about 18.8 microns and 3.7 microns respectively. Thus the range ratio becomes about 5 and the velocity ratio, about 2.7.

The effect of other factors which are likely to add to the width of the velocity distribution (section 5.3E (iii)), some of which cannot be determined also, are not considered here as the effect of recoil velocity is considered at the maximum of the average values.

The details for the range ratio histograms and velocity ratio histograms are shown in table 5.7.

Table 5.7 : Range ratios and velocity ratios :

Beam	Particulars	Fig. No.	Width From	Width to	P. C. of events with ratio $\leqslant 2$
1.8 GeV/ c K^-	Range ratio	5.13(a)	1	5	86
	Velocity ratio	5.14(a)	1	2.6	95
20 GeV/c p	Range ratio	5.13(b)	1	5	70
	Velocity ratio	5.14(b)	1	2.6	93

From table 5.7 it may be observed that the pairs of fragments studied are due to symmetric fission of the prefission nuclei. This is in conformity with the other observations /8, 38, 61, 69-73, 112-115/.

5.3H. Angle between fission fragments (folding angle) :

Fig. 5.15(a), (b) represents the distribution for angular separation between the fission fragment pairs. The average space angle between the pairs of fission

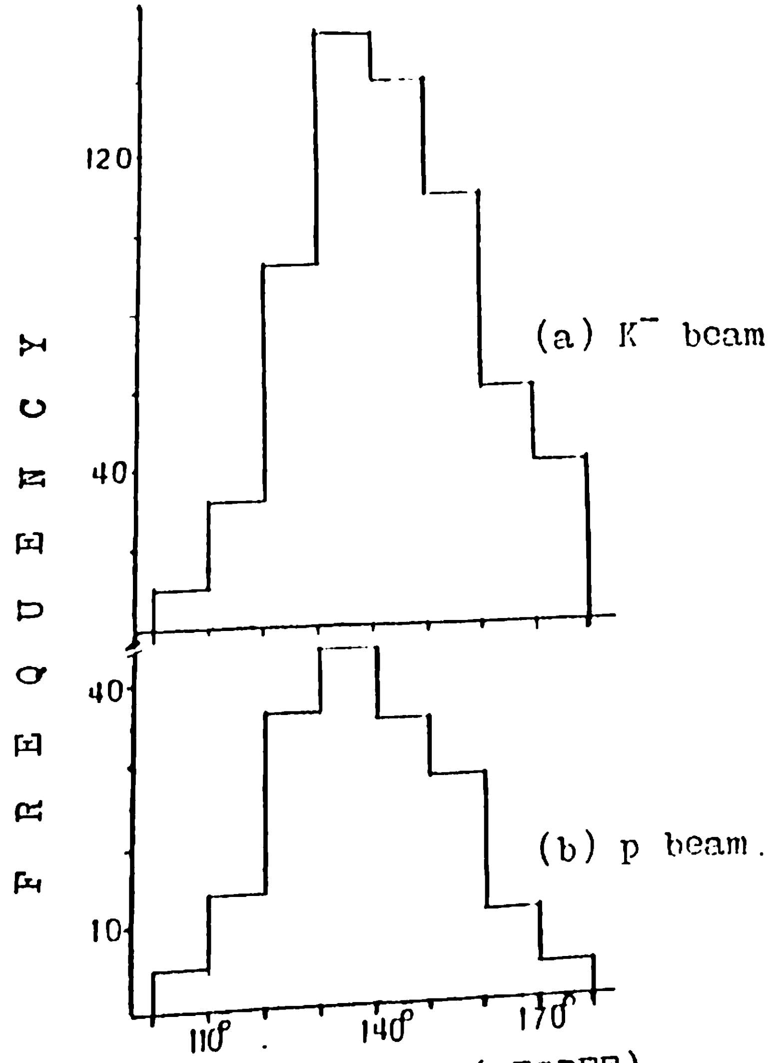

FIG. 5.15:- Folding angle distribution.

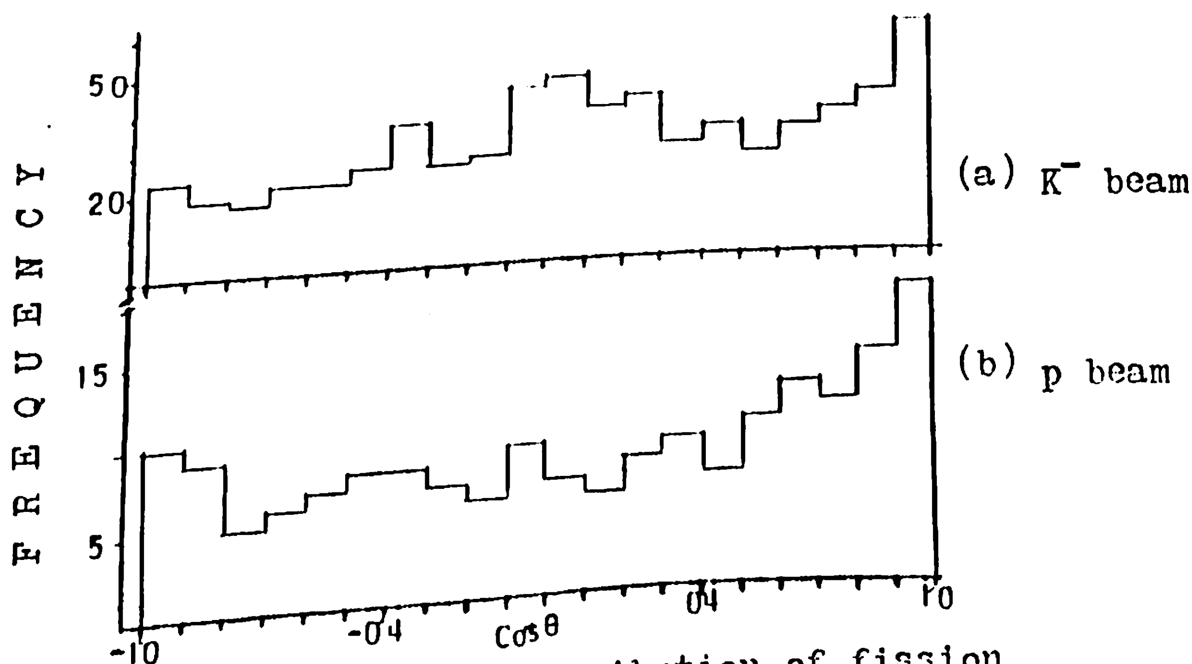

FIG. 5.16:- Angular distribution of fission bisectors.

fragments in 1.8 GeV/c K^- interactions and 20 GeV/c p interactions are about 143° and 138° respectively. Such a collimation between the fission fragments is always expected for fission of a recoiling nucleus. The observed angular separations, however, are likely to have an effect due to other collective motions like rotation of the prefission nucleus.

5.31. Angular distribution of the fission bisectors :

As the collimation of the fission fragments is beleived to be due to motion of the prefission nucleus, to a first approximation the bisector of the angle between the pair of fragments may be taken as the direction of motion of the prefission nucleus. Thus the angular distribution of the fission bisector approximately represents the angular distribution of the prefission nucleus. Some details of the distributions along with some of the informations derived from them are shown in table 5.8.

Table 5.8 Angular distribution of the fission bisector :

Beam	Fig. No.	F/B Ratio	Av.angle* (degrees) (approx.)	Forward+ velocity (in c) (approx.)
1.8 GeV/c K^-	5.16(a)	1.58±0.15	82	0.003
20 GeV/c p	5.16(b)	1.48±0.25	83	0.003

* Average angle of fission bisector w.r.t. primary.

\+ forward velocity of the moving system due to the impact of primary.

The distributions for the fission bisectors (Fig. 5.16(a), (b)) indicate that the resultant momentum transferred by the evaporated particles to the prefission nucleus are isotropically distributed in a system moving in forward direction with respect to the incident primary. The estimated value of the forward velocity, however, may be slightly lower than the actual one. Because, the collective motions like rotation of the prefission nuclei are likely to increase the angle between the fragments (folding angle). Thus the forward velocity may be under-estimated.

Fig. 5.17(b) shows the variation of F/B ratio of the fission bisectors with N_h. The variation of the F/B ratio of the recoiling residues (RR) with N_h may also be represented by Fig. 5.17(a). From these it may be observed that, within limits of experimental error, the variations are similar.

Some aspect of prefission nuclei are compared with those of RR in table 5.9.

Table 5.9 : Some aspects of prefission nuclei and RR.

Beam	Event	Excitation energy (MeV)	Estimated mean (approx.) Charge (Z)	Mass (A)	F/B ratio	Angular distribution
1.8 GeV/c K^-	Fission	450	27	61	1.58±0.15	isotropic
	RR	400	27	61	1.58±0.09	isotropic
20 GeV/c p	Fission	485	24	54	1.48±0.25	isotropic
	RR	430	25	57	1.50±0.16	isotropic

The above results indicate that the process of production of prefission nuclei may be similar to that of RR.

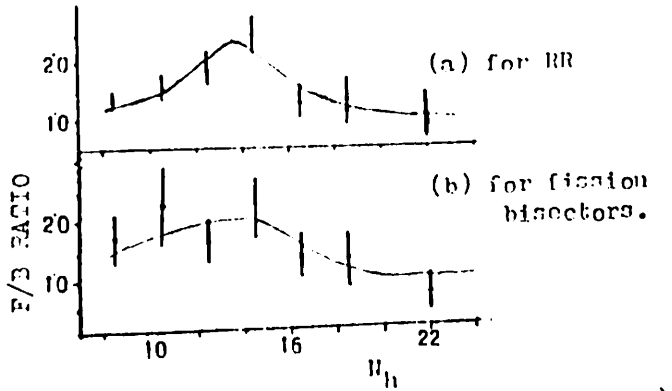

FIG. 5.17:- F/B ratio-N_h plot (comparison).

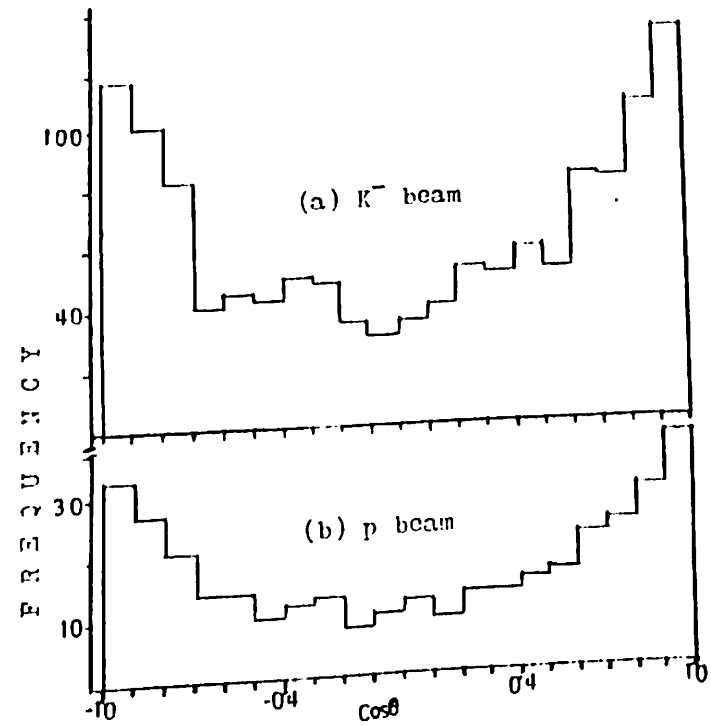

FIG. 5.18:- Angular distribution of fission fragments.

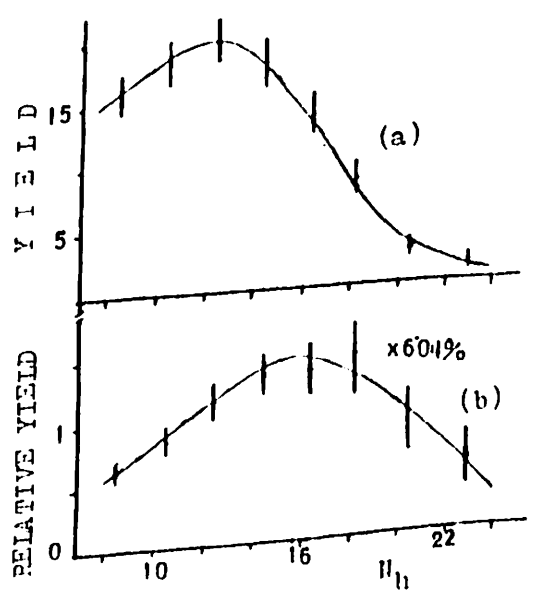

FIG. 5.19:- Yield-N_h plot (fission events).

5.3J. **Angular distribution of individual fission fragments :**

As evident from section 5.3H, the distribution of prefission nuclei deviates from isotropy owing to the forward momentum imparted by the primary to the target nucleus. Also the recoil velocity is chiefly responsible for the observed angle between the pair of fission fragments (section 5.3H, mean about 143° and 138° respectively). This implies that if the direction of recoil velocity acquired by the prefission nuclei lie within about 20° w.r.t. primary, both of the fragments are expected to be in the forward hemisphere; and if these angles exceed about 160°, both of the fragments are expected to be in the backward hemisphere.

The rest will have fragments equally distributed in either direction. The event wise break-up of such distribution of fragments are presented in table 5.10.

Table 5.10 : Event wise break-up of fragment distribution.

Beam	a	b	c	d	e	f
1.8 GeV/c K^-	31	8	17	478	73	33
20 GeV/c p	14	4	6	126	17	10

a = both of the fragments are in forward hemisphere

b = both of the fragments are in backward hemisphere

c = both of the fragments are in perpendicular direction (interval, $\cos\theta < |\pm 0.2|$).

d = one fragment each in forward and backward hemispheres.

e = one fragment in forward hemisphere, other in perpendicular direction.

The particulars for the angular distribution of the fission fragments and some of the informations derived from it are presented in table 5.11.

Table 5.11. Angular distribution of fission fragments.

Beam	Fig. No	F/B Ratio	Forward velocity* (in c) approx.
1.8 GeV/c K^-	5.18(a)	1.16±0.07	0.004
20 GeV/c p	5.18(b)	1.19±0.13	0.004

* Forward velocity of the moving system due to the impact of primary.

The results are in good agreement with those obtained in section 5.3I, indicating that the process of production of prefission nuclei may be similar to that of RR. Also, the the results are consistant with the earlier observations /113, 115/.

5.3K. The yield :

The variation of "the percentage of total fission events (yield)" and "the fraction (per cent) of reaction producing fission events at various N_h values of the stars (relative yield)" with the change of N_h values of the stars are represented in Figs. 5.19(a) and 5.19(b) respectively. The curves, drawn to guide the eye only, indicate that the competition of fission process with other modes of disintegration becomes increasingly important with the increase in energy deposited to the target nucleus to reach a maximum value around $N_h = 14 \pm 2$ and then gradually decreases.

5.4. FISSION PRODUCTS :

The heavy fragments emitted from the disintegration of Ag, Br nuclei as considered herein, are beleived to be the products of fission. A few characteristics obtained from the study of the tracks due to these heavy fragments are compared with those from other investigations (under similar considerations) in Table 5.12.

Table 5.12 : A few characteristics of fission events :

Beam	Excitation Energy (MeV)	Production frequency (p. c.)	Mean value for fragments: range (in microns)	Mean value for fragments: Velocity (in c)	Folding angle (Deg.)	Velocity of pre-fission nucleus (in c)	Mean mass of frag-ment (A)	Ref.
1 GeV p		3			140			
2 GeV p	400	6	9	0.044.	137	0.016	-	/38, 103/
3 GeV p		11			136			
3.5 GeV/c π^-	450	5.1	10.40±0.20	0.047	130	0.020	23	/113, 116/
10.1 GeV/c π^-	-	7.6	9.20±0.14	0.045	131	0.019	23	
17.2 GeV/c π^-	500	7.1	10.40±0.19	0.046	131	0.020	23	
20 GeV p	450	7.2	9.9 ±0.4	0.047	128	0.021	30	/105, 116/
1.8 GeV/c K^-	450	6.04 ± 0.18	9.82±0.10	0.048	143	~0.02	28	P.W.
20 GeV/c p	485	7.08 ± 0.54	10.11±0.20	0.050	138	~0.02	24	

The results of the present investigation are consistant with those of others. Thus, taking the pair of fragments to be emitted due to binary fission, the cross-sections for fission are compared with those of others in table 5.13.

Table 5.13 : Cross-section for fission.

Beam	Target	Detector	Cross-section (mb)	Ref.
0.6 GeV p	Ag	Emulsion	0.3±0.06	/32/
	Ag	Surface-barrier	1.0±0.3	/109/
	Ag	Mica	0.6	/118/
0.66 GeV p	Ag, Br	Emulsion	0.32±0.1	/119/
	Ag, Br	Emulsion	0.11±0.06	/120/
	Ag	Radio-chemical	0.25	/112/
1 GeV p	Ag, Br	Emulsion	7 ± 2	/103/
	Ag	Mica	1.0	/118/
2 GeV p	Ag, Br	Emulsion	30 ± 7	/103/
	Ag	Mica	4.8	/118/
2.9 GeV $\bar{p}$	Ag, Br	Emulsion	40	/101/
3.0 GeV p	Ag, Br	Emulsion	50 ± 10	/103/
	Ag	Mica	3.5	/118/
3.5 GeV/c π^-	Ag, Br	Emulsion	10.2	/116/
17.2 GeV/c π^-	Ag, Br	Emulsion	40	/116/
18 GeV p	Ag	Mica	2.0	/117/
20 GeV p	Ag, Br	Emulsion	36	/116/
25 GeV/c p	Ag, Br	Emulsion	23 ± 7	/114/
1.8 GeV/c K^-	Ag, Br	Emulsion	7.3 ± 0.2	P.W.
20 GeV/c p	Ag, Br	Emulsion	21.6±1.7	P.W.

For 1.8 GeV K^- interactions fragments of average mass(A) about 28 may be expected to be emitted with a cross-section of about 14.6±0.4mb. For 20 GeV/c p interactions fragments of average mass approximately 24 may be expected to be emitted with a cross-section of about 43.2±3.4 mb.

5.5. REMARKS :

From the analysis of the pairs of heavy fragments considered herein, it may be observed that the process of fission is slower as compared to the particle evaporation. Depending on the excitation energy imparted to the target nucleus, the target loses some of the nucleons from it and forms the prefission nucleus. The prefission nucleus normally undergoes symmetric fission giving rise to two heavy fragments which move apert from each other with an average kinetic energy of about 27±5 MeV.

Though the average mass of the fragments may be in the vicinity of (26±2), the inidividual values of the mass of the fragments may extend from 11 to 40. About (85±10)% of these fragments may have mass greater than or approximately equal to 20.

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CHAPTER VI

MULTIFRAGMENTATION

6.1. INTRODUCTION :

A highly excited nucleus occasionally disintegrates by emitting three or more heavy fragments. Such a process of nuclear disintegration by which a nucleus splits into three or more fragments in a short interval of time as compared to that of evaporation of particles, is called "multifragmentation", briefly "MF".

The interest in such a study was created from the observation of alpha-particles formed between two fission fragments and emitted with the most probable energy of about 15 MeV. Various aspects, such as mechanism of division, angular correlation among fragments, mass distribution and energy released, are being studied in connection with the division of a nucleus into three or more fragments /1-7/. Alpha particles and other fragments which are heavier than alpha particles but still lighter as compared to the fragments between which they are formed, may be emitted by the alike process /4, 5/; the process is termed as "light fragment accompanied (ternary) fission", briefly "LTF". The nuclear division resulting in three fragments of comparable mass is called "true ternary fission", briefly "TTF". A ternary division of the nucleus may occur due to a combination of two binary splits, one following the other within a short interval of time; such a process is termed as "two successive scission", briefly "TSS".

There are experimental evidences of split-up of a nucleus into more than three fragments /7-10/. For disintegrations associated with four fragments, considerations have been made in the light of quarternary fission /7-9/. Here, however, such divisions of the nucleus which are associated with emission of more than three fragments are called "higher order fission", briefly, "HOF".

As MF is a process of nuclear disintegration by emission of three or more fragments, TTF, TSS, LTF and HOF are essentially MF events.

The possibility that an excited nucleus might split-up into three fragments of comparable mass has been considered since the discovery of fission /11, 12/. By considering liquid drop model of MF, Swiatecki /13/ has shown that for low charge, when surface energy becomes more important, a division of the nucleus into lowest number of fragments is favoured. As the surface energy becomes less important in relation to the release of electrostatic energy, division into more and more number of fragments come up for consideration - eventually the nucleus may disintegrate in a violent manner into a large number of fragments. The cross-section of ternary and multiple fission (HOF) should gradually increase with increasing Z^2/A where Z and A are atomic and mass numbers of the nucleus under consideration.

Early experiments show that the occurrence of ternary fission is rare /14/ but the frequency may increase with the increase of Z^2/A as well as the initial excitation energy of the target nucleus /15-17/. Also, heavy ion induced reactions have shown that such fragmentation into three or more nuclei may be observed at bombarding energies above about 8-10 MeV/n /10, 17-21/.

Models, such as the sudden snap model /22/, the three point charge model /23/ and the two successive scission model, have been used to explain the ternary fission events. In the sudden snap model, the sudden snap of the neck and snapping back of the nuclear surfaces of the fragments so formed are brought into consideration. In the three point charge model, the nucleus which is about to undergo fragmentation i.e. the "prefragment" is considered as a prototype tri-nuclear system. In the two successive scission model, the prefragment is considered to split initially into two parts; one of them, which may be deformed also, undergoes another binary division. This results in ternary division of the prefragment.

