CHAPTER - III

EXPERIMENTAL TECHNIQUE

3.1 INTRODUCTION

In recent years the studies on hadron-nucleus interactions at high energies have been carried out using mainly the nuclear emulsion and in some cases counter and bubble chamber techniques also. The competitive capabilities of nuclear emulsion are modest in comparison to bubble chamber and counters for studying hadron-nucleon interactions. Emulsion has, however, gained wide acceptance as producer-detector of hadron-nucleus interactions due to its unique spatial and ionization resolution as well as a wide range of sensitivity. Furthermore, it provides the possibilities of event by event studies in 4π geometry with high angular resolution.

A nuclear emulsion consists of three basic components:
(i) Silver halide, mostly bromide with small admixture of iodide.
(ii) Water.
(iii) Gelatine which serves the purpose of matrix material for emulsion and a plasticizer, such as glycerine.

The percentage composition of the above is such that about 71% collisions take place with AgBr (\(\langle A \rangle = 94\)), 25% with light nuclei: CNO (\(\langle A \rangle = 14\)) and 4% with hydrogen. The cross-sections
of reactions with AgBr, CNO or H nuclei, however, depends on the mass and energy of the beam particles [1].

When a charged particle passes through emulsion, it interacts with the electrons of the atoms of the medium. In this process kinetic energy is transferred to these electrons by the incident particle. If the energy transferred to an electron is greater than the ionization potential of the atom, electron becomes free and the atom is said to be ionized. As a result of the ionization of the atoms, some of the halide grains in the emulsion on immersion in a reducing bath, called developer, are turned into grains of metallic silver which appear black. Thus, a series of grains is formed along the trajectory of the particle which is termed as its track. When an incident particle collides with a nucleus, a large number of secondary particles, both charged and neutral come out of it. The charged particles produce their tracks and are thus recorded. The event is termed as 'star' because of its characteristic look in emulsion. The slow, medium and energetic particles are characterized by the ionization that they produce in passing through the emulsion. The track of a particle represents its various characteristics. The observable properties of a track are its range, ionization, scattering, delta rays etc. Characteristics such as mass, charge and energy of particles involved may be determined by measuring these parameters.
3.2 Energy loss by charged particles in passing through matter

When a high energy particle passes through matter, it loses energy through the following processes.

(i) Radiation loss:

(a) Bremsstrahlung
(b) Cerenkov radiation

Bremsstrahlung radiation is important for particles of low mass such as electrons and Cerenkov radiation occurs when velocity of particle is more than velocity of light in the medium. The Bremsstrahlung as well as Cerenkov type of energy loss is not important for the particles we shall study here.

(ii) Collision loss:

A charged particle passing through matter transfers its energy to the atomic electrons through electromagnetic interactions. The electrons are thus raised to some higher energy levels of the atoms. If an electron gets sufficient energy so as to get ejected from the atom, the atom is said to be ionized. If the energy acquired by the electron is not enough to set it free, 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 such inelastic collisions of fast charged particles with atomic electrons is given by the following expression
(- \frac{dE}{dx})_{\text{coll.}} = \frac{4\pi z_e^2 e^4 N}{mv^2} \left[ Z \left\{ \log \frac{2mv^2}{I(1-\beta^2)} - \beta^2 \right\} - C_k \right] \quad (3.1)

where \( z_e \) is the charge and \( v \) the velocity of the particle, \( N \) is the number of atoms per cubic centimeter of the stopping material, \( Z \) and \( I \) represent their atomic number and mean ionization potential respectively, \( m \) is the electron mass, \( \beta = v/c \) : \( I \) is the correction term required only when the velocity \( (v) \) is comparable with \( k \)-shell electron velocities of the stopping-material-atoms but large with respect to those of other orbital electrons.

