2.1 Introduction:

In the present study, the nuclear emulsion has been used as a detector to extract information on the production of particles produced in high-energy hadron-nucleus (h-A) and nucleus-nucleus (A-A) collisions. The Nuclear emulsion is a sensitive detector, which is used to record and store the informations permanently about the charged particles and provides vital informations regarding the number of encounters made by incident particle inside the nucleus. Due to its unique spatial and ionization resolution, rare events can be detected even in the presence of high backgrounds. The tracks of the particles with different ionizing powers appear quite different in emulsion due to its unique spatial and ionization resolution. So it can resolve events separated by few microns. The emulsions have high density and high stopping power, which is about 1700 times more than that of the standard air [1]. Moreover, it is also called a 4π-detector due to its special features of examining in detail about the nuclear interactions.

2.2 Composition of nuclear emulsion:

A nuclear emulsion basically consists of three components [2-4]:

1. Silver halide:-- It is mostly bromide with a small admixture of iodide. Whenever a charged particle passes through nuclear emulsion, some of the halide grains are modified in such a way that when they are immersed in a reducing agent called developer, are turned into black silver grains.

2. Gelatine:-- which serves the purpose of matrix material for emulsion and a plasticizer, such as glycerine.

3. Water:-- which keeps it moist and prevents it from peeling off.

The gelatine of emulsion serves not only as a suspending medium for AgBr phase, but it also coats and protects the surface of grains. The glycerine, which is used as
plasticizer, reduces the brittleness of the emulsion. The chemical composition [5] of the emulsion can be summarized as: 1% hydrogen (H), 16% Carbon-Nitrogen-Oxygen (CNO) and 83% Silver-Bromide (AgBr). The percentage of interactions in emulsion with H, CNO or AgBr group of nuclei depends, however on the energy and identity of the incident beam. The average mass number, \( \langle A \rangle \), of the different groups of nuclei may be obtained by:

\[
\langle A \rangle = \frac{\sum_i N_i A_i}{\sum_i N_i}.
\]

giving the values of mean mass \( \langle A \rangle \) equal to 1, 14, 70 and 94 respectively for H, CNO, emulsion and AgBr groups of nuclei. The average composition of standard emulsion in terms of the number of atoms \( N_i \) per c.c. and mole per c.c. for the element of atomic number \( Z_i \) and atomic weight \( A_i \) are given in Table 2.1 [6].

2.3 Energy loss by charged particles in passing through matter:

When a charged particle interacts with the electron of the matter, it looses energy through the following processes.

2.3.1 Radiation loss:  
(i) Bremsstrahlung

(ii) Cerenkov Radiation

(i) Bremsstrahlung: Radiation produced when a low mass particle such as electron passes through the field of atom or nucleus is called Bremsstrahlung. The radiation loss due to it is proportional to the square of the acceleration of a charged particle of mass \( M \). It has a continuous energy spectrum.

(ii) Cerenkov radiation occurs only when the velocity of the particle traversing the medium is large in comparison with the velocity of light in the medium. Thus the radiation loss is hardly of any importance in our experiment, as they do not play significant role for particles with which we are concerned.

2.3.2 Collision loss:

A charged particle moving through matter transfers energy to the atomic electrons through the electromagnetic interaction. The electrons are thus raised to higher energy levels of the atoms. If the electron gets sufficient energy so as to get ejected from the
Table 2.1: The average chemical composition of standard emulsion.