The investigations on the complex fragments emitted from Ag exposed to energetic protons, indicate that a considerable fraction of their emission cross-section is non-evaporative /24/. The variation of cross-section for such complex fragment production in the high energy (30-350 GeV/c) proton-nucleus (p - Xe, Kr) collisions has been interpreted in terms of critical fluctuations /25, 26/ of the nuclear system (prefragment) in presence of liquid-gas instability similar to that for a macroscopic (molecular) system /27/ near the critical temperature. The mass yield curve, shown to obey a power law /25, 28/, has been taken as an indication for assuming that the fragments are formed in an excited nucleus near its critical point. This may be a consequence of phase transition /29, 30/. The fragments so formed are dispersed simulteneously /25/. Coulomb expansion following nuclear fragmentation has also been considered /25, 31/. Some of the studies involve estimation of the factors like nuclear temperature or initial excitation energy necessary for observation of such phase transition /32, 33/.

The variation of cross-section of fragments (Z = 5 to 12) produced by 2.6 GeV-7.5 proton and 1.3 GeV-13.5 GeV alpha-particle projectiles on Au, though obeys a power law of Z, does not reveal features of fragment formation through "gas-liquid phase transition" /34/. The target residues, however, are created mainly in central collisions /35/.

It has been argued that the fragmentation may be produced immediately by the end of the intranuclear cascade i.e., in a fast process and may be a function of knock-out nucleons /36/ and thus may depend on the characteristics of cascade process.

There are some approaches which treat the multifragmentation as shattering of prefragments into pieces statistically /37, 38/. Cleavage(s) /37, 39/ produced due to blowing out of some of the nucleons by the high energy projectiles from the target nucleus may also be responsible for such events. Under different considerations and conditions, in some of the investigations, the fragments are assumed to be emitted statistically from an intermediate excited system /40/.

There are models in which the heated prefragments are assumed to condense into droplets and the fragments (droplets) are evaporated sequentially /41/. In justifying the use of more convential statistical approach i.e., sequential decay of the excited primary fragments, Fields et al /42/ observed that the complex fragments are also emitted in low multiplicity events during evaporation and fission-like processes - although a number of models either predict or assume that the complex fragments are produced in the high multiplicity multifragmentation processes.

Thus although the study on the fragmentation of the nuclear system into many pieces has drawn considerable attention, the reaction mechanism is far from being understood.

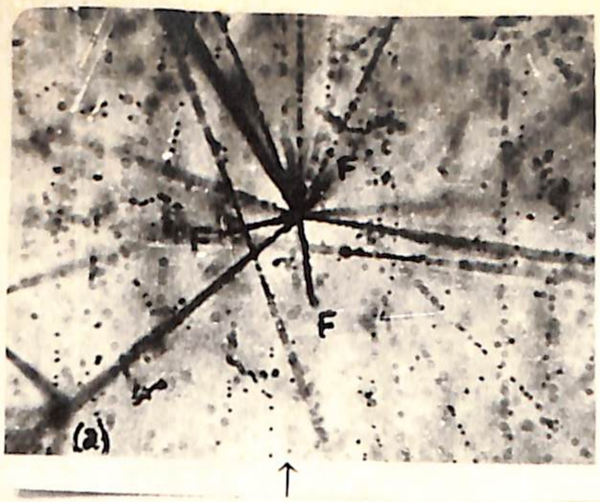
Various methods, such as (i) nuclear emulsion, (ii) coincidence counting (including kinematical coincidences), (iii) radiochemical analysis, and (iv) mica and other track detectors, have been used to study multifragmentation of the target nuclei or of the projectile nuclei or of the compound systems of target and projectile nuclei. Nature of such studies varies from measurement of cross-sections of the products in the fragmentation mass region to the identification of individual events. Reaction kinematics is one of the important considerations for identification of such events /20/.

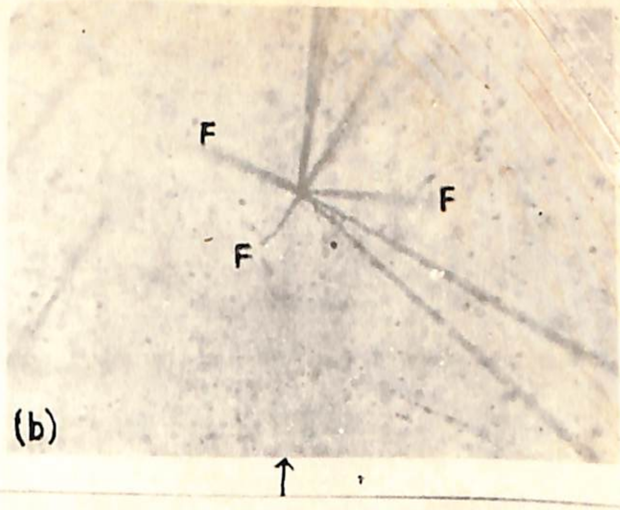
From the triple coincidence measurements, Fatyga et al /43/ have deduced that the average number of complex (intermediate) fragments (Z=3-7, 270 MeV He^3 + Th^{232} reaction) per fragmentation event is close to unity.

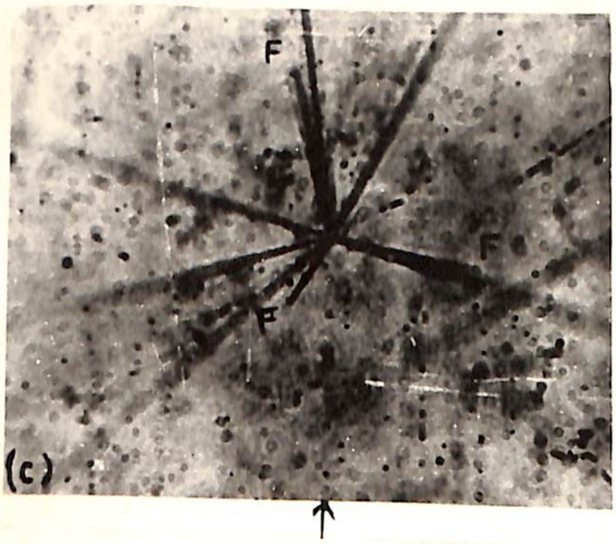
From the studies of the reaction 11.5 GeV p + U, Wilkins et al /44/ opines that the mass region of fragmentation products is formed in events of highest deposition of energy. The fragments, however, are formed with low excitation energy.

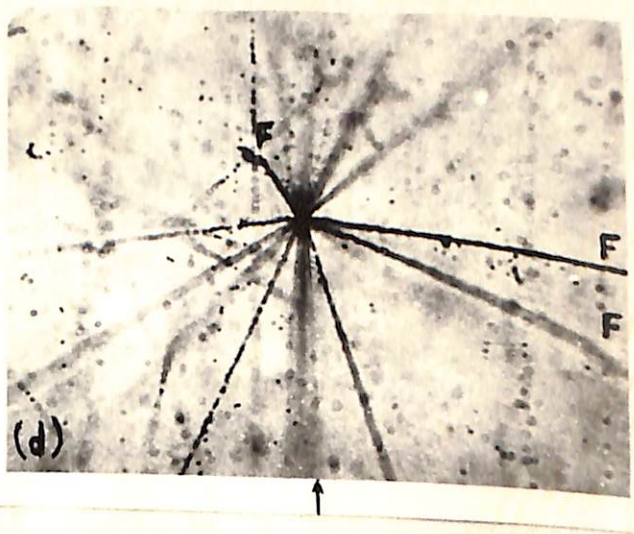
In photonuclear emulsion the multifragmentation events are observed normally as ternary and quarternary fission /8, 9, 45-52/. These studies on the split-up of the target nucleus into more than two heavy fragments provide information that there is an angular correlation among the fragments emitted due to such splits. Such correlation may be dependent on factors like charge of the fragments, number of fragments produced and the dynamical condition of the system undergoing multifragmentation. The observations are consistant with studies using a few other detectors also /1, 7, 15, 19, 20, 22/. Microphotographs of some of the multifragmentation events observed in this investigation are presented in Plate Nos. 5 and 6.

In the present investigation an attempt has been made to study the emission of the fragments due to multifragmentation of silver and bromine nuclei. Some of the characteristics like mass, charge, velocity distribution and angular









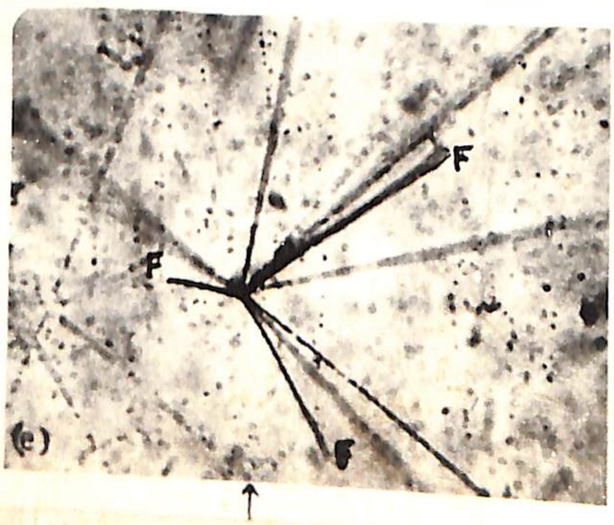
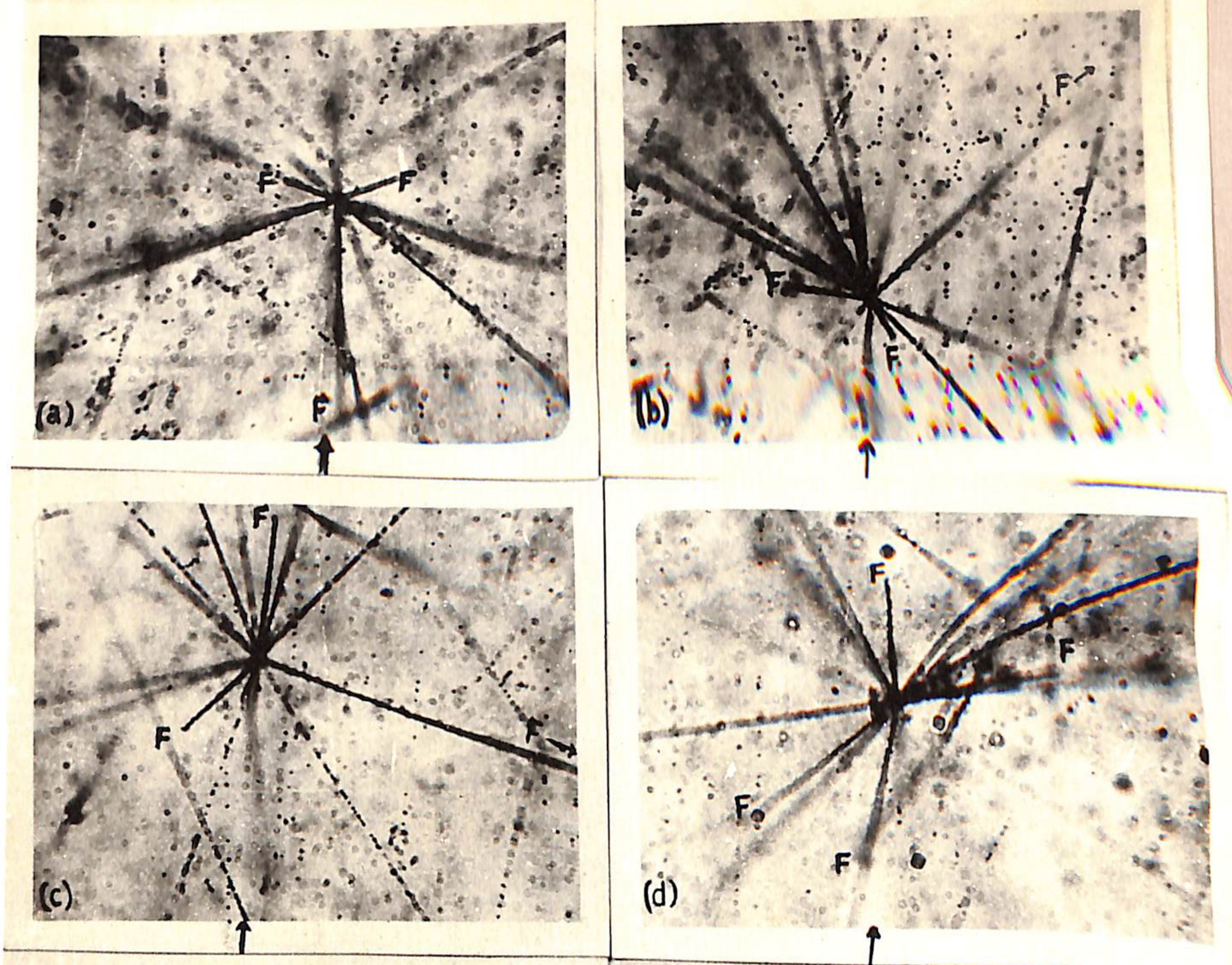


PLATE No. 5
Microphotograph of (a)-(c) TTF events, (d) & (e) TSS events. F represents the fragments, arrow head for beam direction.



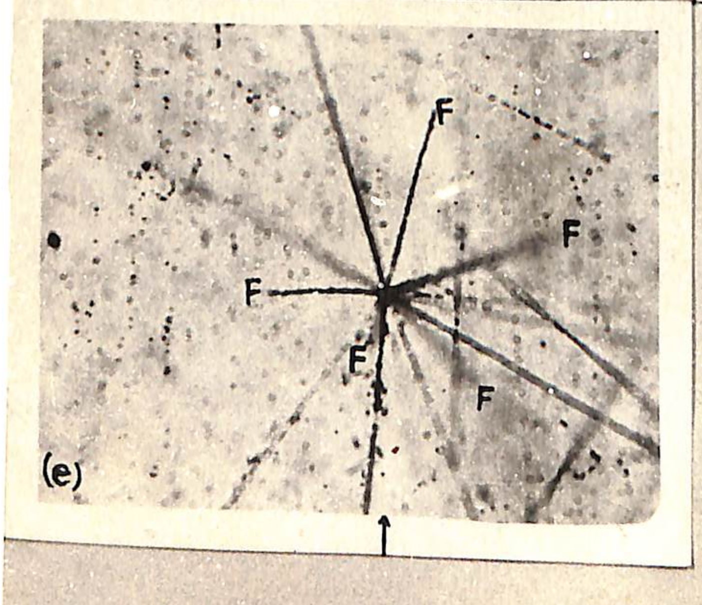


PLATE No. 6
Microphotographs of (a)-(c) LTF events, (d) & (e) HOF events. F represents the fragments, arrow head for beam direction.

distribution, have also been studied in order to derive information regarding their emission.

6.2. EXPERIMENTAL PROCEDURE AND SELECTION CRITERIA :

Each of the disintegration stars with $N_h > 7$, obtained by area scanning, is scrutinized carefully under higher magnification (1875x - oil immersion objective) to detected the presence of three or more tracks due to multifragmentation (MF) events. To accept only the genuine events, the following selection criteria are also adopted.

(i) Alteast two of the tracks should show characteristics (ionisation, end scattering, profile, tapering etc.) appropiate for heavy fragments.

(ii) Ranges of the tracks, except for those of light ($2 \lesssim Z \lesssim 4$) fragments, should not normally exceed 50 microns.

(iii) Dip angle for any of the tracks should not exceed 45° in unprocessed emulsion. This facilitates a check-up of the track profiles.

6.3. RESULTS AND DISCUSSIONS :

6.3A. Frequency and cross-section :

The results in respect of frequency and cross-section of MF events are presented in table 6.1.

Table 6.1 : Frequency and cross-section of MF events :

Beam	Emulsion used (c.c.) approx.	Stars scrutini-zed	No. of MF events	Corrected Freq. (p.c.)	Corrected Cross-sec. (mb)
1.8 GeV/c K^-	123.3	60,000	130	0.61±0.05	0.74±0.07
20 GeV/c p	62.32	5,000	24	1.36±0.28	4.14±0.85

The MF events may further be classified as has been presented in table 6.2.

Table 6.2 : Classification of MF events :

No. of fragments	Classification	No. of events obtained 1.8 GeV/c K^- beam	20 GeV/c p beam
3	TTF	21	3
3	TSS	36	7
3	LTF	56	12
3 (All)	Ternary fission (TF)	113	22
4	HOF	15	2
5	HOF	2	-
All	MF	130	24

6.3B. **Star size distribution :**

Some of the particular relating to the track multiplicity distributions are presented in table 6.3.

Table 6.3 : Track multiplicities of Stars (MF events).

Beam	Events	N_h distribution Fig No.	N_h Mean	N_b distribution Fig No.	N_b Mean	N_g distribution Fig No.	N_g Mean
1.8 GeV/c K^-	TTF	6.1(a)	16.28±0.60	6.2(a)	11.71±0.48	6.3(a)	4.57±0.41
	TSS	6.1(b)	13.29±0.43	6.2(b)	10.25±0.24	6.3(b)	3.14±0.23
	LTF	6.1(c)	15.46±0.44	6.2(c)	11.77±0.36	6.3(c)	3.70±0.20
	TF	6.1(d)	14.96±0.29	6.2(d)	11.27±0.24	6.3(d)	3.68±0.17
	HOF	6.1(e)	13.94±0.61	6.2(e)	10.76±0.39	6.3(e)	3.18±0.39
	MF	6.1(f)	14.82±0.27	6.2(f)	11.21±0.21	6.3(f)	3.62±0.16
20 GeV/c p	MF	6.1(g)	17.25±0.81	-	-	-	-

The average excitation energies/53/ of the nuclei undergoing multifragmentation have been estimated to be about 500 MeV and 540 MeV for 1.8 GeV/c K^- and 20 GeV/c p interactions respectively.

6.3C. Correlation :

The average values of N_b and N_h for various values of N_g are plotted against the corresponding N_g values in Fig. 6.4, the least square linear fits are marked I and II respectively. The corresponding relations may be given by

(I) $$\langle N_b \rangle = 11.55 - 0.03\, N_g$$

(II) $$\langle N_h \rangle = 11.68 + 0.92\, N_g$$

The correlation coefficient ($r = +0.08$) between N_b and N_g is not significant. The 95% confidence interval is about 0.08 ± 0.17. This, together with the slope of $\langle N_b \rangle$ - N_g graph indicate that N_b and N_g may be independent of each other for stars associated with MF events. Such an effect was interpreted by Otterlund et al /54/ as an indication of deposition of very high energy to the target nucleus due to which the nucleus eventually undergoes a multi-body break-up.

6.3D. Charge and mass distributions :

The details of the estimation of the charge and mass of the prefragments are similar to those for residues as has been shown in section 3.4E and consistant with Ref./55, 56/. The distributions are presented in Figs. 6.5(a), (b) and 6.6(a), (b) respectively. The mean charges and masses of the prefragments are about 26 and 58 corresponding to 1.8 GeV/c K^- interactions, and about 23 and 52 corresponding to 20 GeV/c p interactions respectively.

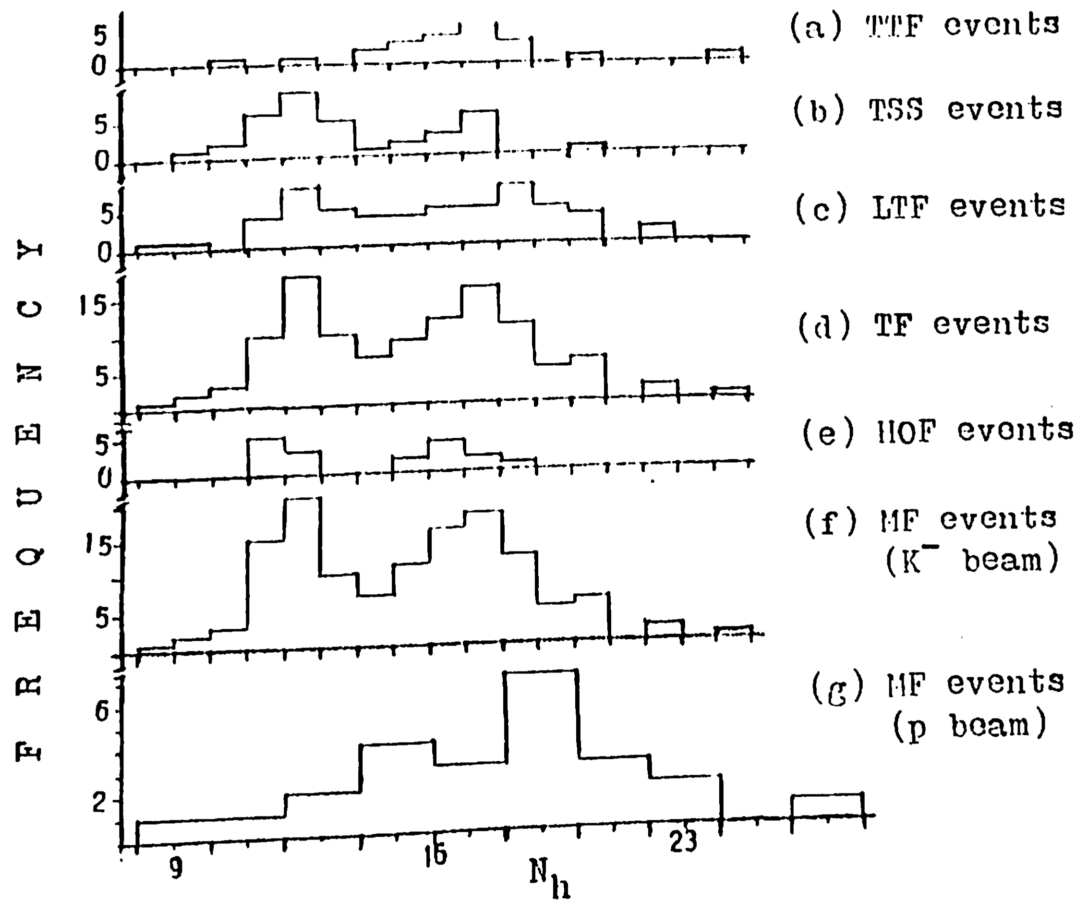


FIG. 6.1:- N_h distribution (MF events).