Equation (3.1) is valid only for homogeneous media, but to apply it to nuclear emulsions one has to sum over various atomic species present. This leads to

\[
(- \frac{dE}{dx})_{\text{coll.}} = \frac{4\pi z_e^2 e^4}{mv^2} \sum_i N_i Z_i \left\{ \log \frac{2mv^2}{I_i(1-\beta^2)} - \beta^2 \right\} - C_{k_i} \quad (3.2)
\]

where \( N_i \) is the density in emulsion of atoms of atomic number \( Z_i \) and ionization potential \( I_i \).

It must be mentioned here that the above expression describes well the energy loss when the velocity of the particle is of the order of the velocity of the fastest electrons of the stopping material and is widely used for identification of the particles in all the visual detectors.
3.3 Details of stacks, scanning method and classification of the tracks

3.3.1 Details of stacks

The details of the stacks such as emulsion type, the nature and energy of primaries, the flux of primaries etc. are given in Table 3.1.

3.3.2 Scanning method

The plates were scanned using Cooke's M4000 series microscopes with the following optics - 15 x 20 for scanning and 15 x 100 oil immersion objective for measurements. The method of area scanning was adopted. The middle plates were chosen for scanning so that the events in these plates could be followed upto longer distances which facilitated the measurements. All the primaries of the selected events were followed back upto the edge to make it sure that the events chosen did not include the secondary interactions. The events where the primaries originated from other interactions were removed from the sample.

From the observed events those which satisfied the following conditions were selected for analysis:

(i) An event must be 3 mm away from edges of pellicles so that the possible distortion effects are avoided.

(ii) The beam track must lie within $\sim 2^\circ$ to its mean direction in the pellicle.
<table>
<thead>
<tr>
<th>Primary particle</th>
<th>Energy (GeV)</th>
<th>Flux (particles/cm²)</th>
<th>Exposure</th>
<th>Type of emulsion</th>
<th>Size of emulsion plates (cm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>p</td>
<td>24</td>
<td>(7.0±0.2) x 10³</td>
<td>CERN</td>
<td>Ilford G5</td>
<td>20 x 10 x 0.060</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Proton Synchrotron</td>
<td></td>
<td></td>
</tr>
<tr>
<td>π⁻</td>
<td>50</td>
<td>~10⁵</td>
<td>SERPUKOV</td>
<td>NIFFI-ŚK</td>
<td>6.2 x 0.06 (diameter)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>π⁻</td>
<td>340</td>
<td>(0.5-1.5) x 10⁴</td>
<td>CERN-SPS</td>
<td>Ilford G5</td>
<td>7.5 x 7.5 x 0.063</td>
</tr>
<tr>
<td>p</td>
<td>400</td>
<td>~5 x 10⁴</td>
<td>FNAL</td>
<td>Ilford K5</td>
<td>14.5 x 9.5 x 0.062</td>
</tr>
</tbody>
</table>

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(iii) To facilitate the measurements, the stars which were produced within $\sim 35 \mu m$ from the top or the bottom surfaces of the pellicles have been excluded from the data.

3.3.3 Classification of the tracks

The secondary tracks have been classified into different groups according to their specific ionization, $g^*$, where $g^* = g/c_0$, $g$ and $c_0$ are Fowler and Perkins parameters for the secondary track and the track of a relativistic singly charged particle with plateau ionization respectively.

The tracks with specific ionization lying in intervals $g^* < 1.4$, $1.4 < g^* \leq 10$ and $g^* > 10$ are respectively named as shower, grey and black tracks and their numbers in a star are denoted by $n_s$, $n_g$ and $n_b$.

The black and grey tracks together are called heavily ionizing or heavy tracks and its number in a star is denoted by $N_h (= n_b + n_g)$.

3.4 Methods of measurements

The track of a particle which is brought to rest in emulsion due to the energy loss is more favourable for carrying out analysis than the ones which merely pass through it. Whether a particle stops or not, it is often possible to identify it by measuring a suitable combination of any two of the following parameters.
(i) Range

(ii) Ionisation

(iii) Scattering

(iv) Delta rays

3.4.1 Measurement of range

The range of a particle in a medium is defined as the total distance traversed by it before its kinetic energy reduces to zero. In emulsion work generally the term residual range is used, it is defined as the expectation value of the path-length required to bring the particle to rest. In fact, the quantity measured experimentally is subject to statistical errors because of the smearing.