<table>
<thead>
<tr>
<th>S.N.</th>
<th>Elements</th>
<th>Z_a</th>
<th>N_i(X10^{-6})</th>
<th>A_i</th>
<th>Mole/c.c. (X10^{-3})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Ag</td>
<td>47</td>
<td>101.01</td>
<td>108</td>
<td>16.764</td>
</tr>
<tr>
<td>2</td>
<td>Br</td>
<td>35</td>
<td>100.41</td>
<td>80</td>
<td>16.673</td>
</tr>
<tr>
<td>3</td>
<td>I</td>
<td>53</td>
<td>0.56</td>
<td>126.93</td>
<td>0.094</td>
</tr>
<tr>
<td>4</td>
<td>S</td>
<td>16</td>
<td>0.135</td>
<td>32</td>
<td>0.216</td>
</tr>
<tr>
<td>5</td>
<td>O</td>
<td>8</td>
<td>94.97</td>
<td>16</td>
<td>16.050</td>
</tr>
<tr>
<td>6</td>
<td>N</td>
<td>7</td>
<td>31.68</td>
<td>14</td>
<td>05.147</td>
</tr>
<tr>
<td>7</td>
<td>C</td>
<td>6</td>
<td>138.3</td>
<td>12</td>
<td>22.698</td>
</tr>
<tr>
<td>8</td>
<td>H</td>
<td>1</td>
<td>321.56</td>
<td>1.01</td>
<td>53.571</td>
</tr>
</tbody>
</table>
atom, the latter is said to be ionized. If the energy acquired by the electron is not sufficient to cause the ionization, it remains in an excited bound state. In either case, the increased energy of the electron is taken from the kinetic energy of the incident particle.

The rate of loss of energy per unit path length due to inelastic collisions of a fast charged particle with atomic electrons was calculated by Bohr [7], using the classical theory. The following expression for the energy loss per unit path length has been obtained by Livingston and Bethe [8], using quantum mechanical treatment.

\[
\left(\frac{dE}{dX}\right)_{\text{coll}} = \frac{4\pi Z^2 e^4 N}{m V^2} \left[ Z \left( \log \frac{2mV^2}{I(1-\beta^2)} - \beta^2 \right) - C \right]
\]

(2.1)

where \(Ze\) and \(V\) respectively the charge and the velocity of the particles, \(Z\) is atomic number and \(N\) is number of atoms per c.c. of material medium, \(I\) represents the mean ionization of the atoms of the medium, \(m\) is mass of the electron, \(\beta = V/c\) and \(C\) is a correction term required only if \(V\) is comparable with \(k\) shell electron velocities of the stopping material atoms but large with respect to those of other orbital electrons.

The above relationship derived from homogeneous media when applied to the nuclear emulsion, by summing over the various atomic species present, may be written as:

\[
\frac{dE}{dX} = \frac{4\pi Z^2 e^4 }{m V^2} \sum_i N_i \left[ Z_i \left( \log \frac{2mV^2}{I_i (1-\beta^2)} - \beta^2 \right) - C_{ki} \right]
\]

(2.2)

where \(N_i\) is the density in the emulsion of atoms of atomic number \(Z_i\) and ionization potential \(I_i\). Eq. (2.2) is widely used for identification of particles in all the visual detectors due to its strong dependence of energy loss on charge and ionization potential \(I_i\).

2.4 Track formation in nuclear emulsion:

A charged particle moving through emulsion gradually loses its energy owing to its electromagnetic interactions with the electrons of the atoms of the medium around its path. Consequently, the energy of the atomic electrons increases and they are raised to excited energy states, which may result into ionization of the atoms, in such a fashion.
that on immersing in the reducing bath (developer) they are turned into grains of metallic silver, which appear to be black grains. The extended path of a charged particle appears as a series of grains and is called ‘track’. The characteristics of a track such as ionization, range, δ-rays, etc., depend on the identity and energy of the particle producing it.

The production of relativistic charged shower particles ($\beta > 0.7$) and grey particles ($0.3 \leq \beta \leq 0.7$) in the interaction of high energy projectile in nuclear emulsion occurs in a very short time after the impact of the projectile, whereas, large number of nucleons and other heavy fragments are emitted due to the de-excitation of residual nucleus which remains in an excited state for a long time on the nuclear scale. Generally the particles emitted in this process known as evaporation are classified as black tracks. In addition to the above mentioned particles some non-interacting projectile fragments are also produced along the direction of the projectile into singly, doubly and multiply charged fragments.

### 2.5 Experimental details:

In this part of the chapter we describe the details of the experimental procedure adopted in the present investigation.