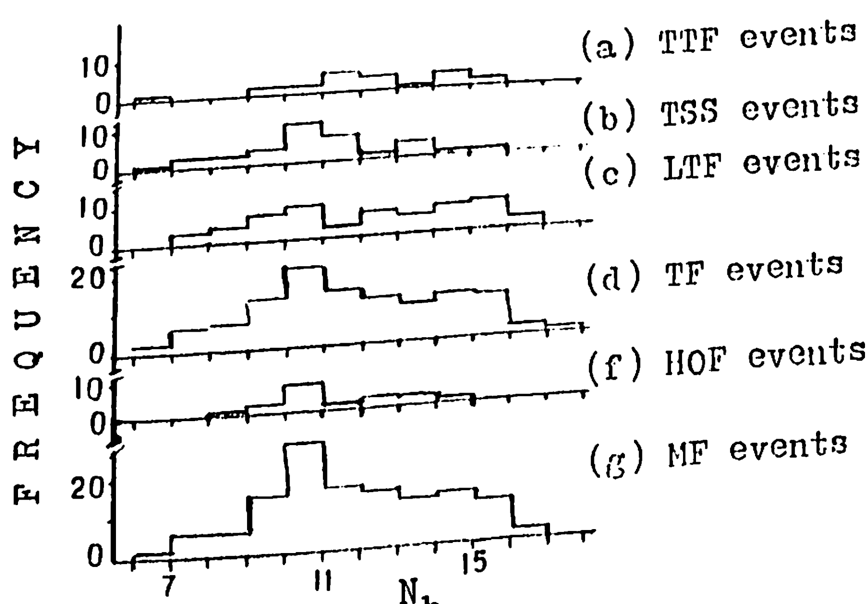


FIG. 6.2:- N_b distribution (MF events).

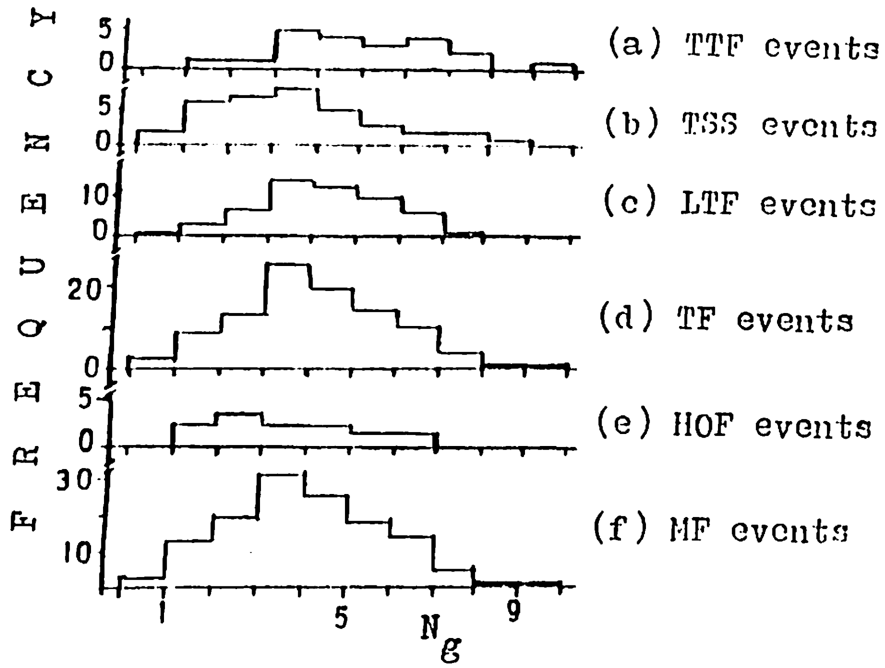


FIG. 6.3:- N_g distribution (MF events).

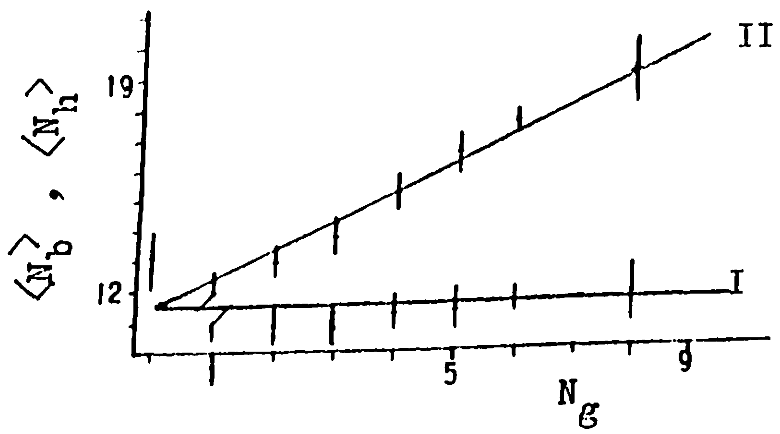


FIG. 6.4:- Relation of N_g with N_b & N_h (MF events).

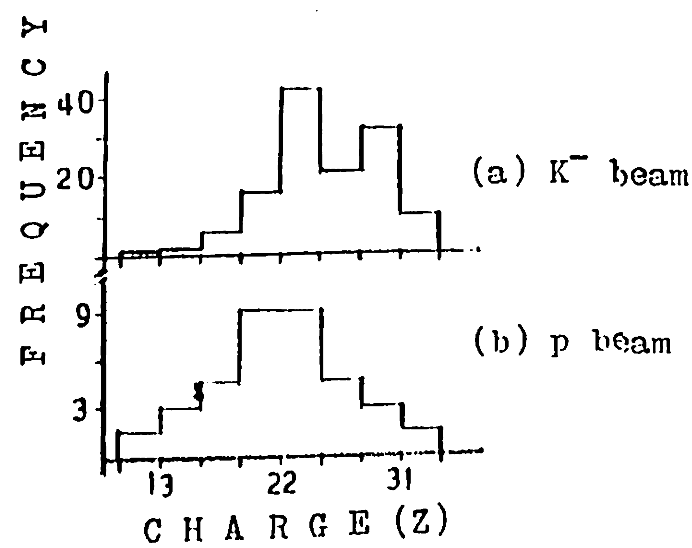


FIG. 6.5:- Prefragment charge distribution.

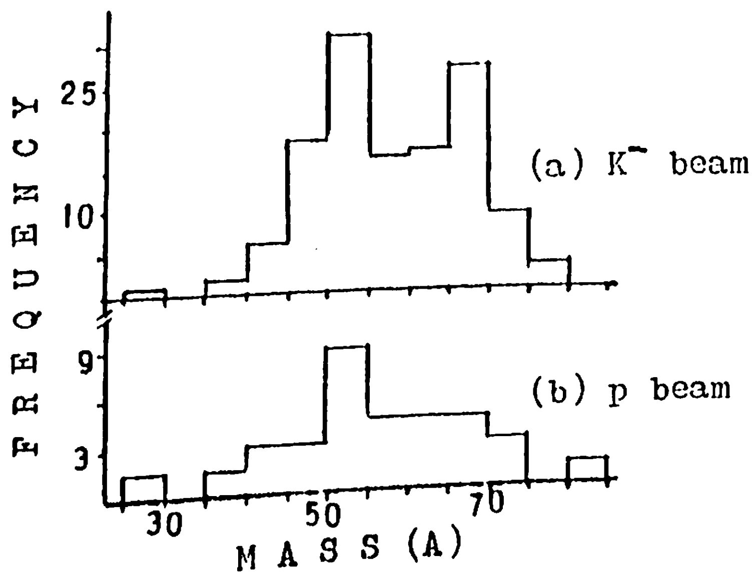


FIG. 6.6:- Prefragment mass distribution.

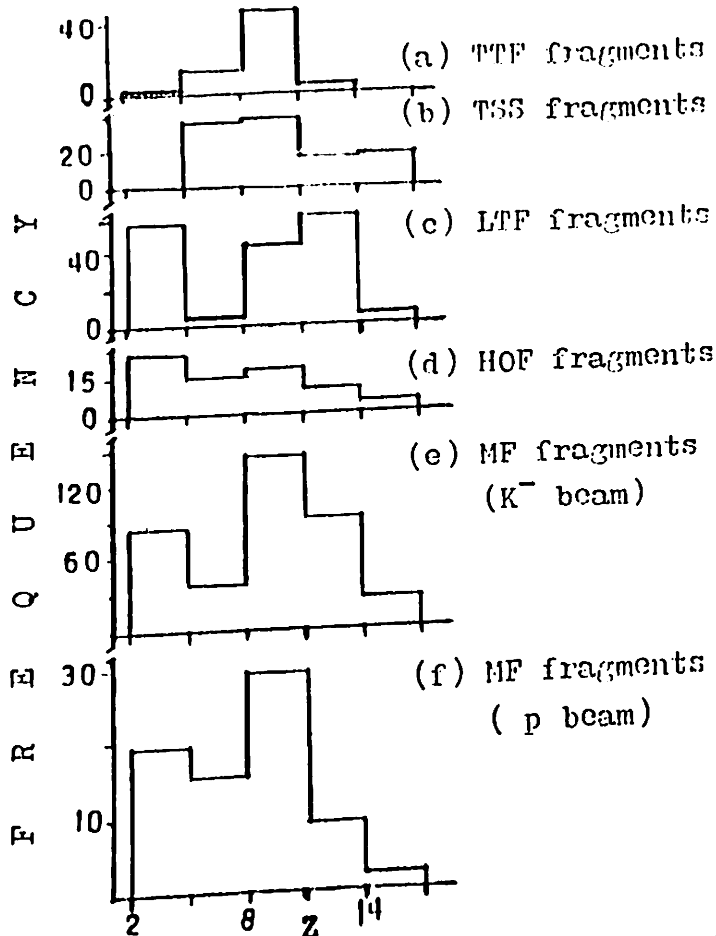


FIG. 6.7:- Charge distribution of MF fragments.

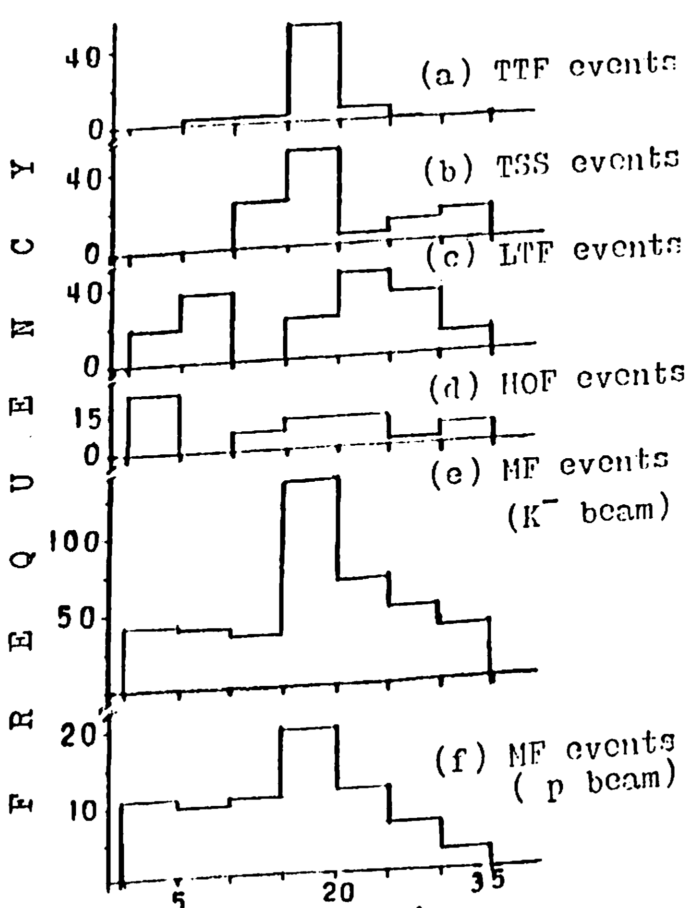


FIG. 6.8:- Mass distribution of MF fragments.

The charges and masses of the individual MF fragments are computed by using break-up schemes (Ref. /8, 20, 52/, also sections 6.1 and 6.4). Some of the particulars relating to the distributions are presented in table 6.4.

Table 6.4 : Charge and mass of MF fragments.

Beam	Events	Charge (Z) Distribution Fig. No.	Width From	Width To	Mass(A) Distribution Fig. No	Width From	Width To
1.8 GeV/c K^-	TTF	6.7(a)	4	12	6.8(a)	9	25
	TSS	6.7(b)	5	17	6.8(b)	11	35
	LTF	6.7(c)	2	17	6.8(c)	4	35
	HOF	6.7(d)	2	17	6.8(d)	4	35
	MF	6.7(e)	2	17	6.8(e)	4	35
20 GeV/c p	MF	6.7(f)	2	17	6.8(f)	4	35

6.3E. Range distributions :

Some of the particulars relating to the range distributions are presented in table 6.5

Table 6.5 : Ranges of MF fragments :

Beam	Events	Range Dsitribution Fig. No.	Mean (Microns)
1.8 GeV/c K^-	TTF	6.9(a)	13.00 ± 0.56
	TSS	6.9(b)	16.56 ± 0.76
	LTF	6.9(c)	19.97 ± 1.76
	HOF	6.9(d)	18.71 ± 1.20
	MF	6.9(e)	17.78 ± 0.79
20 GeV/c p	MF	6.9(f)	16.92 ± 1.19

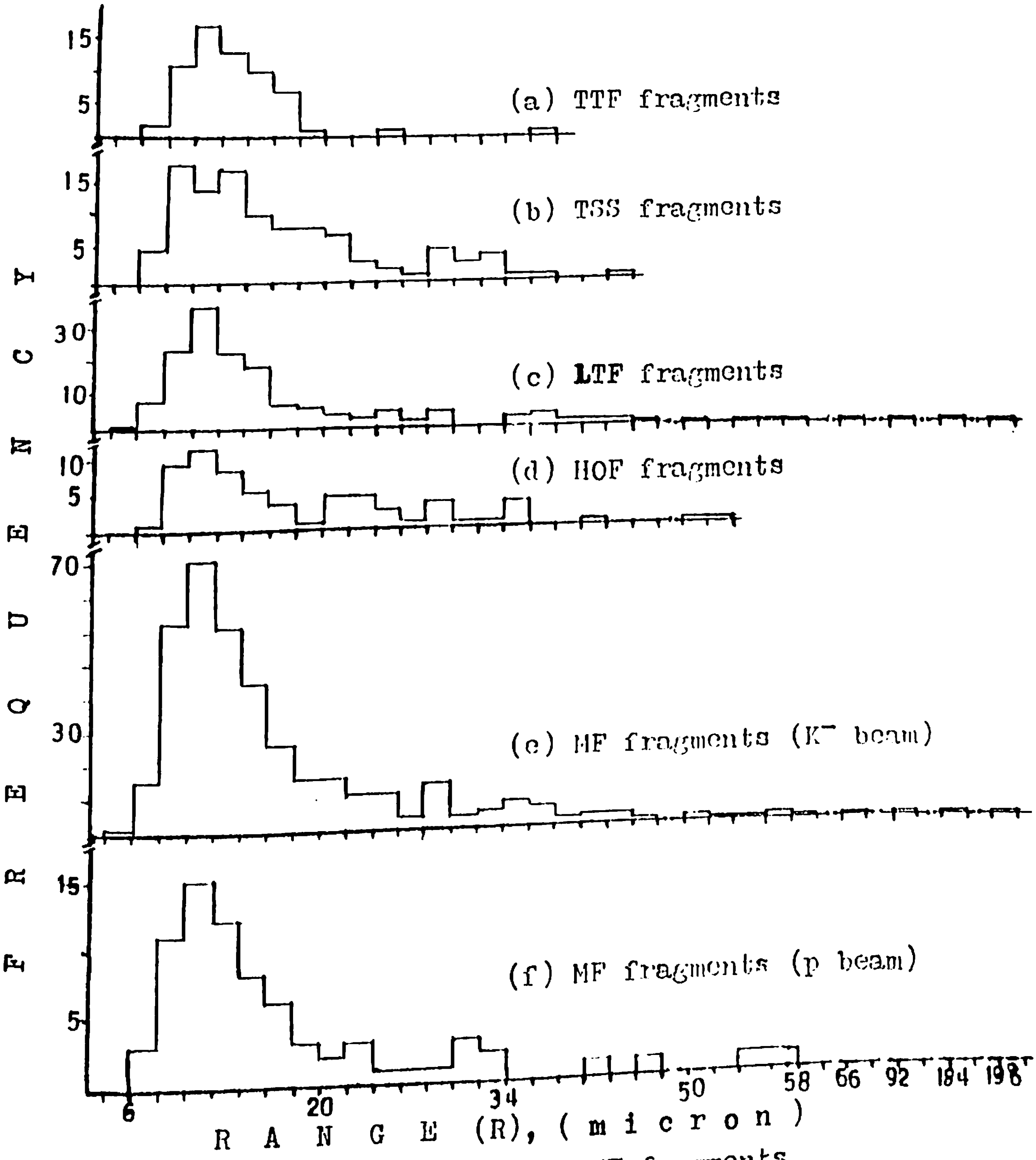


FIG. 6.9 ;- Range distribution of MF fragments.

The average translational kinetic energy (TKE) of the products (total) in the MF events, estimated from range-energy relations /57, 58/, is about 70 MeV.

The average energy of a TTF fragment may be about 23 MeV. The average energies of different types of fragments, however, may lie between 10 MeV (approx.) and 35 MeV (approx.)

For a system of three touching spheres, by adjusting paramters /59/ (for nuclei like O^{16}), a maximum of about 50 MeV Coulomb energy may be expected. This shows that the Coulomb energy alone cannot explain the observed TKE. Factors like recoil momentum, nuclear temperature etc. (as discussed in section 5.3E) are likely to contribute towards the observed TKE.

6.3F. Velocity distributions :

From the range velocity graphs (as in section 2.7) the velocities of MF fragments are estimated. The distributions are presented in Figs. 6.10(a), (b); the mean velocities obtained are about 0.056c and 0.055c respectively for 1.8 GeV/c K^- and 20 GeV/c p interactions.

The distributions have a maximum width from 0.03c to 0.12c. Some of the relevant factors responsible for the observed width have been discussed in section 5.3F.

6.3G. Distribution of the angles between MF fragments.

Some of the particulars relating to the distribution of angles between pairs of MF fragments are presented in table 6.6.

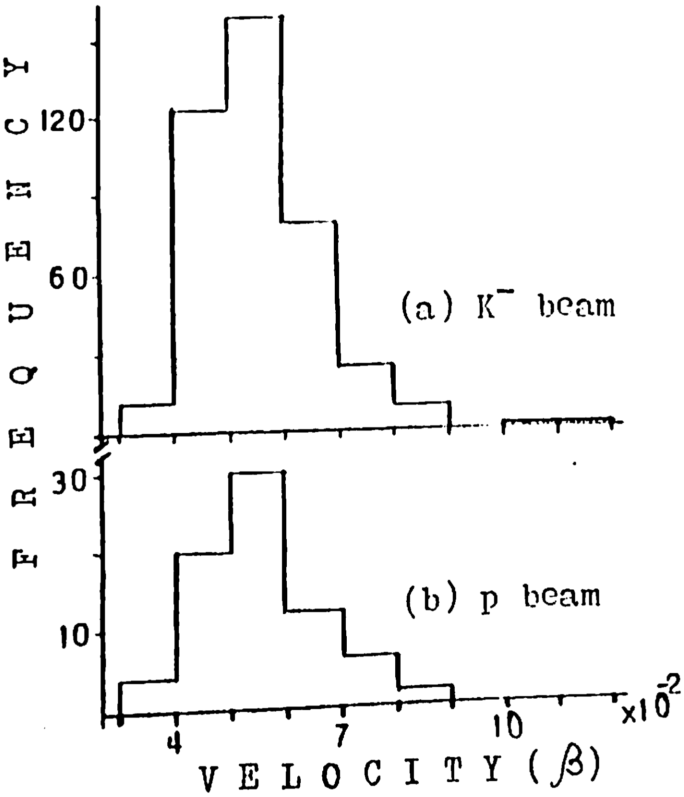


FIG. 6.10:- Velocity distribution of MF fragments.