It should be mentioned here that the particle range in the unprocessed emulsion. After processing, the shrinkage and other distortions which emulsion undergoes affect the particle range. Therefore, these effects must be taken into consideration while computing the true range. It is found that, while the unmounted pellets may suffer both lateral and vertical shrinkage, the mounted pellets commonly undergo the vertical shrinkage only; therefore, the shrinkage factors $S_x = S_y = 1$ and $S_z = S$ for mounted pellets. The vertical shrinkage is given by

$$S = t/t'$$

(3.3)
where $t$ and $t'$ are thickness of the emulsion before and after the processing. The quantities that are measured are the di and the length of the projection of the track on the plane of the emulsion.

In normal emulsion work, the path of a particle is not straight because of the coulomb deflections that it suffers during the passage through the matter. The track is then divided into a large number of straight segments. The length of any segment, say, $i$th, will be equal to $(l_i^2 + z_i^2 \Delta z_i^2)^{1/2}$, where $l_i$ and $\Delta z_i$ are projected length and dip respectively. The sum of the lengths of these segments will be equal to the true length of the track. Thus, the true range may be calculated by using the relation

$$R = \sum_{i=1}^{n} (l_i^2 + z_i^2 \Delta z_i^2)^{1/2}$$

(3.4)

where $n$ is the number of segments into which the track has been divided.

Range–Energy Relation

The empirical relations between range and energy of different particles in emulsions were established by experiments with artificially accelerated protons and deuterons and with particles produced in nuclear reactions [3–6]. The range-energy relation for protons having energies between 10–300 MeV has been expressed
by

\[ z = KH^n \]  \hspace{1cm} (3.5)

where \( K \) and \( H \) are constants. For et al. [7], using the results of other workers have obtained the best values of these constants for different particles.

3.4.2 Ionization

The ionization caused by a charged particle may be determined by measuring any one of the following quantities on the track of the particle.

(a) Grain density
(b) Blob density
(c) Blob and gap
(d) Integral gap length
(e) Delta rays
(f) Track width

However, it is found that all the methods have certain limitations and none is applicable to all types of tracks. We discuss below only those methods which have been used for the identification of the particles.

(a) Grain density:

The grain density is defined as the number of grains per unit path length. The track of a particle in emulsion appears as
a minute trail of silver grains. For higher velocities of particles, the grains are well separated and can be easily counted. However, it is observed that the grain density, \( g \), is affected by the degree of development of emulsion. For accurate results, it is therefore required to determine the ratio \( \tilde{g} = \frac{g}{g_0} \) known as normalized grain density which is obtained by dividing the grain density, \( g \), with the grain density, \( g_0 \), on a track of a relativistic particle of charge \( e \), lying in the same region of emulsion.

(b) Blob and gap method:

When the velocity of the particle is small, the grains are frequently formed close together, and their true number becomes uncertain. In such cases the blob and gap method is used for estimating the ionization. A blob is defined as a single grain or a cluster of grains with no gaps visible between them and the length of a gap is defined as the distance between the inside edges of two neighbouring blobs. The method is based on the observation of O'Geallaigh [9] who observed that,

\[
H(\ell) = B \exp(-g\ell) \tag{3.6}
\]

where \( H(\ell) \) is the number of gaps of length greater than \( \ell \) and \( B \) is the number of gaps with \( \ell = 0 \). Fowler and Perkins [8] observed on the tracks of relativistic cosmic ray particles of different charges that the gap length distribution is exponential and also
confirmed the measurements carried out by O'Ceallaigh on lightly ionizing particles. It follows that the numbers $N_1$ and $N_2$ of gaps of lengths exceeding $l_1$ and $l_2$ per unit length of the track, yield a measure of the coefficient of the exponent, $g$:

$$g = \frac{1}{l_2-l_1} \log_e \left( \frac{N_1}{N_2} \right)$$  \hspace{1cm} (3.7)

The procedure of Fowler and Perkins [8] for determining the ionization may be summarized as follows:

(i) The value of $g$ can be obtained by putting the value of $B_0$ and $\alpha$ for a relativistic particle in eqn. (3.8).