#### 2.5.1 Stack used:

Two stacks of BR-2 emulsion with printed grid on air-surface, exposed to a 4.5A GeV/c silicon and carbon beams at the Synchro-phasotron of Joint Institute of Nuclear Research (JINR), Dubna, Russia, are used in the present study. The details of the pellicles and incident flux of the beam are given in Table 2.2.

#### 2.5.2 Scanning procedure:

An interaction event in the emulsion is recognized as STAR due to its characteristics. The process of searching the recorded events in nuclear emulsion is known as ‘scanning’.
Table 2.2: Details of stacks used.

<table>
<thead>
<tr>
<th>Stack Number</th>
<th>Nature of Beam</th>
<th>Dimension of pellicles (cm³)</th>
<th>Incident Beam Flux (X10³ Nuclei/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y9-1 to 40</td>
<td>¹²C</td>
<td>18.6 x 9.7 x 0.06</td>
<td>~ 0.69</td>
</tr>
<tr>
<td>160-11 to 70</td>
<td>²⁸Si</td>
<td>17.1 x 9.8 x 0.06</td>
<td>~ 2.36</td>
</tr>
</tbody>
</table>

In the present work, the method of line scanning has been used to pick up interaction stars using the JAPAN made NIKON (LABOPHOT and TC-BIOPHOT) microscopes with 8cm movable stage using 40X objectives and 10X eyepieces. In this method the beam tracks were picked up at least 3mm from the entrance edge of the pellicle to eliminate the distortion effects. The primary interactions based upon the following criteria were selected as:
(i) The beam flux should be uniform and not very large.
(ii) Beam should not be dipping, so that it may traverse considerable length in an emulsion plate.
(iii) Length of the pellicles should be considerable large.
(iv) The mean direction of the primaries was kept along the X-axis of the microscope stage. The projected angle, \( \theta_p \), with respect to the mean direction and angle of dip, \( \delta_p \), of the incident primaries were measured. The tracks with \( \theta_p \leq 2^\circ, \delta_p \leq 0.5^\circ \) and having minimum ionization were accepted as primaries due to beam particles.
(v) In order to facilitate the measurements, the stars which were produced with in 35 \( \mu \)m from the top or the bottom surfaces of the emulsion have been excluded from the analysis.
(vi) The tracks were also followed back in order to make sure that the events were due to genuine primaries.
In order to facilitate various measurements, the interaction events were examined under a total magnification of 10x95 using 10x eyepieces and 95x oil immersion objective.

2.5.3 Classification of secondary tracks:

The tracks associated with the interactions are classified into following groups [9].

2.5.3.1 Shower tracks:

The tracks having specific ionization $g^* = g/g_o < 1.4$ and relative velocity $\beta > 0.7$ are taken as shower tracks, where $g_o$ is the Fowler and Perkins parameter for plateau ionization of relativistic particles. The number of such tracks in an event is represented by ‘$N_s$’. Shower tracks producing particles are mostly pions, with small admixture of charged K-mesons and fast protons.

2.5.3.2 Grey tracks:

The secondary tracks having specific ionization in the interval $1.4 < g^* \leq 10$ are known as grey tracks. The numbers of such tracks in a star are designated by ‘$N_g$’. This corresponds to protons with velocity in the interval $0.3 \leq \beta \leq 0.7$ and range $\geq 3.0$ mm in emulsion. Grey tracks are associated with the recoiling protons and have energy range (30-80) MeV. The sum of the number of grey and shower tracks in such an interaction is known as compound particle multiplicity and their number in a collision is represented by $N_c = N_g + N_s$.

2.5.3.3 Black tracks:

The secondary tracks having specific ionization $g^* > 10$ are classified as black tracks, which is represent by ‘$N_b$’. This corresponds to protons of relative velocity $\beta < 0.3$ and range in emulsion $R < 3.0$ mm. The particles producing black tracks are mainly the fragments emitted from the excited target. This ionization corresponds to protons with energy range $< 30$ MeV.
2.5.3.4 Heavily ionizing tracks:

The black and grey tracks taken together are termed as heavily ionizing tracks. Thus these tracks correspond to $g^* \geq 1.4$ or $\beta \leq 0.7$. Their number in a star, $N_h = (N_b + N_g)$ is a characteristic of the target.