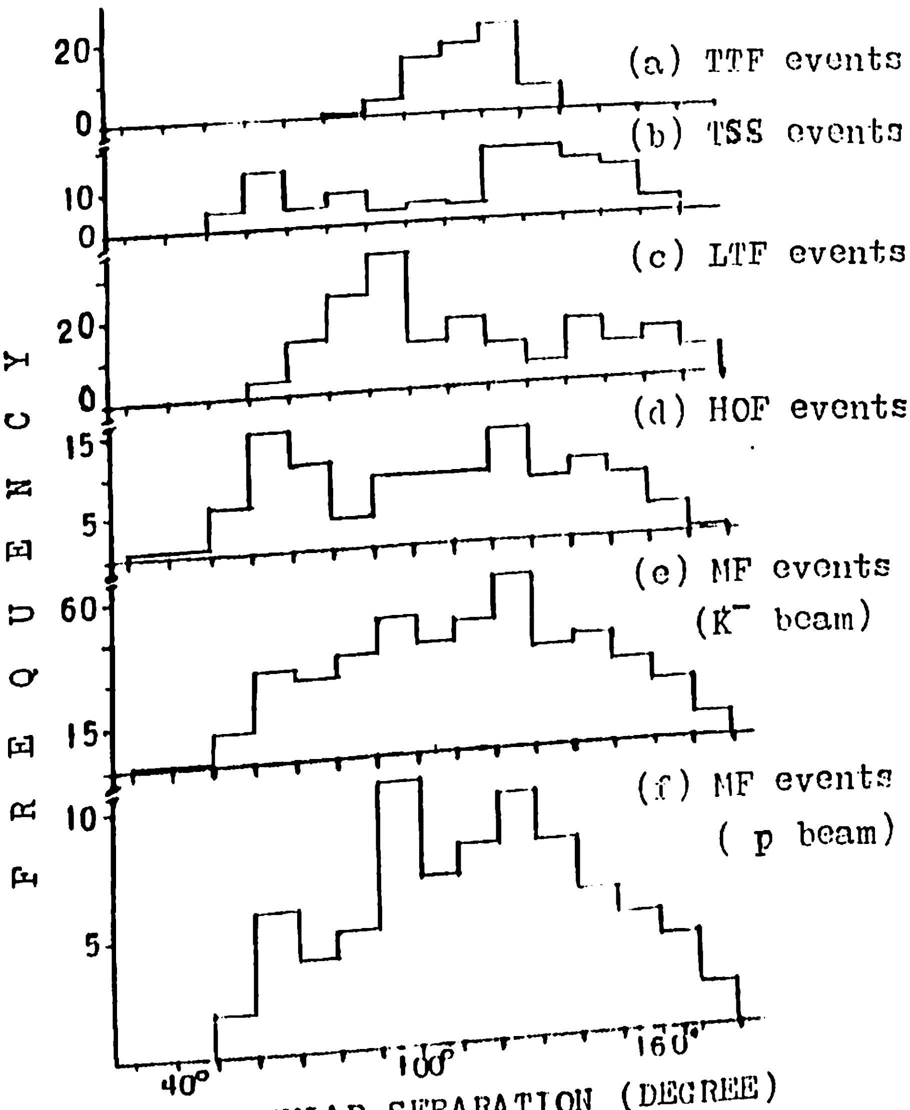


FIG. 6.11:- distribution for angular separation among fragments.

Table 6.6 : Angular separation of MF fragments :

Beam	Events	Distribution for angular separation	
		Fig. No.	Mean (Degree)
1.8 GeV/c K^-	TTF	6.11(a)	116.3±1.4
	TSS	6.11(b)	115.6±3.2
	LTF	6.11(c)	115.0±2.4
	HOF	6.11(d)	106.7±3.3
	MF	6.11(e)	113.3±1.5
20 GeV/c p	MF	6.11(f)	114.2±3.5

The distributions are consistant for split-up for the moving prefragments under various possibilities as had been discussed in section 6.1.

6.3H. Angular distribution of individual fragments :

Some of the particulars relating to the angular distribution of the individual fragments with respect to the primary beam direction have been presented in table 6.7.

Table 6.7 : Angular distribution of MF fragments :

Beam	Events	Fig No.	F/B ratio
1.8 GeV/c K^-	TTF	6.12(a)	1.28±0.14
	TSS	6.12(b)	1.12±0.23
	LTF	6.12(c)	1.24±0.21
	HOF	6.12(d)	1.00±0.26
	MF	6.12(e)	1.16±0.13
20 GeV/c p	MF	6.12(f)	1.17±0.29

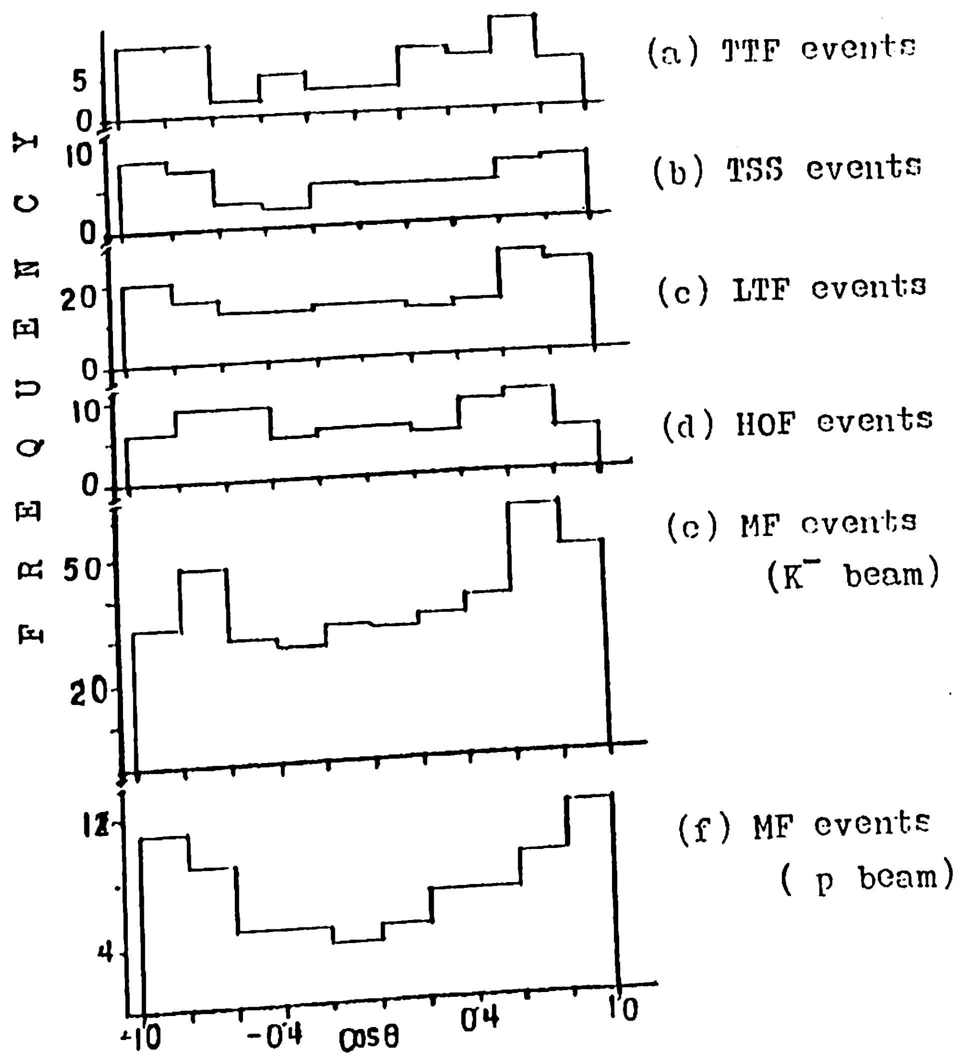


FIG. 6.12:- Angular distribution of MF fragments.

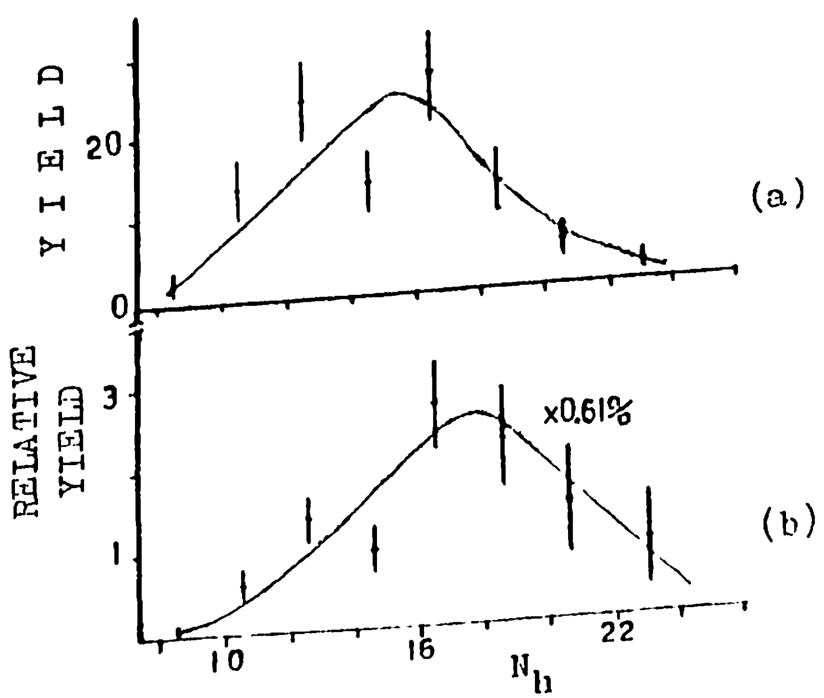


FIG. 6.13:- Yield- N_h plot (MF events).

The distributions show that the fragments may be assumed to be emitted from a prefragment nucleus moving with an average forward velocity of about 0.004c along the beam direction.

6.31. The Yield :

The variation of "the percentage to total MF events (i.e., the yield)" and "the fraction (per cent) of reaction producting MF events at various N_h values (i.e. the relative yield)" with the change of N_h values of the stars have been presented in Figs. 6.13(a), (b) respectively. The curves, drawn to guide the eye only, indicate that the occurrence of MF events increases with heavy track multiplicity (i.e. the energy deposited to the target nucleus) to reach a maximum around $N_h = 17 \pm 1$.

MF events are expected to occur when a very high excitation energy is deposited to the target nucleus /60/. It has also been observed the emission frequency of light fragments like Li^8 is strongly dependent on excitation energy /61/ and consequently an increase in the number of light fragments ($Z \lesssim 5$) may be observed for high multiplicity events /26, 54/. This leads to a belief that the decrease in the frequency of MF events after reaching a peak value around $N_h = 17 \pm 1$, as seen in this investigation, may be due to non-observation of some of the MF events where emission of light fragments are predominant or due to appearance of another decay channel like vaporisation /62/.

The frequency of ternary fission events has been expressed as a fraction (per cent) of frequency of binary fission events in order to compare the results of this investigation with those of others in table 6.8.

Table 6.8 : P. C. of TF w.r.t. fission :

Beam	Target	P.C. of TF w.r.t. fission (approx)	Type of TF	Detector	Ref.
11.1 MeV/n S^{32}	Ni^{58}	3	3 heavy fragments	ionisation chamber	/63/
1-3 GeV p	Ag, Br	2	fragments of comparable mass	emulsion	/47/
1.8 GeV/c K^-	Ag, Br.	8	All TF	emulsion	/8/
3.5 GeV/c K^-	Ag, Br	2	fragments of comparable mass	emulsion	/43/
7 GeV p	Ag	2.6	-	Diacel	/64/
10.1 GeV/c K^-	Ag, Br	4	fragments of comparable mass	emulsion	/49/
17.2 GeV/c K^-	Ag, Br	4	- do -	- do -	
20 GeV p	Ag, Br	4	- do -	- do -	/48/
1.8 GeV/c K^-	Ag, Br	8.8±0.9	All TF	emulsion	P.W.
20 GeV/c p	Ag, Br	17.6±4.0	- do -	- do -	

Thus the emission of heavy fragments as a result of multifragmentation process is rare as compared to binary fission events.

The cross-section for ternary fission of Ag exposed to 7 GeV p, obtained by using diacel track detector /64/, is about 0.11 mb. In the present investigation which include LTF events also, the cross-sections of TF are about 0.64±0.06 mb and 3.80±0.81 mb respectively for 1.8 GeV/c K^- and 20 GeV/c p interactions. Thus the results of this investigation are comparable with those of others.

6.4. MF PRODUCTS :

The selection of the MF events are made under the break-up schemes, some details of which are as follows :

For ternary division of the prefragment, depending on the track characteristics and angular separation among the fragments, three schemes viz, TTF, TSS and LTF have been considered and adopted (section 6.1). In Fig. 6.14 the schematic (average) co-planer representations of the aforesaid types of ternary division is presented. The corresponding particulars as obtained in this investigation are presented in table 6.9.

Table 6.9 : Particulars as per break-up schemes :

Particulars (description)	Indication*	For types of events		
		TTF	TSS	LTF
Mean range (microns) (approx)	1	10.8	10.6	10.4
	2	12.4	15.1	13.3
	3	15.8	24.0	36.2
Mean angular separation (Degree) approx.	θ_{12}	127	147	154
	θ_{13}	117	126	105
	θ_{23}	105	73	86
Charge(Z) Width	1	4-12	10-17	7-17
	2	4-12	5-10	7-17
	3	4-12	5-10	2-4
Average charge(Z) approx.	1	8	13	11
	2	8	7	11
	3	8	7	3
Mass(A) width	1	9-25	20-35	16-35
	2	9-25	11-20	16-35
	3	9-25	11-20	4-9
Average	1	18	29	25
	2	18	16	25
	3	18	16	7

*1 Fragment marked 1 in Fig 6.14
2 " " 2 " " "
3 " " 3 " " "
θ angular separation e.g., θ_{12} angular separation between fragments 1 and 2.

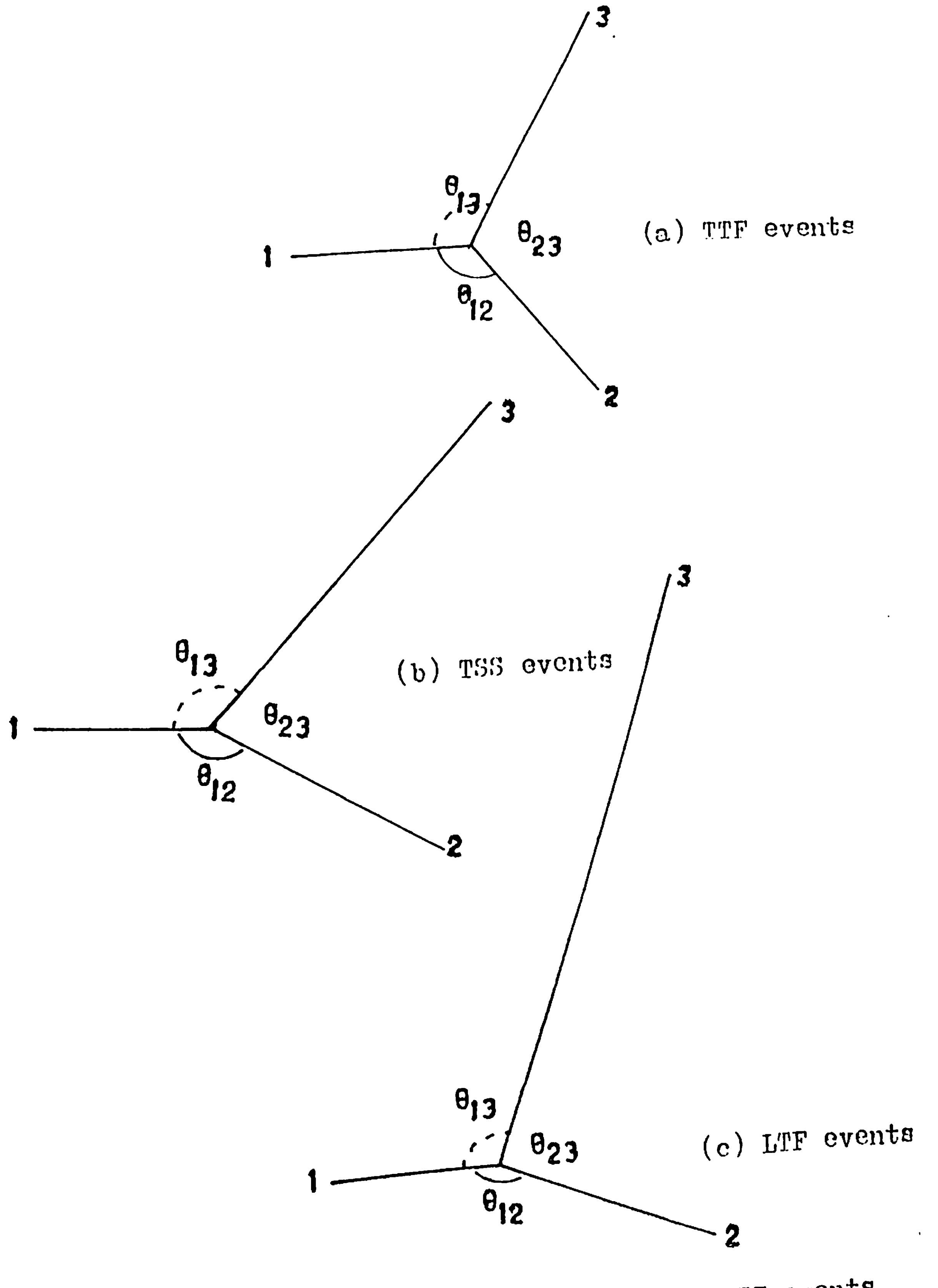


FIG. 6.14:- Schematic co-planer diagram for TF events.

It has been observed that the average space angle between the tracks of the two fragments having longer ranges in emulsion is the smallest. For TSS events this may be understood in the customary manner /19, 20/ by assuming that the fragments having longer tracks arise out of the second scission i.e., by division in flight of a deformed or excited fission fragment. Again, had there been no second scission only one fragment would have moved along the bisector of the angle between the two second scission fragments; assuming this direction to be the direction of motion of the fragment undergoing second scission one can expect a folding angle of about 162° between the fragments arising out of the first scission. Like those for the fission events (section 5.3I), the bisector of the folding angle (i.e. fission bisector) due to the first scission may also be expected to be isotropically distributed in a manner consistant with the fission of moving prefragment; this view finds some support in the angular distribution of MF fragments also (section 6.3H). This leads to a belief that the prefragments undergoing TSS may be under an aggregate influence of a random recoil momentum and also of forward momentum due to initial impact of the primary. As for the LTF (and also TTF) events there may be two possibilities. Firstly, it may arise out of simulteneous emission of the light fragment formed in between two asymmetric fission fragments; lighter fragments have longer ranges and may be directed closer to the lighter of the two heavy fragments (due to Coulomb repulsion). Alternatively, it may be assumed that the recoil momentum on the prefragments may be directed a little closer to the direction of emission of the fission fragments which have longer tracks. During high energy disintegration under similar situation as the fission events are predominantly symmetric, the assumption of recoil momentum as the probable cause of the observed collimation may be more reasonable.

Fleitcher et al /16/ observed that ternary fission events must be co-planer in the centre of mass system within an experimental error of ±15° and there will be a general lack of co-planerity in the laboratory system. The situation, however, may differ by an extent for high energy particle induced reactions. It may be observed that Deka et al /50/ obtained about 50% of the observed ternary events to be co-planer. Also in this investigation, within limits of experimental error about 50% of the observed ternary events may be called to be co-planer.

Some of the characteristics of MF events (prefragments) are compared with those of RR in table 6.10.

Table 6.10 : Characteristics of prefragments and RR.

Beam	Events	Excitation Energy (MeV) of target	Estimated mean (approx)		
			Charge (Z)	Mass (A)	Forward velocity (in c)
1.8 GeV/c K^-	MF (Prefragment)	500	26	58	0.004
	RR	400	27	61	0.005
20 GeV/c p	MF (Prefragment)	540	23	52	0.004
	RR	430	25	57	0.005

From table 6.10 it may be observed that though the prefragments are formed at relatively higher excitation energies of the target nuclei, their characteristics like charge, mass and forward velocity due to initial impact of primary are almost similar.

The average value of mass(A) obtained for the MF fragments in 1.8 GeV/c K^- interactions is about 18 and has a cross-section of about (2.33±0.22)mb. For 20 GeV/c p interaction the corresponding values are about 16 and (12.77±2.61)mb respectively.

6.5. REMARKS :

From the above analysis it is evident that the MF fragments are emitted from a prefragment moving under the influence of both recoil momentum and initial forward momentum due to the impact of primary. Depending on the excitation energy available to the target nucleus, it loses some of the nucleons and forms the prefragment. The emitted fragments move with an average energy of about 23±10 MeV. Though the occurrence of such events are rare in comparison with the process of fission, it has a definite contribution towards the emission of heavy fragments.

The mass(A) of the individual fragments emitted during such disintegration may vary from about 4 to about 35. About (35±10)% of these fragments may have mass greater than or approximately equal to 20.

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CHAPTER VII

HYPERNUCLEI

7.1. INTRODUCTION :

Hypernuclei(HN), studied first in 1953 using photonuclear emulsion /1/, constitute a distinct class of nuclear species. They consist of a bound state of nucleons and hyperon(s) forming a nucleus like object, some of which are essentially heavy.

By now it is well known that the lamda hyperons may be produced in nuclear interactions in which the available kinetic energy is sufficient to provide all the rest mass of the hyperons or of K^+K^- pairs. The predominant interactions for production of lamda hyperons /2-13/ may be considered as : (i) Strangeness exchange reaction, (ii) Conversion of heavier hyperons, and (ii) multinucleon processes. The strageness exchange reaction is characterized by emission of a high energy (about 90 MeV and above) pion. The conversion process is more frequent for light hypernuclei. The multinucleon process, expected to contribute to the production of heavy hypernuclei, is indicated normally by the emission of a fast (about 80 MeV and above) nucleon. Quark models have also been adopted to explain some of the observations /13-16/.

A fast hyperon or an HN may occasionally be ejected at the earlier stages of interaction but such emission may be infrequent /17-19/. As the fraction of HN expected to be produced by evaporation is low enough as compared to the observed number of heavy HN, the lamda hyperons in most cases are expected to remain trapped inside the residue /9, 18-21/. The average recoil momentum of the residual nucleus /22/ should allow it to produce a short but recognisable track in nuclear emulsion before a subsequent decay, leading to the formation of a double centred star (D.S.). Plate Nos. 7 and 8 show some of the microphotographs.

While scrutinizing the events in photonuclear emulsion, sometimes triple centred nuclear disintegrations are also observed /23-26/. During high energy nuclear disintegrations a number of lamda hyperons or heavier hyperons may be created within the target nucleus. As the heavier hyperons normally decay by strong interactions /2, 27, 28/, the slowly moving heavy HN formed by heavier hyperons are not expected to produce recognisable tracks; occasional studies on lighter hypernuclei of this kind show that the decay stars are very small and thus become inconvenient for identification /29, 30/. However, two or more lamda hyperons, created either directly or preferantially by conversion of heavier hyperons ($S \leq -2$) may be tagged to one or more nuclear fragments /27, 31, 32/ causing the triple centred stars. The occurrence of such events involving heavy fragments is, ofcourse, very rare.

A number of investigations have been made on subjects like binding energy of hypernuclei and behaviour of lamda hyperons inside HN /2, 33-47/. One of the subjects creating considerable interest is the life time of lamda hyperons /48-56/ and its dependence on A of the HN. From the delayed fission life time measurements /57/ one may expect that the life time of a heavy HN to be within about 10^{-10} sec. From these, to a first approximation, it may be taken that with the increase of A of HN the life time of the concerned lamda hyperon decreases and consequently the decay rates increase.

HN may decay by a number of channels /58-64/. The energy released is dependent on the decay channel, the principal modes being (i) mesonic and (ii) non-mesonic. Some of the relatively rare modes of decay are termed as readiative (photonic), leptonic and pi-plus mesonic decay. Investigations on decay rates and branching ratios /36, 53, 65-69/ show that for free lamda and very light HN the principal

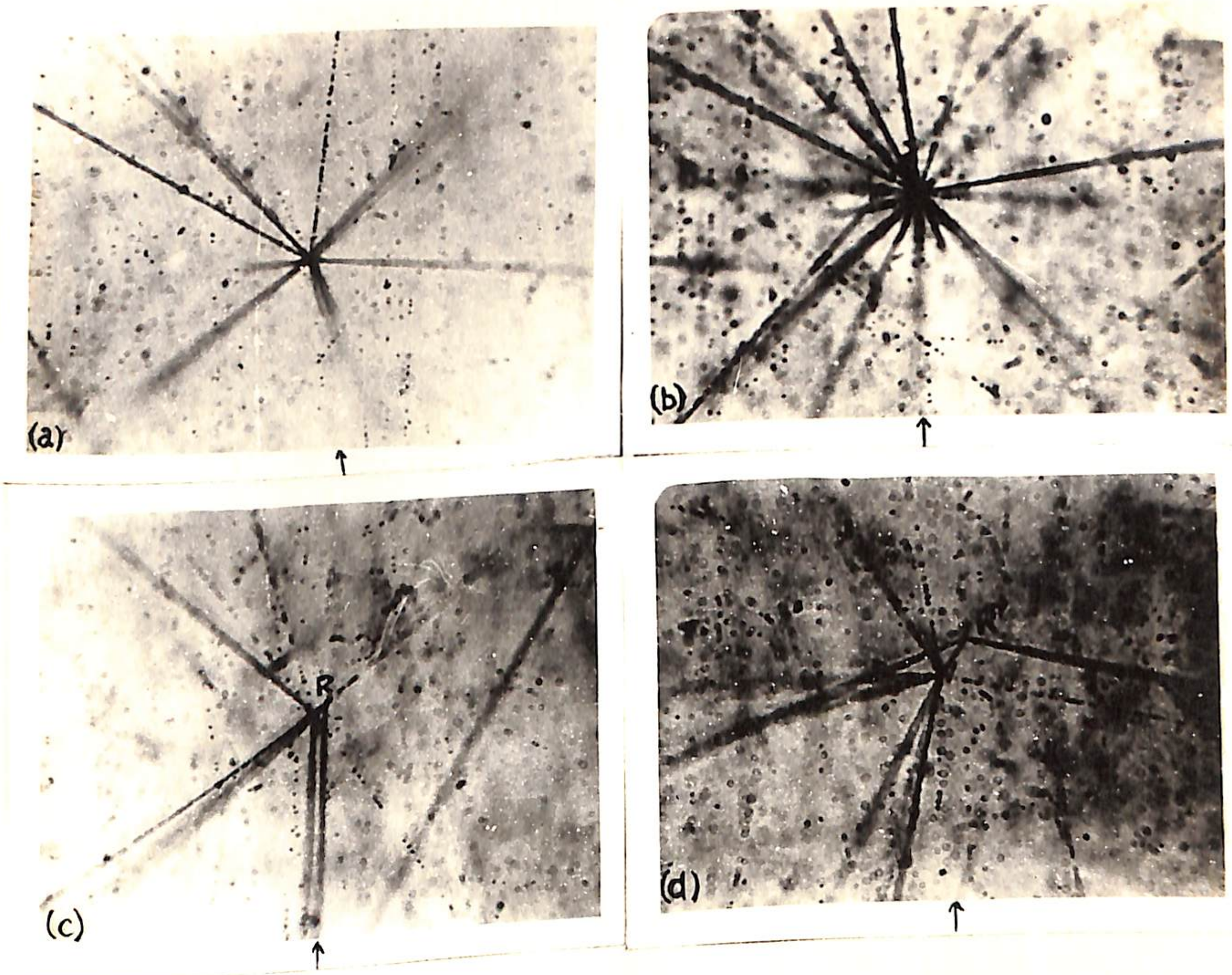
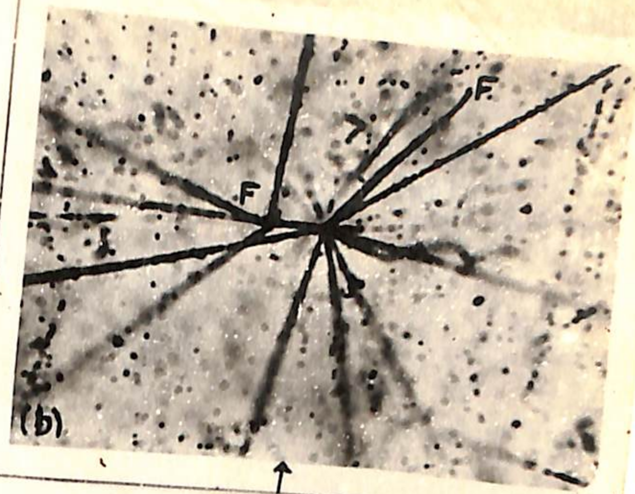
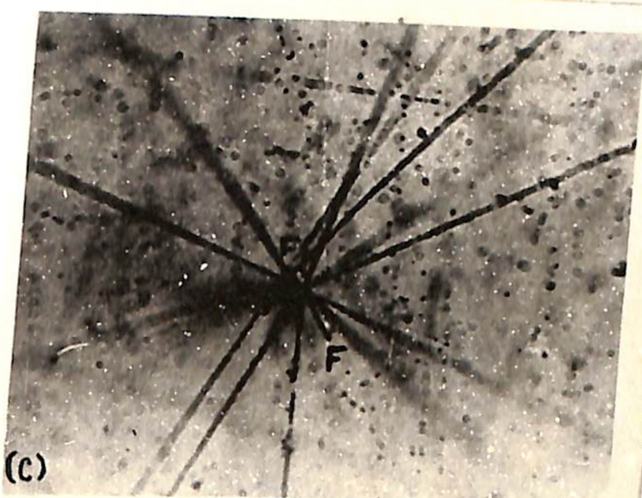
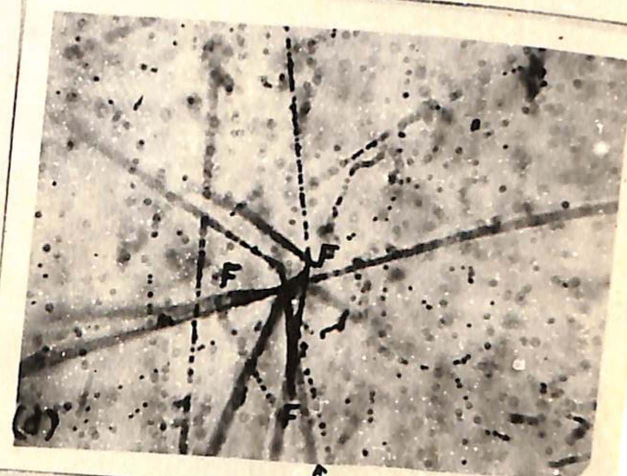


PLATE No. 7

Microphotographs of (a) & (b) UDS events, (c) & (d) RHN events. R represents the RHN, arrow head for beam direction.







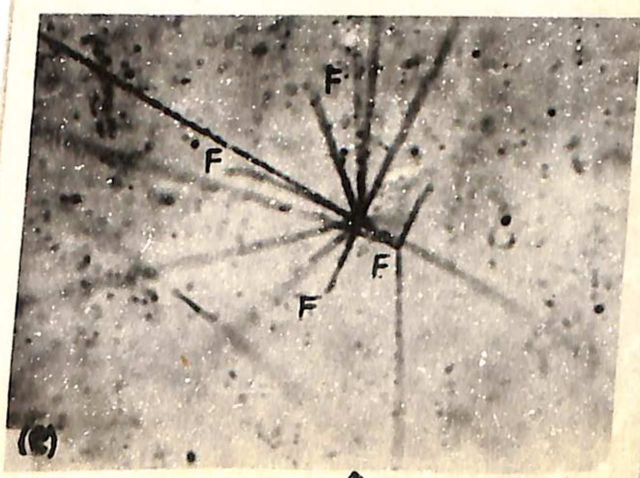


PLATE No. 8
Microphotographs of (a)-(c) FHN events, (d) & (e) MHN events. F represents the fragments, arrow head for beam direction.

mode of decay is mesonic. The non-mesonic decay process turns out to be quite important
for HN of A=5/49, 66, 70/ and becomes dominant for heavy HN. (i) A relatively higher
binding energy of lamda particles in heavier HN, (ii) Pauli blocking, and (iii) increased
nuclear density of heavier HN are taken as the reasons for it /71/. The non-mesonic
decay have two channels viz, proton stimulation and neutron stimulation /72/. Cuevas
et al /73/ have shown that the non-mesonic decays of short range ($\leqslant$ 10 microns)
heavy HN proceeds mostly by neutron stimulation.

It has been argued that often it becomes difficult to implant a lamda
hyperon dip inside the nucleus /74/. Also, the probable existance of surface hyperon
states may lead to a change in the surface tension of the nucleus /56/ which in turn
may be important for processes like fission.

It is expected that the existance of lamda hyperons should shrink
the nuclear core /74/. But the presence of lamda particles, as has been derived by
Koleshikov et al /75/, leads to relatively small additional effects between the isobaric
pairs of HN and the corresponding pairs of nuclides (without lamda hyperons).

Thus it becomes evident that there are a number of phenomena
associated with the production, interaction and decay of lamda hyperons in nuclei
which are yet to be well understood - particularly in respect of heavy HN /27/.

However, it has been observed that a large fraction of lamda hyperons
produced in the nuclear interactions are emitted along with the heavy fragments in
which they are trapped. They decay predominantly non-mesonically releasing a large
amount of energy — each decay causing a secondary star in nuclear emulsion. In the
present investigation an attempt has been made to study the emission of heavy fragments
($A \gtrsim 20$) containing such trapped hyperons.

7.2. EXPERIMENTAL PROCEDURE AND SELECTION CRITERIA :

The disintegration centres, obtained by area scanning, are scrutinized carefully (1875x - oil immersion objective) to detect the presence of associated hypernuclear decay stars by eliminating background events like chance coincidence, collision, capture, scattering. Measurements on range, angle, dip etc. are done as usual.

To accept only the genuine events the following criteria are adopted.

(A) UDS (Un-separated double star) events :

The range of the inter-connecting track between the two disintegration centres should not exceed 1.5 microns in the projected plane. The events are called "UDS" as tracks from the primary and secondary disintegration centres are not separated. As such, in this case the Ag, Br events are selected under the criterion $N_{ht} > 7$, where N_{ht} represents the total number of heavily ionising tracks from both the disintegration centres.

(B) SDS (Separable double star) events :

The range of the inter-connecting track between the two disintegration stars should be at least 1.5 microns in the projected plane; this facilitates identification tracks from the primary star. The dip angle of the track due to the HN should not exceed 60° and for other fragments (as in fission and multifragmentation) it should not exceed 45° in unprocessed emulsion. The criteria for further classification of these events are detailed below :

(i) **RHN (Recoiling hypernuclei)events :** The range of the inter-connecting track (due to RHN) should not exceed 10 microns. The track characteristics of RHN should be similar to those of RR (section 4.2).

(ii) **SHN (Short range hypernuclei) events :** The range of the inter-connecting track due to SHN (between the two stars) should be between 10 microns and 35 microns. The track characteristics of SHN should be similar to those of ST (section 4.2).

(iii) **FHN (Fission hypernuclei) events :** Criteria in respect of track characteristics, range, range ratio and relative oriantation of the tracks are similar to those for fission events (section 5.2), except that one of the fission fragments should be due to an HN called "FHN".

(iv) **MHN (Multifragmentation hypernuclei) events :** The MHN events are similar to those of MF events (section 6.2) in respect of track characteristics and ranges under further consideration that one of the concerned fragments should be due to an HN called "MHN".

7.3. RESULTS AND DISCUSSIONS :

7.3A. UDS Events :

7.3A1 Frequency and cross-section :

The frequency and cross-section of UDS events along with some of the relevant particulars are presented in table 7.1.

Table 7.1 : Frequency and cross-section (UDS events)

Beam momentum (GeV/c)	Vol. of emulsion (c. c.) approx.	No. of stars scrutinized	No. of UDS events	Corrected* Freq. (p.c.)	Corrected* C-S. (mb)
1.8, K^-	51.4	25000	189	0.76±0.06	0.91±0.07
20, p	16.32	5000	3	0.06±0.03	0.18±0.11

* Scanning correction only.

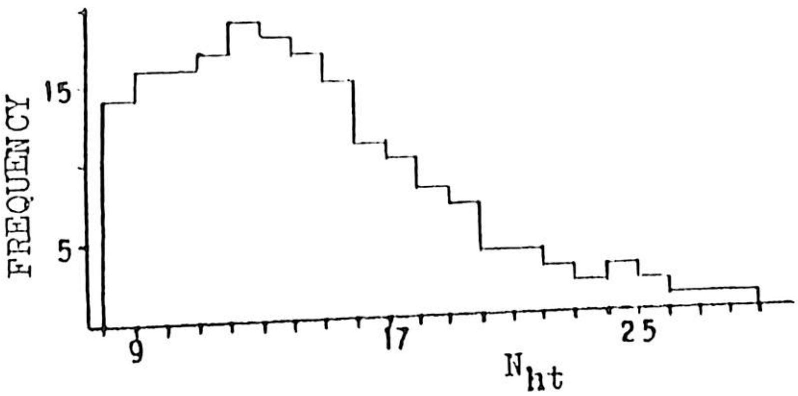


FIG. 7.1:- N_{ht} distribution (UDS events).

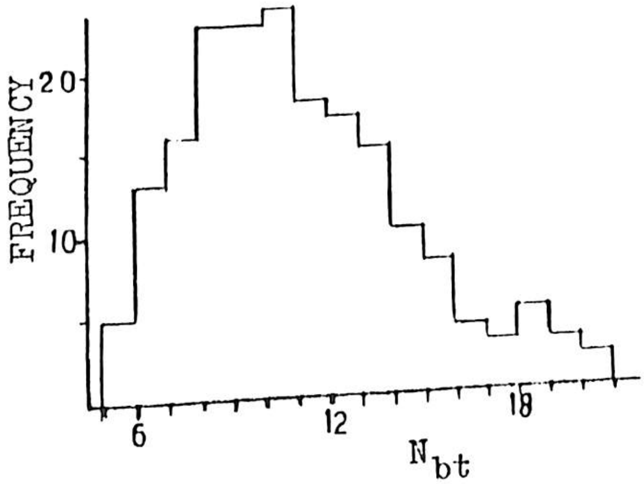


FIG. 7.2:- N_{bt} distribution (UDS events).

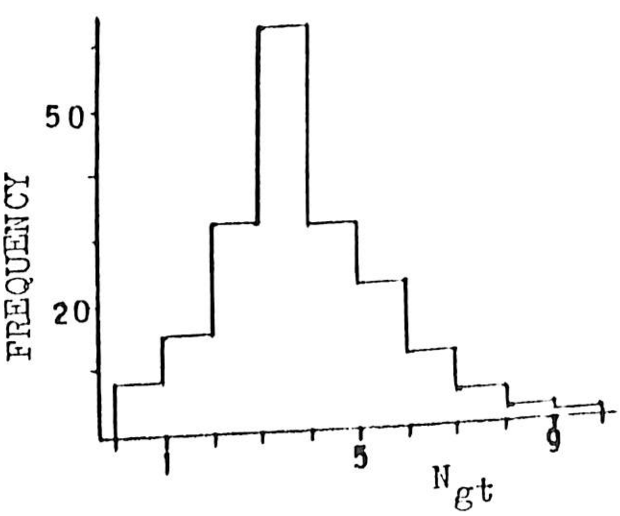


FIG. 7.3:- N_{gt} distribution (UDS events).

7.3A2. Star size distribution :

The relevant particulars relating to the distribution of heavily ionizing tracks associated with both the disintegration stars taken together are presented in table 7.2.

Table 7.2 : Track multiplicities of stars (UDS events) :

Beam momentum (GeV/c)	N_{ht} distribution		N_{bt} distribution		N_{gt} distribution	
	Fig No.	Mean	Fig. No.	Mean	Fig. No.	Mean
1.8, K^-	7.1	13.92±0.32	7.2	10.61±0.25	7.3	3.31±0.12

N_{ht} = total heavily ionizing track multiplicity

N_{ht} = total black track multiplicity

N_{gt} = total grey track multiplicity

7.3B. SDS events :

7.3B1 Frequency and cross-section :

Relevant particulars in respect of production frequency and cross-section of different classes of SDS events are presented in table 7.3.

Table 7.3 : Frequency and cross-section (SDS events) :

Beam momentum (GeV/c)	Vol. of emulsion (c.c.) approx.	No. of stars scrutinized	Classes of events	Events observed	Corrected Freq. (p.c.)	Corrected C.-S. (mb)
1.8, K^-	51.4	25000	RHN	238	1.10±0.07	1.33±0.09
	92.5	45000	SHN	7	0.02±0.01	0.02±0.01
	92.5	45000	FHN	55	0.12+0.02	0.15±0.02
	123.3	60000	MHN	12	0.06+0.02	0.07±0.02
20, p	16.32	5000	RHN	5	0.12+0.05	0.35±0.16

The cross-sections of individual fragments from FHN and MHN events are about 0.30±0.04 mb and 0.21±0.06 mb respectively.

In analogy with the MF events (section 6.3A), to a first approximation, the MHN events may also be classified as shown in Table 7.4.

Table 7.4 : Classification of MHN events :

No. of fragments	Classification (type)	No. of events
3	TTF (HN)	2
3	TSS (HN)	2
3	LTF (HN)	7
4	HOF (HN)	1

7.3B2 **Star size distribution :**

The relevant particulars relating to the distribution of heavily ionizing tracks associated with the primary stars of the SDS events have been presented in table 7.5.

Table 7.5 : Track multiplicities of stars (SDS events).

Type of events	N_h distribution		N_b distribution		N_g distribution	
	Fig. No.	Mean	Fig. No.	Mean	Fig. No.	Mean
RHN	7.4(a)	11.93±0.22	7.5(a)	8.60±0.16	7.6(a)	3.33±0.09
SHN	-	14.00±1.21	-	9.86±0.91	-	4.14±0.76
FHN	7.4(b)	13.24±0.52	7.5(b)	9.78±0.40	7.6(b)	3.45±0.19
MHN	7.4(c)	16.33±0.88	7.5(c)	12.42±0.79	7.6(c)	3.92±0.33

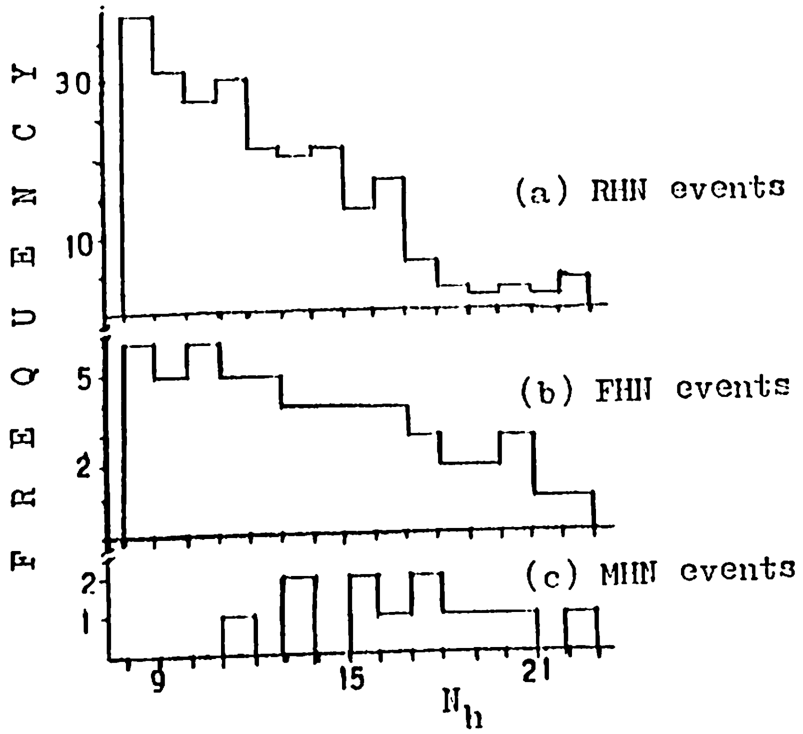


FIG. 7.4:- N_h distribution (HN events).

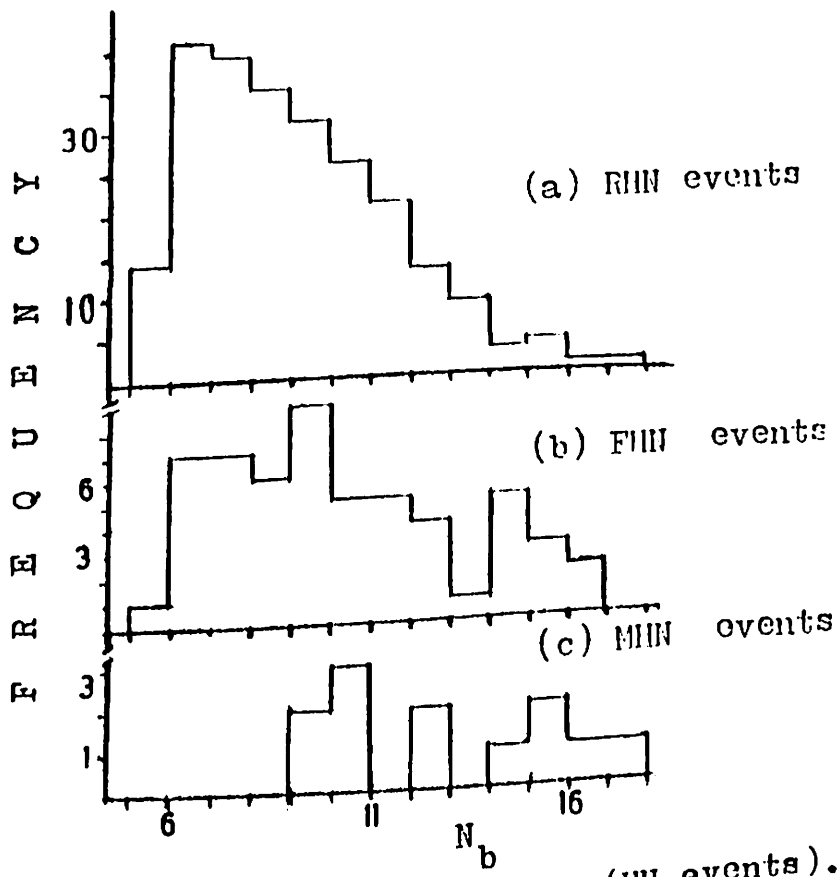


FIG. 7.5:- N_b distribution (HN events).

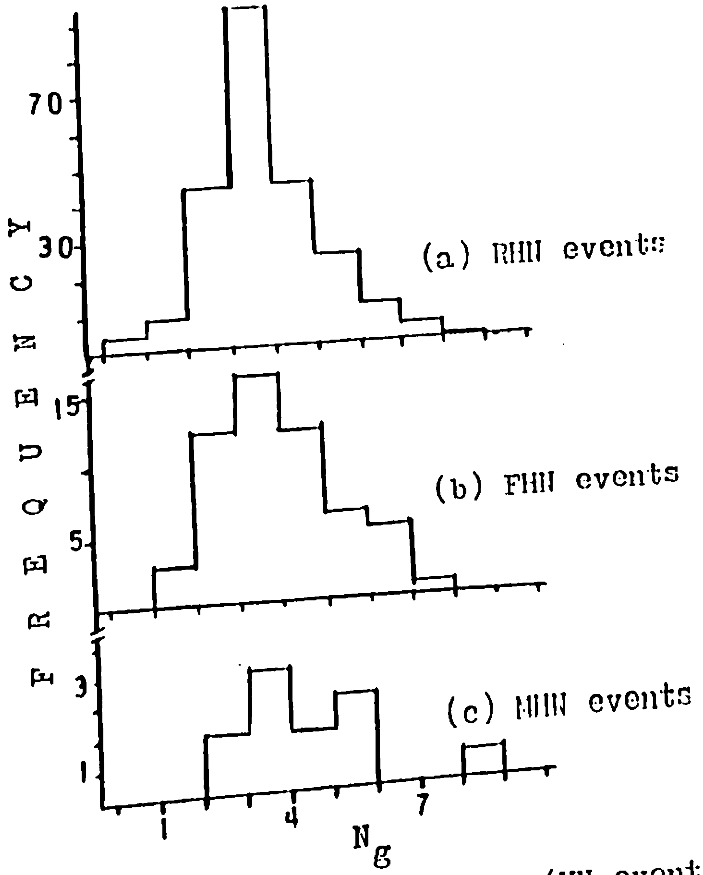


FIG. 7.6 :- N_g distribution (HH events)

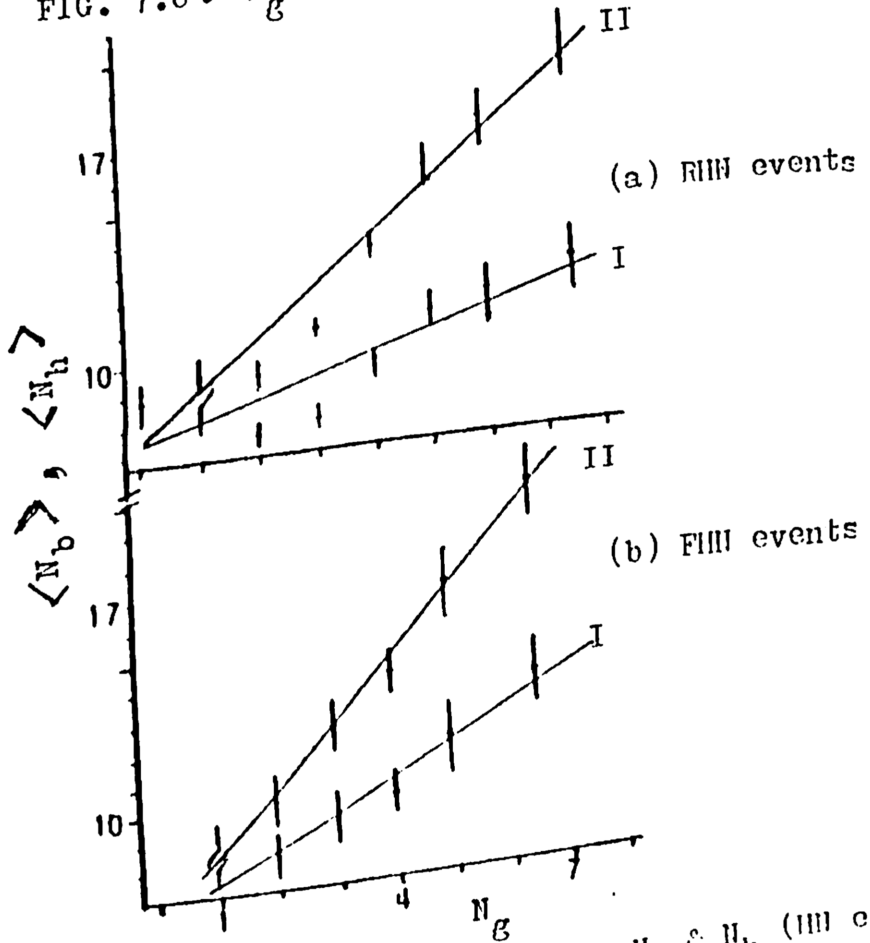


FIG. 7.7:- Relation of N_g with N_b & N_h (HH events).

The average excitation energies of the target nuclei producing RHN, SHN, FHN and MHN are estimated /76/ to be about 400 MeV, 450 MeV, 450 MeV and 550 MeV respectively. This shows that like MF events, the MHN events also are likely to prefer the occurrence at excitation energies higher than those for other types of SDS events.

7.3B3. Correlation :

The average values of N_b and N_h for various values of N_g are plotted against the corresponding N_g values for (a) RHN and (b) FHN events in Figs. 7.7(a), (b) respectively. This least square linear fits, marked I and II in the Figs., may be represented by

(a) I $\langle N_b \rangle = 7.44 + 0.57\, N_g$

II $\langle N_h \rangle = 7.50 + 1.54\, N_g$

(b) I $\langle N_b \rangle = 6.51 + 0.98\, N_g$

II $\langle N_h \rangle = 6.63 + 1.93\, N_g$

The relevant particulars for correlation co-efficient between N_b and N_g are presented in table 7.6.

Table 7.6 : Correlation co-efficients :

Event classification	Correlation co-eff. 'r'	95% C. I. of 'r'	Remarks
RHN	+0.46	0.46±0.10	The correlations
FHN	+0.49	0.46±0.21	are significant.

7.3B4. Charge and mass distributions :

The estimation of the charges and masses of the heavy hypernuclei has been done in the light of the sections 3.4E, 4.3A4, 5.3D and 6.3D. This is consistant with ref. /77/. The particulars relating to the distributions are presented in table 7.7.

Table 7.7 : Charge and mass distributions :

Particulars	Charge(Z) distribution				Mass(A) distribution			
	Fig. No.	Width From	Width To	Mean (approx)	Fig. No.	Width From	Width To	Mean (approx)
RHN	7.8(a)	11	34	27	7.9(a)	26	27	61
Prefission HN	7.8(b)	15	35	27	7.9(b)	30	75	61
Prefragmentation HN	7.8(c)	16	31	24	7.9(c)	35	70	54
Fragments of FHN events	7.10(a)	8	18	14	7.11(a)	16	40	30
Fragments of MHN events.	7.10(b)	2	16	8	7.11(b)	4	35	17

The heavy HN which travel more than 10 microns in emulsion like the SHN as considered herein, are taken to be due to fragmentation of target nuclei in some of the investigations /25, 73/ where the mass(A) of these hypernuclei are shown to be within about 20 to 40. Thus, the mass of these SHN may be assumed to be $A \gtrsim 20$.

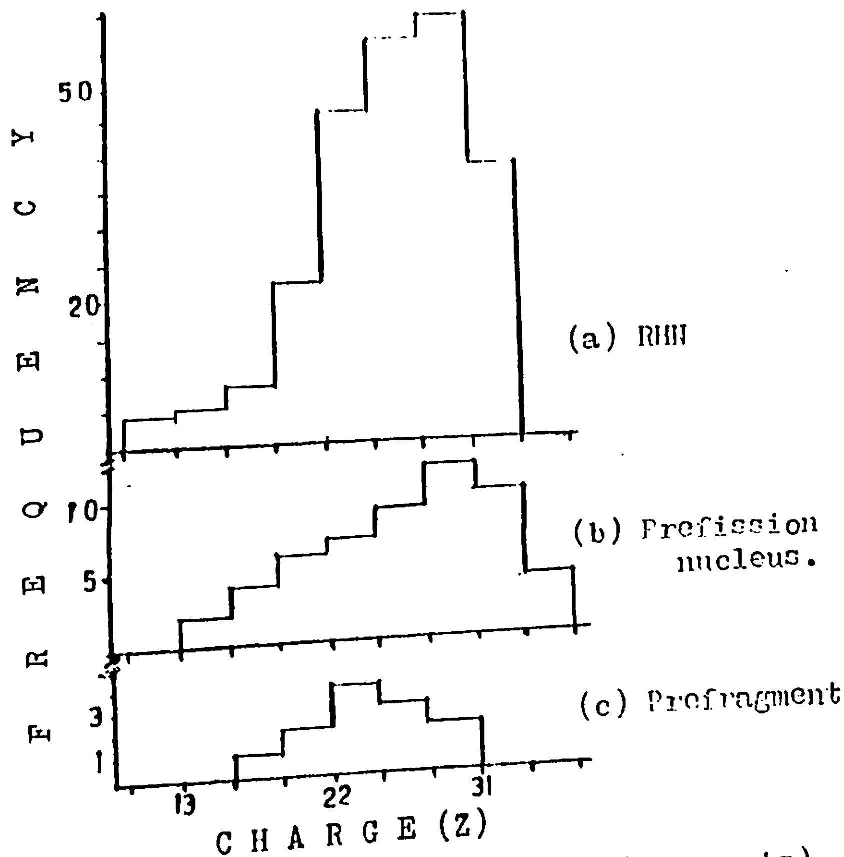


FIG. 7.8:- Charge distribution (HH events).

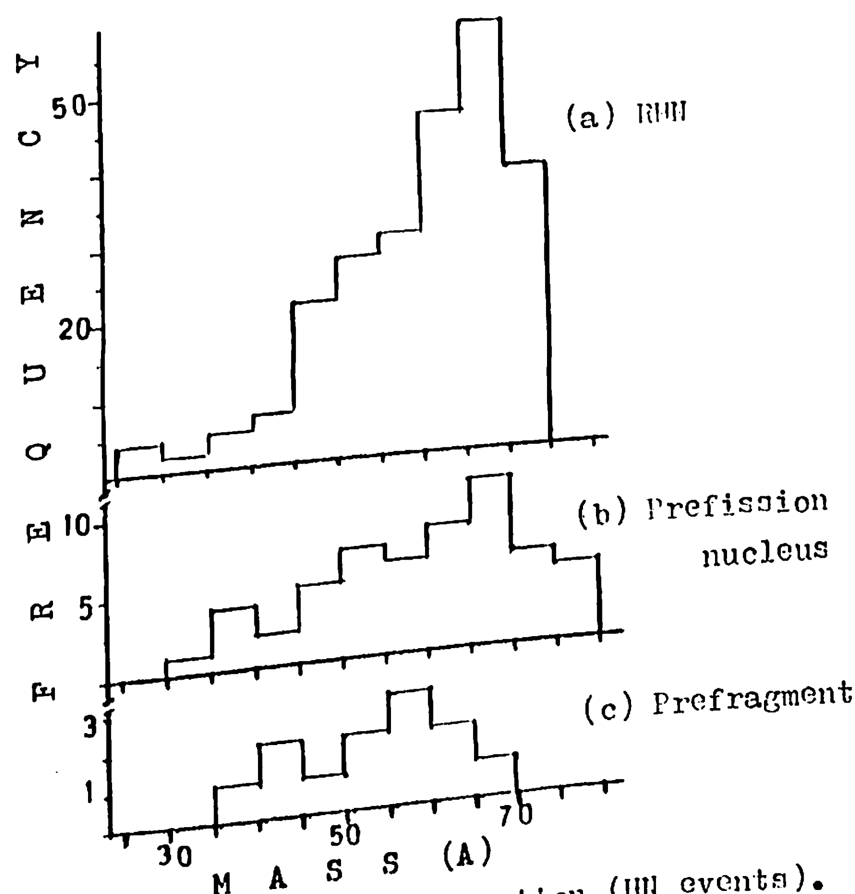


FIG. 7.9:- Mass distribution (HH events).

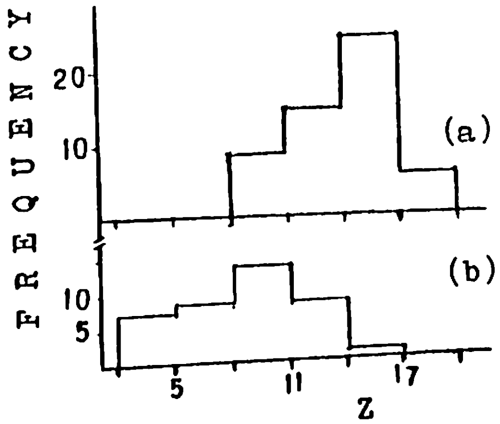


FIG. 7.10:- Charge distribution of fragments (HN events).

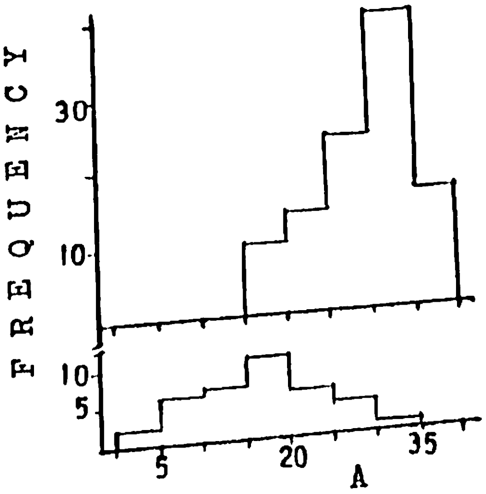


FIG. 7.11:- Mass distribution of fragments (HN events).

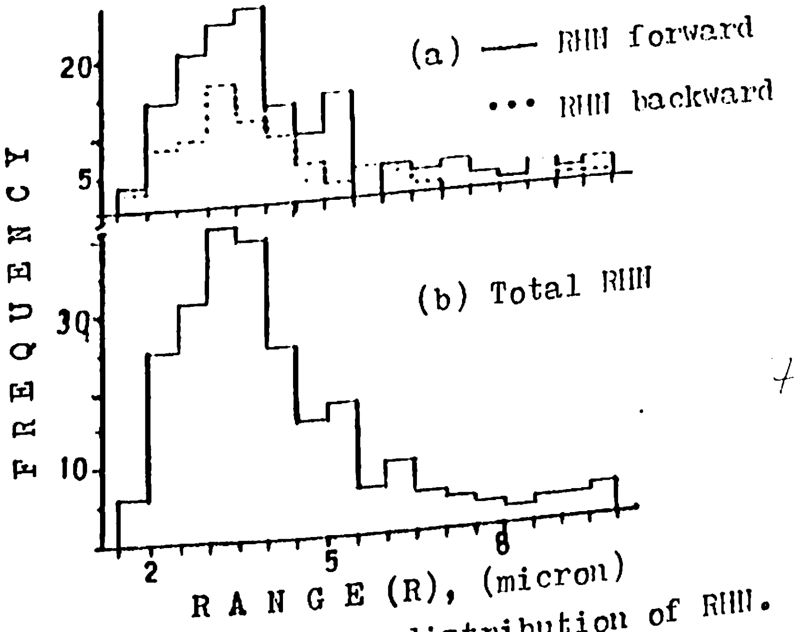


FIG. 7.12:- Range distribution of RHN.

7.3B5 Range distribution :

Particulars relating to the range distributions are presented in Table 7.8.

Table 7.8 : Ranges of different fragments :

Type of events	Particulars	Fig. No.	Mean range (microns)
RHN	Forward	7.12(a)*	4.21±0.15
	Backward	7.12(a)+	3.94±0.18
	Total	7.12(b)*	4.14±0.11
FHN	FHN	7.13(a)*	8.43±0.37
	Other fragments	7.13(a)+	9.88±0.63
	Total	7.13(b)*	9.15±0.37
MHN	MHN	7.14(a)*	23.25±5.08
	Other fragments	7.14(a)+	13.70+1.48
	Total	7.14(b)*	16.80±2.06

* histograms represente by continuous lines.

\+ histograms represented by discrete lines.

The mean range obtained for SHN fragments is

R = 17.28±2.12 microns.

On the average, from the observed ranges and range energy relations /78-81/, the mean energy of an RHN may be estimated as about 12 MeV while the translational (total) kinetic energies for FHN and MHN events may be around 50-55 MeV and 65-70 MeV respectively.

The individual RHN, like the recoiling residues (RR), may have any value of range within the range limits of observation (for any N_h value of the stars). However,

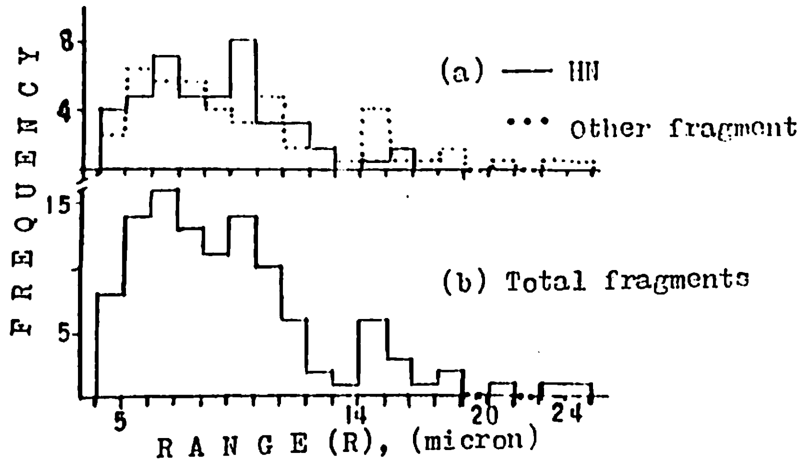


FIG. 7.13:- Range distribution of FHH fragments.

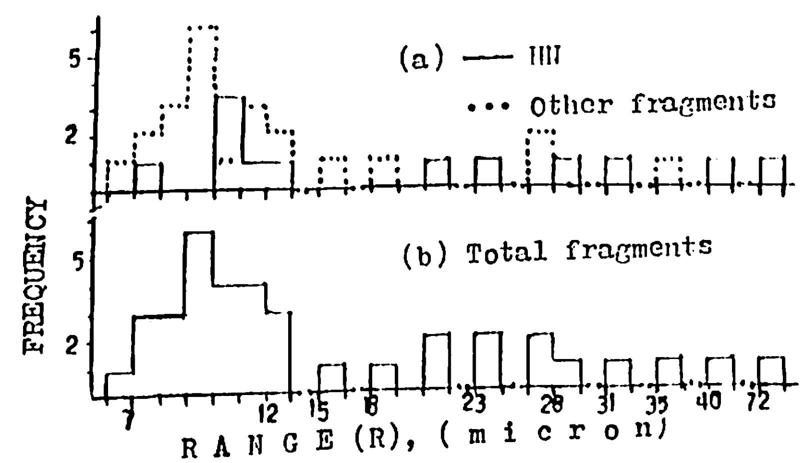


FIG. 7.14:- Range distribution of MHH fragments.

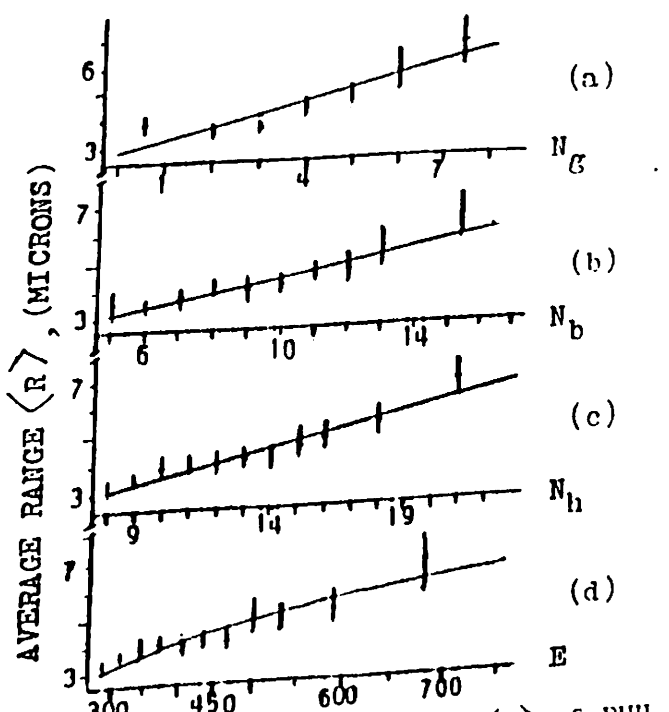


FIG. 7.15:- Variation of ⟨R⟩ of RHH.

as seen from Fig. 7.15(a), (b), (c), approximately linear relationships exist between the average range and N_g, N_b, N_h respectively. They may be represented by

$$\text{(a)} \quad \langle R \rangle = 2.90 + 0.45\, N_g$$

$$\text{(b)} \quad \langle R \rangle = 1.87 + 0.27\, N_b$$

$$\text{(c)} \quad \langle R \rangle = 1.41 + 0.23\, N_h$$

Range, hence energy or momentum of RHN may depend on initial excitation energey also (Fig. 7.15(d)).

These views have some support from the earlier investigations /82/.

7.3B6. **Velocity distribution :**

Range-velocity curves (as in section 2.7) have been used to find the velocity distributions. Some details are presented in table 7.9.

Table 7.9 : Velocity of different fragments :

Type of events	Fig. No	Velocity (in c) Width From	To	Mean (approx)
RHN	7.16(a)	0.005	0.045	0.021
FHN	7.16(b)	0.020	0.090	0.047
MHN	7.16(c)	0.030	0.090	0.051

The observed mean velocities are in close conformity with those for RR, fission fragments and MF fragments.

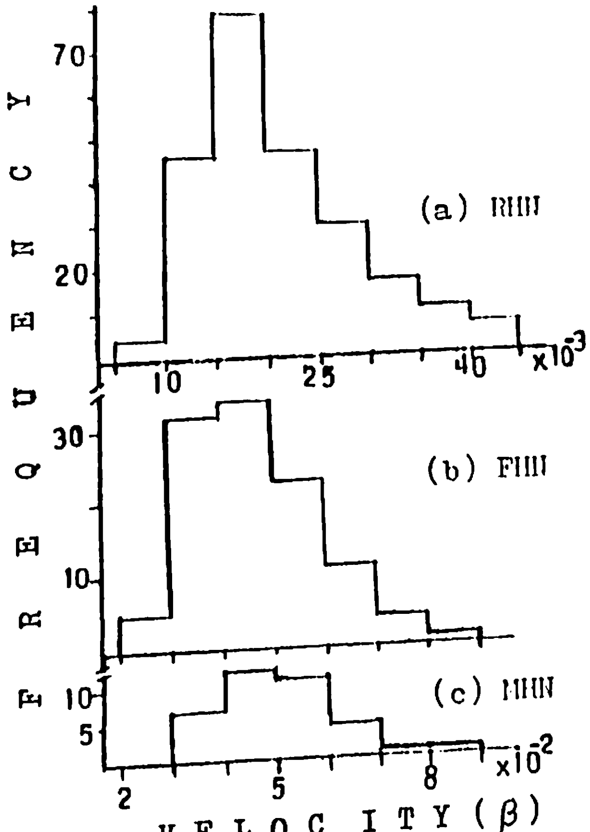


FIG. 7.16:- Velocity distribution (HN events).

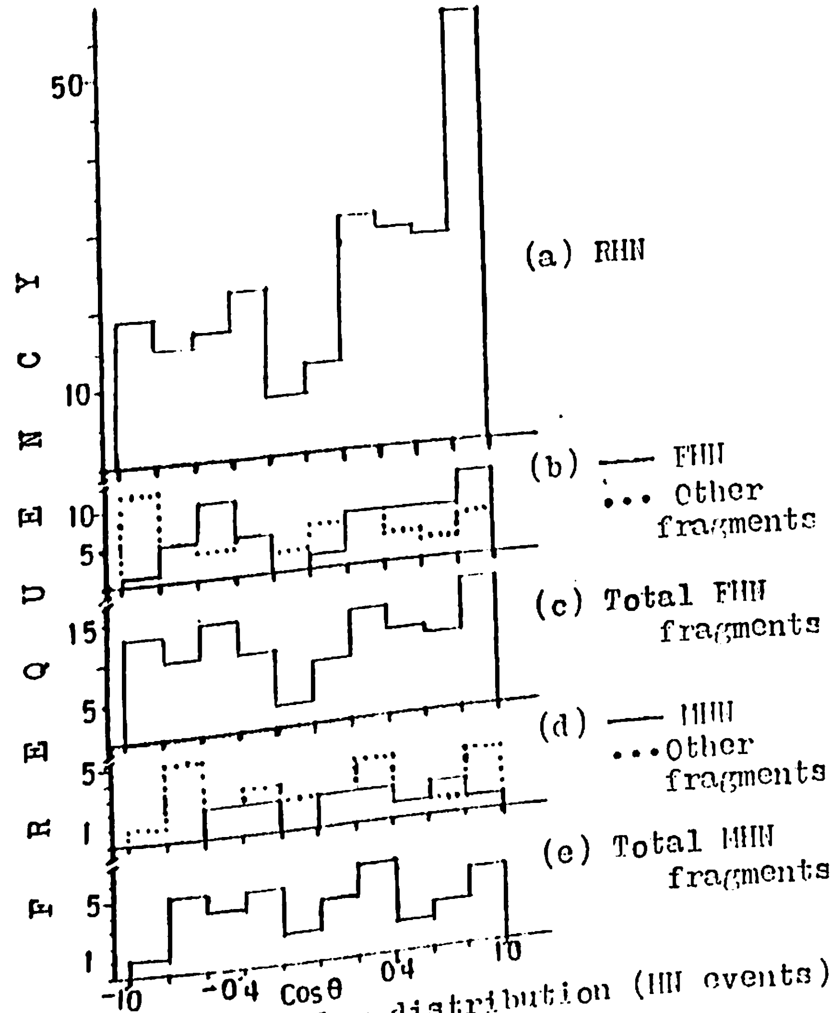


FIG. 7.17:- Angular distribution (HN events).

7.3B7. Angular distribution :

Relevant particulars relating to the angular distributions of the individual fragments have been presented in table 7.10.

Table 7.10 : Angular distribution of individual fragments :

Type of events	Particulars	Fig. No.	F/B ratio w.r.t. primary.
RHN	RHN	7.17(a)*	1.99±0.29
FHN	FHN	7.17(b)*	1.52±0.43
	Other fragments	7.17(b)+	0.77±0.23
	Total	7.17(c)*	1.11±0.22
MHN	MHN	7.17(d)*	1.50±0.97
	Other fragments	7.17(d)+	0.91±0.40
	Total	7.17(e)*	1.07±0.38

* histogram represented by continuous lines.

\+ histogram represented by discrete lines.

F/B ratio of SHN events w.r.t. primary is obtained to be 1.33±1.02.

The forward velocity of RHN with respect to the direction of incident primary is 0.007c.

The angular distribution of fission bisector of FHN events with respect to the incident primary has been shown in Fig. 7.18. The F/B ratio is compared with that of an earlier investigation /83/ in table 7.11.

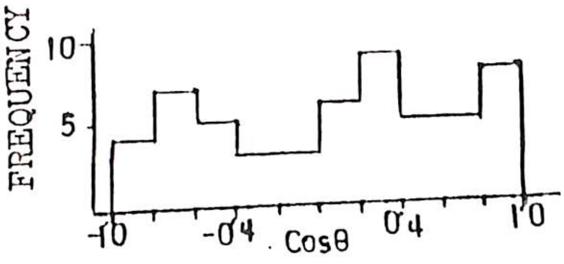


FIG. 7.18:-Angular distribution of fission bisector (FHN events).

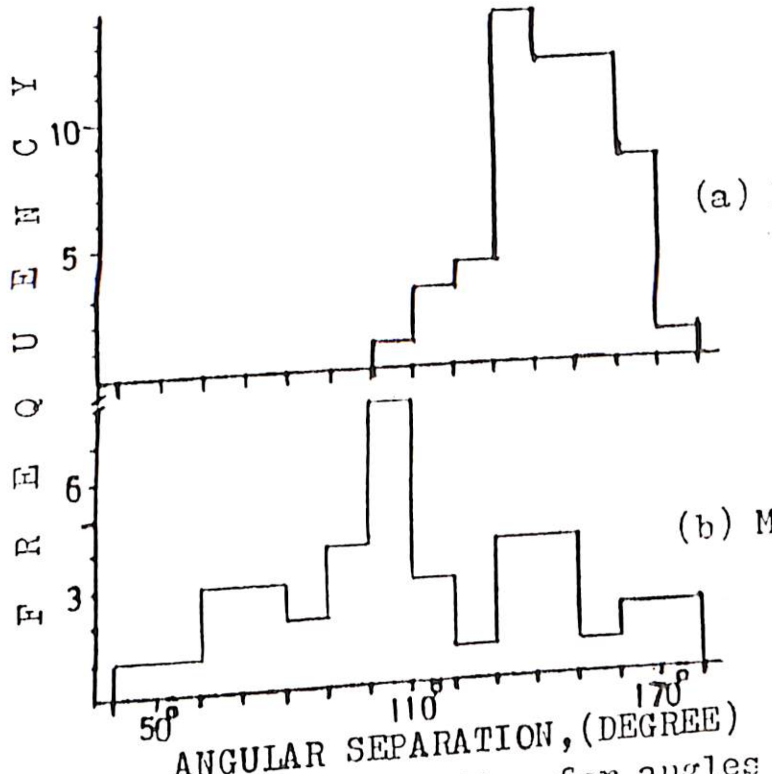


FIG. 7.19:- distribution for angles among fragments (HN events).

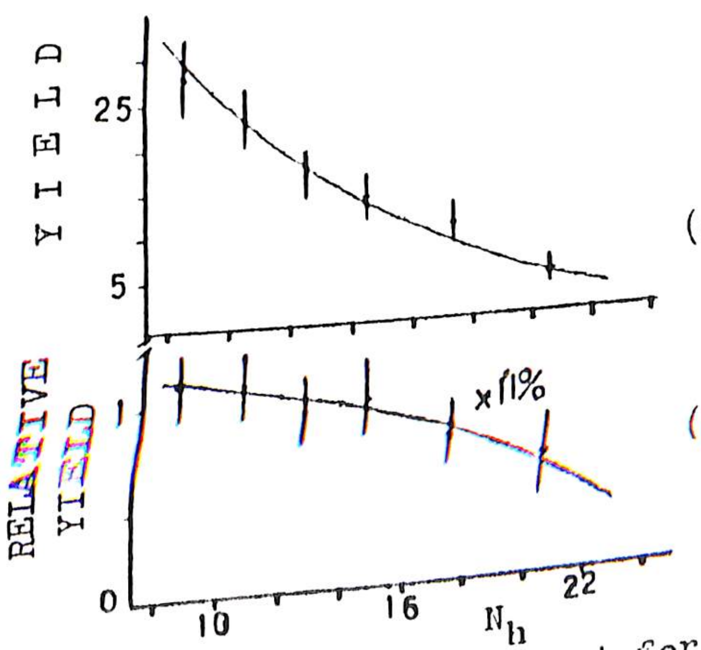


FIG. 7.20:- Yield-N_h plot for RHN events.

Table 7.11 : F/B ratios of fission bisectors :

K^- Beam momentum (GeV/c)	F/B ratio	Forward velocity w.r.t. incident primary (in c)	Ref.
1.5	1.50±0.52	-	/83/
1.8	1.42±0.30	0.008	P.W.

The results are consistant with those of earlier investigations.

Particulars relating to the distribution of angles among fragments for FHN and MHN events are presented in table 7.12.

Table . 7.12 : Angles among fragments :

Type of events	Fig No.	Mean angle (Degrees)
FHN	7.19(a)	144
MHN	7.19(b)	111

The F/B ratio of RHN with respect to the beam direction often has been taken as an indication about the validity of the spallation model of the production of heavy HN, in particular RHN.

While arguing that RHN is not due to HN of A-10 to 20 as was assumed in some of the studies /30/ but due to RR which captures a lamda hyperon, Kenyon /21/ has shown that the evaporated particles and fragments bear a backward correlation w.r.t. the direction of RHN.

The results of this investigation are compared with some of the other investigations in table 7.13.

Table 7.13 : F/B ratios (RHN events) :

K^- beam momentum GeV/c	F/B ratios: of RHN w.r.t. primary	F/B ratios: of black tracks w.r.t. RHN	Ref.
0.8	2.46±0.10	0.59±0.10	/21/
0.8	2.30±0.10	0.50±0.03	/84/
1.5	2.14±0.13	0.56±0.10	/84/
3.5	1.75±0.18	0.76±0.15	/84/
6.0	1.25±0.30	0.74±0.07	/84/
1.8	1.99±0.29	0.72±0.05	P.W.

The observed F/B ratio of black tracks w.r.t. SHN is 0.48±0.13. This gives additional support to the belief ... that SHN are heavy fragments.

The table 7.13 shows that the RHN has a preference to be emitted in the forward direction. It has been shown /85/ that the fraction of RHN that may escape observations in the laboratory system is small enough to affect the results greatly. The results obtained in this investigation are consistant with those of others.

7.3B8. **The Yield :**

Figs. 7.20(a), (b) shows the nature of variation of production of RHN (briefly, yield) and relative number (percent) of interaction producing RHN (briefly, relative yield) respectively with N_h.

Some of the characteristics of RHN are compared with those of RR in table 7.14.

Table 7.14 : Comparison of characteristics (RHN and RR events) :

Type of events.	Excitation (energy (MeV) approx.)	Mean values (approx) of charge (Z)	mass (A)	velocity (in c)	F/B ratio w.r.t. primary
RHN	400	27	61	0.021	1.99±0.29
RR	400	27	61	0.022	1.58±0.09

Table 7.14 shows that the general characteristics of emission of RHN are similar to those of RR. The higher F/B ratio and consequently a higher component of velocity of RHN along the beam direction may be caused by the captured lamda hyperon. The lamda hyperons, produced as a consequence of initial impact of the primary beam on the target — may carry adequate forward momenta. Thus a higher component of velocity of RHN along the beam direction as compared to that of RR may be observed. Otherwise, the mechanism of emission of RHN may be similar to that of RR.

A comparison of some of the characteristics of FHN and fission events have been made in table 7.15.

Table 7.15 : Comparison of characteristics (FHN and fission events) :

Type of events	Excitation energy (MeV)	Prefission Charge (Z)	Prefission Mass (A)	Folding angle (Degrees)	F/B ratio of fission bisector	Fragment velocity (in c)
FHN	450	27	61	144	1.42±0.30	0.047
Fission	450	27	61	143	1.58±0.15	0.048

From table 7.15 it may be observed that the characteristics of FHN and fission events may be similar.

In table 7.16, some of the characteristics of MHN and MF events are compared.

Table 7.16 : Comparison of characteristics (MHN and MF events) :

Type of events	Excitation energy (MeV)	Prefragment		Fragment		
		Charge (Z)	Mass (A)	Angular separation (Degrees)	Velocity (in c)	F/B ratio
MHN	550	24	54	111	0.051	1.07±0.38
MF	500	26	58	113	0.054	1.16±0.13

Table 7.16 shows that the observed characteristics of MHN and MF events are similar.

The RHN,FHN, MHN events may be produced in similar process as those for RR, fission, MF events. Also, as for the SHN and ST events, the emission of SHN and ST fragments does not seem to be understood from cascade-evaporation theory in respect of their mass and energy but they are likely to have similar mass and energy; also the events have similarities in respect of excitation energy of the target and thus may originate in a similar process.

7.3C. Life time of RHN :

One of the important properties of an HN is its life time. It is beleived that heavier HN have shorter life time.

A total of 109 DS events with a recoiling residue each at the second Λ (lamda) decay centre, briefly "RRS" events have been collected. The primary disintegration centres have N_h = 11.88±0.47 and the average range of HN is 4.17±0.16 microns. The corresponding distributions do not differ significantly from those of RHN.

The range and angular distributions of RRS have been presented in Figs. 7.21 and 7.22 respectively. The mean range of RRS is 2.15±0.10 microns and F/B ratio w.r.t. the direction of motion of HN is 2.38±0.53.

The mean velocities of HN and RRS are estimated to be about 0.021c and 0.013c respectively. The average forward velocity of the decaying HN while ejecting the RRS may be estimated as 0.005c approximately. Adopting the procedure of Bhalla et al and Choudhury et al /55/, a curve showing the relationship between F/B ratio of RRS and life time(T) of HN is drawn (Fig. 7.23). From this, the estimated mean life turns out to be about $(1.6^{+1.4}_{-0.6}) \times 10^{-12}$ sec., (consistant with those of earlier investigations). Such a result gives a very high value of Q^- (about 10^4)/25, 55/, where Q^- stands for the non-mesonic to pi-minus mesonic branching ratio. The result differs greatly from the theoretical (estimated) values too /68, 69/.

From the results of Bocquet et al /57/ the life time of a heavy HN may be expected to be about 10^{-10} sec. Further, measurements on branching ratios do not show Q^- to exceed 200. Thus the life time obtained in this investigation may be small.

Again from the simple kinematical relations and law of radioactive decay, by assuming that half of the HN decay after travelling about 4.17 microns under a uniform retardation, the estimated life time becomes about 1.5×10^{-12} sec. On the other hand, the life time estimated for the HN of mass A≈60 (approx) is about 2.6×10^{-12} sec. when half-life is calculated by using the empirical relation of Powell et al /76/. These results are almost similar with that obtained from Fig. 7.23.

As towards the end of the range of a heavy ion the retardation is expected neither to be uniform nor to be charge independent, the values obtained as in the above may not be correct. Thus it becomes evident that the considerations as in Ref. /55/ may not be adequate to estimate the life time.

7.3D. The frequency of DS events :

The frequency of the observed DS events, which include both UDS and SDS events, are compared with those of others in table 7.17.

Table 7.17 : Frequency of observed D.S. events :

Beam momentum (GeV/c)	Frequency (per cent)	Ref.
0.8 K^-	3.0 ± 0.2	/77/
1.5 K^-	2.8 ± 0.2	/77/
3.5 K^-	1.6 ± 0.9	/77/
1.8 K^-	1.87 ± 0.09	P.W.
20 p	0.16 ± 0.06	P.W.

The table 7.17 shows that the results obtained in this investigation are consistant with those of others. Improved technicques of observation of DS events like grain co-ordinate measurement and track reconstruction /86/ may increase the production cross-section only by a small factor /77/ i.e. merginally.

7.4. REMARKS :

The heavy hypernuclei appear as a consequence of capture of hyperons by heavy fragments.

The observed cross-section of production of heavy HN by various mechanisms along with some of their characteristics are presented in table 7.18.

Table 7.18 : Cross-section of heavy HN :

Type fragments.	1.8 GeV/c K^- beam HN with $A \gtrsim 20$ only		20 GeV/c p beam HN with $A \gtrsim 20$ only
	Cross-section (mb) approx.	Mean velocity (in c) approx.	Cross-section (mb) approx.
RHN	1.33	0.021	0.35
SHN	0.02	-	
FHN	0.15	0.047	
MHN	0.02	0.051	

From table 7.18 it may be observed that the cross-sections of emission of heavy HN by the four processes viz. RHN, SHN, FHN and MHN are very small but finite. Thus, though merginally, hypernuclei contribute towards the emission of heavy fragments in the processes similar to those of RR, ST, fission and multifragmentation.

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CHAPTER VIII

CONCLUDING REMARKS

The emission of heavy fragments ($A \gtrsim 20$) during high energy disintegration of the target nuclei is a complex phenomenon. A number of processes like spallation, fission and multifragmentation are responsible for their emission. Also, on occasions some of the produced particles like lamda-hyperons may be bound with some of such heavy fragments.

Eventhough indications have been obtained for the validity of the cascade-evaporation theory of nuclear disintegration, it is observed that the diverse aspects of the high energy disintegrations cannot be explained on its basis alone. Competing processes of heavy fragment emission are also to be considered along with the cascade-evaporation process so as to understand the gross features of high energy disintegrations.

Some of the characteristics of the nuclear disintegrations responsible for the emission of heavy fragments, are presented in table 8.1.

Table 8.1 : Some of the characteristics of disintegrations.

Events	Production cross-section (mb)	Excitation energy (MeV)	$\bar{N}_h$	95% C.I. of N_g-N_b correlation co-eff.	Forward velocity of the fragment emitting system (in c)
Spallation as (a) RR	43.2±6.3	400	11.90±0.08	0.19±0.05	0.005
(b) ST	0.92±0.06	450	13.30±0.23	0.08±0.13	0.012
Fission	7.31±0.22	450	13.27±0.14	0.30±0.07	0.004
MF	0.74±0.07	500	14.82±0.27	0.08±0.17	0.004

The average forward velocity of the heavy fragment emitting system (like those for recoiling residues and fission events) may be expected from the considerations of particle evaporation to be about 0.003c. As seen from table 8.1 the experimental values, except those for short track events, agrees reasonably well with the expected value.

On the basis of the cascade-evaporation theory, the equipartition of energy of the target nucleus is assumed to be accomplished in the relatively fast "cascade" process that comes into being soon after the impact of the incident primary. Also, some of the nucleons are knocked off in the process and the rest of the nucleus gets heated. Subsequently during de-excitation by the slower "evaporation" process, particles and light fragments are emitted sequentially. The time interval between two successive emissions in this sequential break-up may depend upon the excitation energy of the target nucleus also. Often the reaction comes to an end leaving behind a heavy residual mass that recoils due to the momentum imparted during this process. Also, towards the end of such a process, ultimately some of the excited residual mass may split-up into two or more heavy fragments. Thus the process like fission and multifragmentation may compete with the process of evaporation. A significant correlation (as has been observed for the recoiling residue and the fission events) between the number of cascade particles and the number of evaporated particles is often taken as a signature of equilibrium decay, like that assumed for the cascade-evaporation process. The correlation may not be significant (as observed for the short track (ST) and multifragmentation events) when the target nuclei may undergo (i) pre-equilibrium disintegration, (ii) smooth transition from cascade to evaporation, (iii) multi-body break-up or ejection of quasibound and unbound nuclear systems, or (iv) a combination of some of these possibilities.

The percentage of occurrence of each type of the heavy fragment emitting disintegrations i.e., the "yield", has been observed to vary with the number of heavily ionizing tracks(N_h). Fig. 8.1 shows the variations. In general, the disintegration stars occur by obeying a systematic trend which may be exponential in nature. Only a fraction of the total disintegration stars contain heavy fragments emitted by the processes discussed herein. Such a fraction (per cent) at a particular N_h value is called the "relative yield". The nature of variation of the relative yield (for each type of events) with N_h may be represented by the plots as shown in Fig. 8.2.

Figs. 8.1 and 8.2 show that the spallation events are more abundant at lower N_h values i.e., at lower multiplicities while multifragmentation is a process showing preferance to occur more abundantly at higher multiplicities. The Figs. also show that the occurrence of the events at still lower multiplicities is probable. However, the frequency of some of the events like multifragmentation may be very small.

Some of the characteristics of the fragments under consideration are presented in table 8.2.

Table 8.2 : Some of the characteristics of fragments :

Events	Production cross-section (mb)	Charge(Z) width From	Charge(Z) width To*	Mass(A) width From	Mass(A) width To*	Average velocity (in c)
Spallation as (a) RR	43.2±6.3	11	32	20	75	0.022
(b) ST	0.92±0.06	-	-	(20^+)	(40^+)	0.062
Fission	14.6±0.4	6	18	11	40	0.048
MF	2.33±0.22	2	17	4	35	0.056

* Lower limit only; + Discussed in section 4.4.

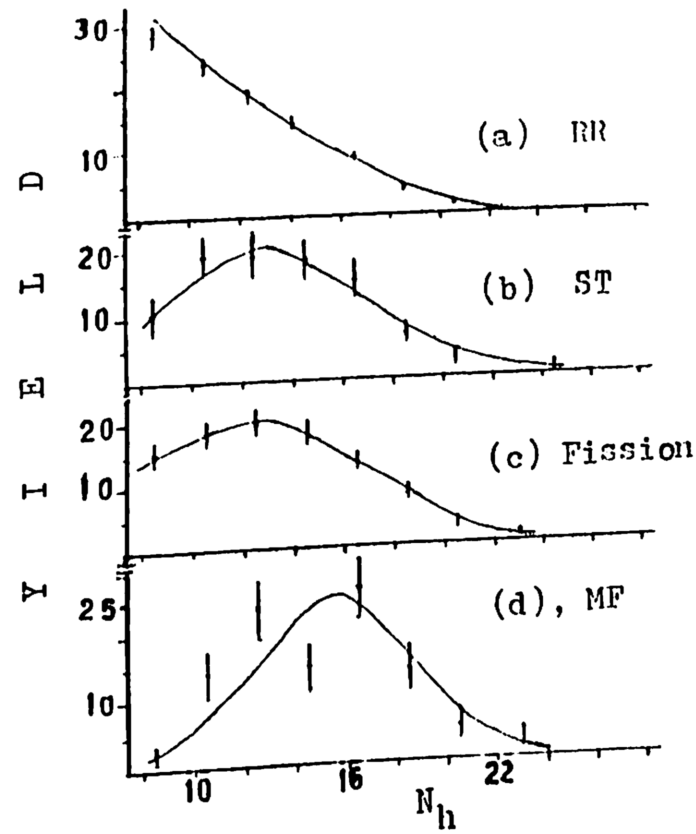

FIG. 8.1:- Yield-N_h plots (compiled)

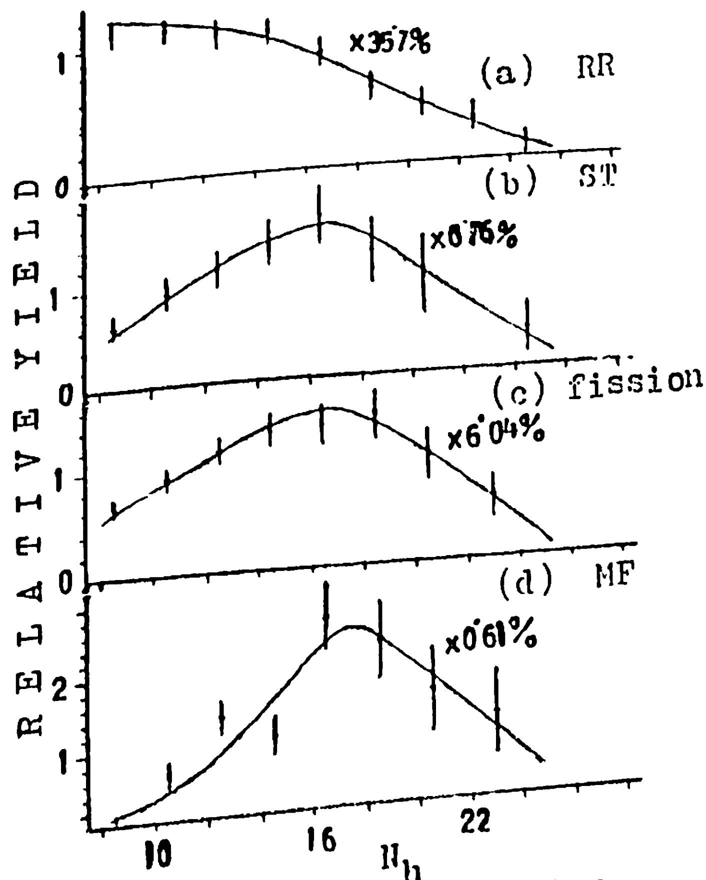

FIG. 8.2:- Yield(relative)-N_h plots (compiled).

Almost all of the spallation products are heavy ($A \gtrsim 20$). About (85±10)% of the fission fragments and about (35±10)% of the multifragmentation fragments are also heavy.

For events with energetic spallation products, i.e., for short track events, though the value of $\bar{N}_h$ (table 8.1) and the variation of yield with N_h (Figs. 8.1 and 8.2) are similar with those for fission events, there is no significant correlation between N_b and N_g. The average velocity of the fragment (short track) emitting system is considerably higher. The black tracks of the disintegration stars have considerable anisotropy w.r.t. the short tracks. The charges, masses and momenta of the energetic spallation products cannot be understood from the evaporation considerations. Rather, these heavy products may be emitted by some exotic process prior to attaining equilibrium of the disintegrating system.

The intergrated charge and mass distributions of the fragments have been presented in Figs. 8.3 and 8.4 respectively. The distributions are consistant with the typical U shaped mass yield curve for high energy nuclear disintegrations. The "deep" region of the curve may be at about Z=20±3 and A=40±5.

From the present investigation it becomes evident that only a single mechanism like spallation, fission or any other process alone cannot account for the observed heavy fragment emission. Also, the emission of the disintegration products of mass corresponding to those in the deep region of the mass yield curve may be caused practically by all of the processes of heavy fragment emission considered herein.

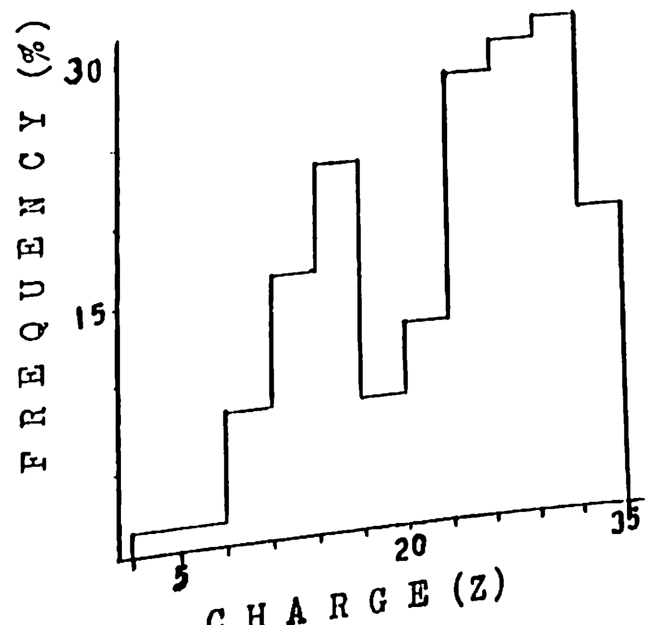

FIG. 8.3:- Integrated charge distribution.

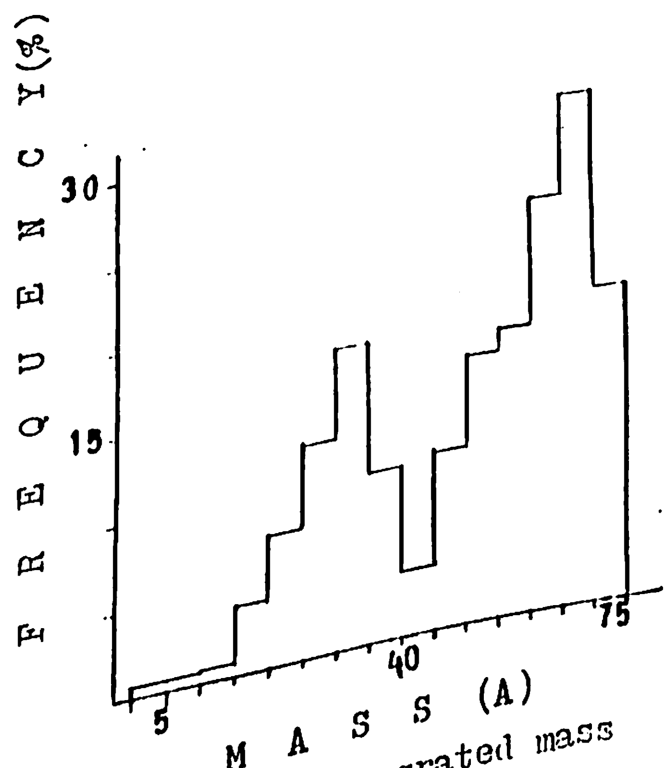

FIG. 8.4:- Integrated mass distribution.

The results of the investigation with two beams of different energy on the frequency of occurrence of various types of events have been summerized in table 8.3.

Table 8.3 : Frequency (per cent) of events :

Beam	Spallation		Fission	Multifragmentation
	RR	ST		
1.8 GeV/c K^-	35.7±5.2	0.76±0.05	6.04±0.18	0.61±0.05
20 GeV/c p	43.0±6.5	1.24±0.22	7.08±0.54	1.36±0.28

A total of about (1.87±0.09)% and about (0.16±0.06)% of the observed disintegrations due to the 1.8 GeV/c K^- and 20 GeV/c p interactions respectively, emit heavy hypernuclei. It has been observed that such emission may occur due all of the processes, viz, spallation, fission and multifragmentation.

As seen from table 8.3, the frequency of occurrence of the various types events in the two beam energies does not change appreciably. This is in conformity with the observation that eventhough there may be certain changes in the individual details, the gross feature of the mass yield curve (i.e., the typical U shaped mass distribution) is rather insensitive to the bombarding energy.

It has been observed that the target nuclei disintegrate by forming unequilibrated systems also, in addition to undergoing disintegration by equilibrium processes. The equilibrium processes seem to be the dominant processes. However, the exact role played by the different mechanisms at different stages of the reactions is not clearly understood. On the whole, the phenomenon appears to be rather complicated.

In the present investigation we have studied some of the characteristics of heavy fragments as well as the disintegrations causing their emission. The results indicate that all of the processes discussed herein, viz. spallation, fission and multifragmentation contribute to their emission. Out of the observed fragments about 77% comes from spallation, about 21% from fission and about 2% from multifragmentation. However, perhapes it will be useful to investigate the emission in more details. Some of the detectors like solid state nuclear track detectors can also be used with well defined targets. Another advantage of the solid state nuclear track detectors is the fragment detection threshold, which differs from one specific variety to another. These make it convenient to derive more information on the subject. Also, the coincidence measurements are likely to provide additional information towards the understanding of the emission of heavy fragments. Further, the heavy ion induced reactions are also important sources of information towards the emission of heavy fragments as they may conveniently be used to derive information from the study of the projectile fragments. Because of their high velocity, the projectile fragments can be identified more readily with a desired degree of precision than the slowly moving target fragments.

On occasions the excited nuclei emit clusters like Li^8 and Be^8. While discussing the emission of these clusters on the basis of the cascade-evaporation theory, it has been shown in the previous works (Ref. /77/ of Chapter III) that very high nuclear temperatures are to be invoked for explaining their emission. This has been considered as a limitation of the cascade-evaporation theory. The present investigation shows that out of some 68 multifragmentation (LTF) events, a total of 11 light fragments are due to Li^8 and Be^8. Thus the studies on emission of such clusters may provide more information not only on the characteristics of the disintegrating nuclei but on the emission of heavy fragments also.

The presence of lamda hyperons in the disintegrating target nuclei may change the characteristics of the nuclear disintegrations, particularly in respect of the emission of heavy fragments. A comparative study on the emission of heavy fragments by using different projectiles at similar centre of mass energy may reveal important informations relating to such changes of the properties of nuclei in presence of the lamda hyperons.

Though the nuclear emulsion is a convenient tool for investigations on nuclear disintegrations, much remains to be understood about this detector regarding the motion of the slowly moving heavy fragments. Such studies may be useful not only for a better understanding of the emission of heavy fragments but also to obtain useful results for problems like the determination of the life time of heavy hypernuclei.

Further works in such fields will surely enrich our knowledge regarding the high energy disintegration of complex nuclei.

APPENDIX

VOLUME CORRECTION (for events identified by scrutinizing practically flat tracks):-

The centre of a disintegration star in photonuclear emulsion is a dark space where the profiles of the individual tracks cannot be resolved unambiguously. On the average, this space may be considered to be spherical about a central point. The dimension of the space in the X-Y plane (plane of vission) can be ascertained by measuring the mutually perpendicular diameters of the space with the help of a micrometer eye-piece. Let $\bar{d}$ be the mean diameter.

A track is considered to be flat if it lies in the plane of any portion (along Z axis) of the central dark space within the finite dimension of the track from the point of its origin. Thus the solid angle covered around the disintegration centre during observation of the flat tracks of mean range $\bar{R}$ is given by $\delta = \tan^{-1}(\bar{d}/2\bar{R})$ (Fig. A. 1.). Hence, the volume correction may be made by using the relation (2.8.3).

In order to estimate the dimension of the central dark region of the disintegration star, the distributions for mutually perpendicular diameters of 218 random stars from 1.8 GeV/c K^- interactions and 151 random stars from 20 GeV/c p interactions are presented in Figs. A.2(a) and A.2(b). The distributions have mean values of about 1.75±0.01 microns and 1.77±0.01 microns respectively.

Because of the strinkage of emulsion along Z-axis, the eye estimation of the mean dimension of the central dark space along the said axis is likely to have a larger fluctuation than the estimated standard error. However, it is known that

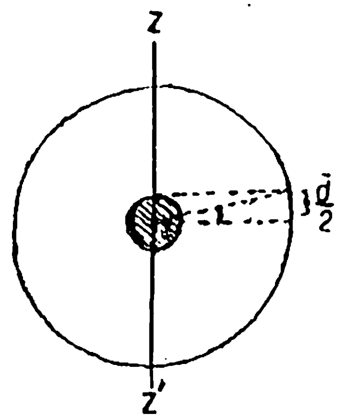

FIG. A.1:- Representation of "dip"

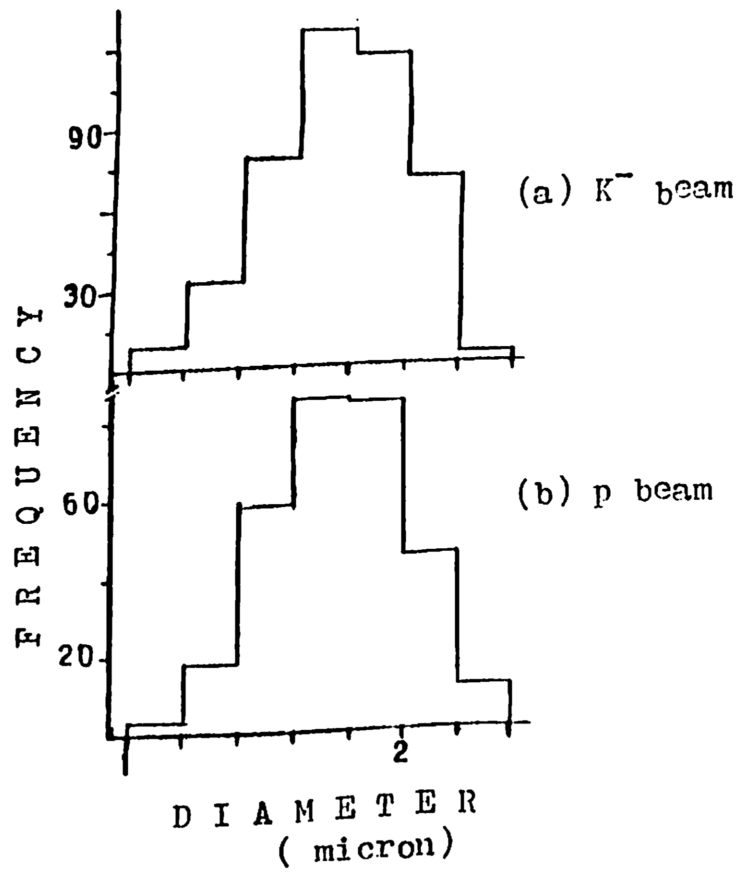

FIG. A.2:- Distribution for diameters.

about 68% of the observed diameters have values within one standard deviation (S = 0.252 microns approximately) of the distribution of diameters. Thus, the error in eye estimation of the mean size (diameter) of the central dark space of the disintegration stars along Z-axis is unlikely to be more than one standard deviation of the distribution along X-Y plane. Taking the error in estimating the size of the central dark space as S, the fractional error may be computed as $(S/\bar{d})$. This error is considerably large. As such this introduces considerable uncertanity in estimating the frequency and cross-section for production of the events. Error of estimation has been computed by taking this source of error into account.

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Kamaleswar Goswami

(Kamaleswar Goswami)

LIST OF PUBLICATIONS

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TO BE PUBLISHED :

(17) Nuclear disintegrations associated with spallation residues.

(18) On observation of binary fission during high energy reactions.

(19) On emission of heavy fragments during high energy interactions.

MEMORANDUM

I do hereby declare that I have not submitted any of the works described in this thesis for any higher degree of this or any other University.

I devoted myself whole time at least for four years in the study on **"emission of heavy fragments (A $\gtrsim$ 20) from silver and bromine nuclei during high energy interactions"** by using photonuclear emulsion detector. All of the measurements and analyses reproduced in this thesis are done by me. I have done some of the scanning works also. Some of the measurements and the final results have been carefully checked by Dr. T. D. Goswami, Professor and Head of the Department of Physics, Gauhati University, Guwahati - 781 014.

Kamaleswar Goswami.

(Kamaleswar Goswami)