(ii) For lightly ionizing particles having $g < 0.35$, the value of $g$ should be determined by counting the total number of blobs alone.

(iii) If $g > 0.35$, the blob and gap method should be used to find $g$.

(iv) The gap length should be so chosen that $l_g \sim 2.5$ and the number of blob counted is about four times the number of gaps i.e. $N_B > 4N_g$.

The statistical error in the measurement of $g$ for blob and gap counting method is given by $dg/g = \frac{1}{\sqrt{N_g} l_B H}$, provided the number of blobs counted is more than about four times the number of gaps.
Fowler and Perkins [8] have further obtained the following empirical relation between $B$ and $g$

$$B = g \exp(-ag) \quad (3.8)$$

where $a$ is a parameter which is determined largely by developed grain size and is almost independent of the optical resolution of the microscope. The value of $a$ is determined by using the relations (3.7) and (3.8). Normally, its value is between 0.6 and 0.9 $\mu$.

3.4.3 Scattering:

When a charged particle passes through a material medium, its direction of motion continuously changes as a result of frequent small deviations due to Coulomb scattering by the atomic nuclei near its line of motion. Such effect is called scattering. The additive effect of a large number of such single deflections constitutes multiple Coulomb scattering. The scattering depends upon the charge, velocity and momentum of the particles. Hence the measurement of scattering coupled with range or ionization gives the information about the mass and energy of the particle.

The average angular deviation $\bar{\alpha}$ between successive chords of the track of a particle of charge $ze$ is related to its momentum $p$ and velocity $v$ by the relation
\[ \alpha = \frac{kZ}{pv} \tilde{G}^2 \]  

(3.9)

where \( k \) is nearly constant for a given value of \( C \).

In general two methods have been employed for determining the value of \( \bar{\alpha} \)

(a) Constant cell size method

(b) Constant Sagitta method

(a) Constant cell size method:

Fowler [10] has suggested a method for measuring \( \bar{\alpha} \).

According to this method a track is aligned along one of the directions of motion of the stage of the microscope, say x-axis. The micrometer screw attached for motion is moved by equal amounts of distance and the readings of the \( y \)-coordinates are noted from the scale attached to the eye-pieces. The angular deviations, \( \alpha_c \), between the successive chords can be deduced from the second differences of the readings. The length through which the micrometer screw is moved each time is termed as a "Cell length", \( C \). The mean of the absolute values of the second differences, \( \bar{D}_c \), gives a measure of \( \bar{\alpha}_c \). Conventionally \( \bar{\alpha}_c \) is always converted into \( \bar{\alpha}_{100\mu} \) through the following relation.

\[ \bar{\alpha}_{100\mu} = \frac{\overline{D}_c}{C} : \frac{180}{\pi} \times (\frac{100}{C})^2 \]  

(3.10)

where \( \bar{\alpha}_{100\mu} \) is the mean r.d.r deviation in degrees for \( C=100 \ \mu m \).
The value of $\overline{D_c}$ so obtained is always more than the true signal of the track because of certain errors involved in the measurements. These errors arise from (i) grain noise and reading errors (ii) distortions in emulsion (iii) non-linearities in the motion of the microscope stage (iv) spurious scattering. These errors are termed as "noise".