In order to correct for any possible loss of the very dipping tracks in the experiment, only those heavily ionizing particles have been considered for average multiplicity calculations which are having $\theta_d < 30^\circ$ and a geometrical correction factor $K$ has been attached to each heavily ionizing particle with $\theta_d < 30^\circ$ such that $K=1$, when $150^\circ \leq \theta_s \leq 30^\circ$.

Otherwise,

$$K = \frac{\pi}{2 \sin^{-1} \left( \frac{\sin 30^\circ}{\sin \theta_s} \right)}$$

where $\theta_s$ is the space angle of the track with respect to the beam.

The total number of charged particles produced in an interaction is denoted by $N_{ch} = N_b + N_h + N_g = N_g + N_h$.

2.5.4 Identification of projectile fragments:

In a peripheral collision only a part of the projectile nucleus is directly involved in the collision. Therefore, the projectile nucleus breaks up into singly charged fragments, neutral particles and also into multiply charged fragments. During data analysis these fragments have also been grouped into doubly and multiply charged fragments based on the following criteria:

**Doubly charged PFs ($Z = 2$):** The particles having $g^* \approx 4$ with no change in ionization along a length of at least 2 cm from the interaction vertex and having an angle of emission $\theta < 4^\circ$.

**Multiply charged PFs ($Z \geq 3$):** The particles with $g^* > 6$, $\theta < 4^\circ$ and without any change in ionization along a length of at least 1 cm from the vertex have been put under the category of multiply charged PFs ($Z \geq 3$).
It is needless to mention that the above cited charged projectile fragments do not include the grey and/or black tracks producing particles since those are considered as target fragments.

The charge estimation of PFs has been done by ionization measurements and by δ-ray countings. It is not possible to separate fragments of charge $Z = 1$ by these methods. However, their number has been estimated and excluded from the multiplicity of shower particles and the details may be found elsewhere [10].

2.5.5 Ionization measurement:

The ionization caused by a particle can be determined by any one of following methods on the track of a particle.

(i) Grain – density
(ii) Blob – density
(iii) Blob and gap densities
(iv) Delta - ray density etc.

We give only a brief account of those methods, which have been used in the present experiments.

2.5.5.1 Grain density:

The grain density is defined as the number of grains per unit path length. The density of the developed grains depends on the charge and velocity of the particle, which is a function of ionization loss of that particle. However, it is observed that the grain density, $g$, is affected by the degree of development of emulsion. Therefore, in order to obtain accurate value of ionization a parameter known as specific ionization ($g^* = g / g_o$) is obtained by dividing it with the grain density on a track of a relativistic particle lying in the same region of emulsion. The grain density, $g^*$, is proportional to the ionization loss per unit length, that is,

$$ g^* \propto \frac{dN}{dr} \propto -\frac{dE}{dX} \propto Z^2 / \beta^2 f(\beta), $$

The above equation for singly charged particle ($Z = 1$) reduces to

$$ g^* \propto 1 / \beta^2 f(\beta), $$
Hence some idea about the velocity of the particle can be obtained by the measurement of grain density.

2.5.5.2 Blob density:

When the velocity of a particle is not too high, some of the grains in the tracks are clogged together and to form blobs. It then becomes difficult to count the number of grains accurately, because the true number of grains is uncertain. In such cases, the number of individually resolved grains or blobs is counted. This method is known as ‘blob counting’ and has its application to a limited range of ionization.

2.5.5.3 Blob and gap densities:

When a charged particle has small velocity, it will produce more ionization, the grains are frequently formed close together, and due to this the exact counting of grains becomes very uncertain. In such condition, blob and gap method is commonly used for determining the ionization produced.

The method is based on the observations by O’Ceallaigh [11] that, over a limited range of ionization, the lengths of the gaps (defined as the distance between the inner edges of two consecutive blobs) occurring in the tracks of ionizing particles in emulsions show exponential distribution of the form:

\[ H(L) = Be^{-gl} \]  \hspace{1cm} (2.3)

where \( H(L) \) denotes the density of the gaps having lengths greater than 1 and \( B \) is the Blob density. The coefficient, \( g \), in Eq. (2.3) has been shown by Fowler and Perkins [12] to give a good measure of the ionization caused by the particle.