The effect of all forms of noise and spurious scattering is eliminated by assuming the errors to vary as $C^n$. The value of $\overline{a_{100\mu}}$, corrected for noise, may be obtained from the following relation

$$\overline{a_{100\mu}} = \frac{2}{\pi} \left\{ \frac{D_2^2 - (C_2/C_1)^{2n} D_1^2}{C_2^3 - C_1^3 (C_2/C_1)^{2n}} \right\}^{1/2} \quad (3.11)$$

where $D_2$ and $D_1$ are the second differences for two cell sizes, $C_2$ and $C_1$ in units of $100\mu$ respectively. The errors are thus eliminated by calculating the second differences for the two cell lengths. The value of the scattering parameter, $\overline{a}$, has been determined by carrying out scattering measurements on tracks with small cell sizes of 50 $\mu$m or 100 $\mu$m. Due to the choice of smaller cell sizes good number of cells were available for scattering measurements even for comparatively shorter tracks.

(b) Constant Sagitta method:

The constant cell size method can be used only for those tracks where velocity of the particle do not change or the velocity...
changes are small, i.e., for faster particles. This method cannot be applied to low energy tracks, where velocity of the particle changes and hence the value of D changes rapidly with the residual range. A convenient method of measurement on such tracks is to vary continuously in the size of the cell, keeping the probable value of D as constant.

Using the power law approximation for the range energy relation, it may be shown that

\[ C_n^{3/2} = \frac{1}{2} R^{0.581} M^{0.42} Z^{0.16} \]  \hspace{1cm} (3.12)

where \( C_n \) is the cell length at the residual range \( R \). Thus, it is possible to compute, for a particle of any mass and charge, a series of successive values of cell size, such that the value of D remain constant and equal to any desired value. Fay et al. [14] have prepared various schemes for protons and \( \pi \)-mesons for different values of \( \bar{D} \). Using 1.0 \( \mu \)m proton scheme, the value of \( \bar{D} \) on ending tracks have been measured. The masses of the particle have been computed using the following relation

\[ \frac{M}{M_N} = \left( \frac{\bar{D} \bar{N}}{\bar{Z}} \right)^{2.276} \left( \frac{Z}{\bar{Z}} \right)^{0.381} \]  \hspace{1cm} (3.13)

where \( M, \bar{D}, \bar{N}, \) and \( \bar{Z} \) denote the mass, mean value of D and charge of the known particle. The value of \( Z \) is determined by counting delta rays over certain residual range.
3.4.4 4D correction ("cut off procedure")

The constant Sagitta method gives accurate results if \( \bar{D} \) is determined by using a very large number of cells. Sometimes the number of cells is not large enough, the large deflections due to single scattering should therefore be excluded. This is done by excluding all individual values of \( D \) greater than 4\( \bar{D} \). This is referred to as the 4\( \bar{D} \) "cut-off procedure". This operation is repeated till all the values of \( D \) are in the 4\( \bar{D} \) limit. This is a tedious operation in dealing with a long track. A less drastic method is to replace all values of \( D \) greater than 4\( \bar{D} \) by the value 4\( \bar{D} \). This method retains more of the original information and has the advantage that the procedure for determining \( \bar{D} \) converges much more rapidly than when the large signals are completely removed. Therefore, the "4\( D \)" replacement method is more commonly used.

3.4.5 Delta rays

When a charged particle passes through a medium, its electric field disturbs the atomic electrons. The interactions constitute energy transfers of varying amount. If an electron receives kinetic energy exceeding \( \sim 2 \) KeV in such an encounter, its track branching out from the main track will be sufficiently large to be observed. Such electron tracks are known as delta rays. The formation of delta rays in emulsion depends upon the grain size
of the emulsion, the scattering of these slow electrons, and the sensitivity of the emulsion.

3.5 Measurements of angles

(i) Projected angle

To measure the space angle of a track with respect to the primary, its projected angle in X-Y plane with respect to the x-direction is measured. This is done by using the poniometer attached with the eyepiece. The eyepiece graticule is set parallel first to a beam track and then along the track, the difference between the angles for the two positions gives the projected angle.

(ii) Dip angle

In the processed emulsion, if $\Delta Z$ be the difference between Z-coordinates at two points on a track separated by a distance $\Delta X$, then the angle

$$\theta_d = \tan^{-1} \left( \frac{\Delta Z}{\Delta X} \right)$$

is called the dip of that part of the track. The dip in the unprocessed emulsion may then be given as

$$\theta_d = \tan^{-1} \left( S.F \times \frac{\Delta Z}{\Delta X} \right)$$

where S.F is shrinkage factor of the emulsion. Thus the dip
angle of a track is calculated by measuring the Z-coordinates of two points on the track separated by a known distance.

(iii) face angle

Knowing the dip angle and projected angle with respect to X-axis in the XY plane the space angle of a track can be calculated using the expression

\[ \theta_s = \cos^{-1} \left[ \cos \theta_p \times \cos \theta_d \right] \]  \hspace{1cm} (5.16)

The angular opening between the tracks in the forward cone is very small. For such tracks it is difficult to measure the projected and dip angles due to overlapping. In such cases the X, Y, Z coordinates have to be measured. The star vertex is moved along the X-axis of the stage and when the track look separated their X, Y and Z coordinates are measured. The projected angle for such tracks can be calculated by

\[ \theta_p = \tan^{-1} \left( \frac{Y}{X} \right) \]  \hspace{1cm} (5.17)

where X and Y are change in X and Y coordinates of a point on the track with respect to star vertex. The dip of such a track is calculated by noting down the change in Z and X coordinates of a point on the track with respect to star vertex using the relation

\[ \theta_d = \tan^{-1} \left( \frac{Z}{X} \right) \]  \hspace{1cm} (5.18)
unit charge which produce tracks of the same grain density, varies inversely to the ratio of their masses

\[
\frac{\alpha_1}{\alpha_2} = \frac{M_2}{M_1}
\]  

If one knows the plot of \((\alpha - q)\) for a known particle, say proton, then similar plots for other particles can be obtained. Using Barkas data [16] for proton we obtain graph for \((\alpha - q^*)\) method for various other particles, and is shown in Fig. 3.1. The mass distribution of a random sample of singly charged particles identified by \((\alpha - q^*)\) method is given in Fig. 3.1. The distinct peaks obtained correspond to different masses of pion, proton, deuteron and triton indicating that the identification is almost unambiguous.

(ii) The stopping particles have been identified by carrying out the following sets of measurements.

(a) Mass determination by constant Sagitta method.
(b) Residual range versus integral number of delta rays.

The constant Sagitta measurements have been carried out on stopping tracks to determine mass of the particles using 1.0 μm and 0.5 μm proton scheme [14] and results so obtained were further confirmed by measuring the integral number of delta rays over certain range of the track. The standard curves between residual range and integral number of delta rays for different particles have been shown in Fig. 3.3.
Fig. 3.1 Variation of $g^*$ with mean deviation for different particles.
Fig. 3.2 Mass spectrum of different particles identified by \((\bar{a}-g^-)\) method.
Fig. 3.3 Variation of the integral number of delta rays with residual range for different particles.
The space angle is then determined using the relation (3.16). This method is tedious and used only when the angular separation between the tracks is very small.

3.6 Identification of particles

In practice, it is not possible to make measurements on all the tracks. Therefore, one has to impose certain criterion for selecting tracks for various measurements. In experiments at 24 and 50 GeV/c, measurements have been made on tracks having

(i) dip angles $\leq 11^\circ$ in the unprocessed emulsion,
(ii) normalized grain density $g^* \geq 1.4$, and
(iii) length 1.0 mm, corresponding to atleast 20 cells of cell length 50 $\mu$m.

The track parameters measured for the identification of the particles are the range $R$, the scattering parameter, $\bar{x}$, specific ionization, $g^*$, and integral number of delta rays. The following combinations of parameters have been used for the identification of particles, depending upon the nature of the track.

(i) The non-stopping particles have been identified by the multiple scattering and normalized grain density, $(\bar{x} - g^*)$ method. As we know that the grain density is independent of the mass of the particle and only depends on its velocity and charge, the scattering parameters for two particles of masses $M_1$ and $M_2$ of
REFERENCES