They also observed that the value of \( g/g_0 \), where \( g_0 \) corresponds to the ionization of a relativistic singly charged particles, is practically independent of the degree of development of the emulsion and it was suggested that the parameter \( g \) may be taken to be the most useful parameter for measuring the ionization caused by a particle. Fowler and Perkins [12] have suggested the following method for finding the value of \( g \). If \( H_1 \) and \( H_2 \) respectively represent the number of gaps of lengths greater than \( l_1 \) and \( l_2 \) per unit length of the track, then the value of \( g \) may be given as:
2.5.5.4 Delta ray density:

When the energy transferred by a charged particle, while traveling through nuclear emulsion to an atomic electron in a single collision is large enough so that these electrons produce secondary ionization, the result is a series of short tracks with length greater than a certain minimum length are called as delta ray [12, 13]. A minimum length of 1.58μ from the axis of the particle track is counted as delta-ray. The delta ray density is generally used in identifying the particles of projectile fragments.

2.5.6 Angular measurement:

The angle of emission of a particle is determined by finding the space angle of the corresponding tracks with respect to the primary. Since the direct measurement of the space angle is not possible, its value is deduced by the following relation [1]:

\[ \theta_s = \cos^{-1}\left[ \cos \theta_p \times \cos \theta_d \right] \]

where \( \theta_p \) and \( \theta_d \) represent the projected and dip angles respectively of particular tracks.

However, if the angular separation between the tracks in the forward cone is very small, then it becomes difficult to measure the \( \theta_p \) and \( \theta_d \) directly due to overlapping of the tracks. In such cases, the coordinate method is used. In this method the primary of an event is aligned along the X-motion of the microscope. The (X,Y,Z) coordinate of the vertex of the given event is measured as (X₀,Y₀,Z₀). The stage is moved by a known distance and the (X₁,Y₁,Z₁) coordinates of a point on that particular tracks are measured. Knowing \( \Delta X \), \( \Delta Y \) and \( \Delta Z \), the projected and dip angles are found using the relations:

\[ \theta_p = \tan^{-1}\left( \frac{\Delta Y}{\Delta X} \right) \]

\[ \theta_d = \tan^{-1}\left( \frac{S.F \times \Delta Z}{\Delta X} \right) \]
where $S.F$ is the shrinkage factor, which is defined as the ratio of the thickness of unprocessed to the processed emulsion. The errors in space angle using this method is small due to accurate measurement of position coordinates $(X,Y,Z)$.

2.5.7 Target identification:

The exact identification of target in emulsion experiment is not possible since the medium is composed of H, C, N, O, Ag and Br nuclei. The events produced due to collisions with different targets in nuclear emulsion are usually classified into three main categories on the basis of the multiplicity of heavily ionizing tracks in it. Thus, the events with $N_h \leq 1$, $2 \leq N_h \leq 7$ and $N_h \geq 8$ are classified as collisions with hydrogen $(H, A_T = 1)$, group of light nuclei $(CNO, <A_T> = 14)$ and group of heavy nuclei $(AgBr, <A_T> = 94)$ respectively.

However, the grouping of events only on the basis of $N_h$ values does not lead to the right percentage of events of interactions due to light and heavy group of nuclei. In fact, a considerable fraction of stars with $N_h \leq 7$ are produced in the interactions with heavy group of nuclei. Therefore we have used the following criteria [10, 14].

**AgBr events:**

(i) $N_h > 7$, or
(ii) $N_h \leq 7$ and at least one track with range $R \leq 10 \mu m$ and no track with $10 < R \leq 10 \mu m$

**CNO events:**

(i) $2 \leq N_h \leq 7$ and no track with $R \leq 10 \mu m$.

**H events:**

(i) $N_h = 0$, or
(ii) $N_h = 1$, and no track with $R \leq 10 \mu m$. 
References:


