CHAPTER 2
EMULSION TECHNIQUE—METHODS OF MEASUREMENTS

2.1 Details on Nuclear Emulsion.

2.1.1 Importance of nuclear emulsion technique in the study of high-energy disintegrations.

Photographic emulsions have been used as detectors of charged nuclear particles ever since Reinschum discovered, in 1911, that alpha particles were capable of producing tracks which were observable under a microscope. Blau and Wambacher, in 1937, first obtained the record of disintegration of an emulsion nucleus by cosmic ray particle. Ilford, in 1946, produced nuclear research emulsions which were sensitive to make accurate measurements on the properties of nuclear particles. In fifties nuclear emulsion technique held an outstanding position in the field of high energy interactions when most of the discoveries of those days were made by it. Thereafter bubble chamber has been invented and developed into an extremely powerful tool and the electronic techniques have been much refined. There are other techniques and each has some distinctive advantages. Scintillation counters have relatively high resolution time (about $10^{-9}$ sec.). Čerenkov counters have a great advantage of velocity resolution ($\Delta \beta \approx 0.001$). Spark chamber is ideal for looking into rare events. Bubble chamber has a repetition time much higher than that of a cloud chamber.
Main disadvantages of emulsion technique are lack of tire resolution, small area of field of view and inability for unique identification of target nucleus.

In spite of these limitations emulsion technique serves as a most useful device till to-day for some of its specific performances, mentioned below, which are unattainable by any other device.

a) Emulsion technique permits microscopic track measurements of high precision. Energy and momentum of a very low energy particle can be known from its track length measurements.

b) There is a possibility of event by event study with a high degree of angular resolution. In counter experiments large angle measurements are not possible.

c) Recording of heavy tracks provides additional informations regarding the excitation of the nucleus and the number of encounters made by the incident particle inside the nucleus.

d) This technique allows high stopping power and less distortion effect in comparison to those in chamber techniques.

e) Emulsion serves both as a target and as a detector. It is compact in size.

f) There are some recent advances of the emulsion technique by the use of pulse magnets for exposing emulsion in strong magnetic fields.
2.1.2 Composition of Nuclear Emulsion.

Nuclear photographic emulsion consists of gelatine in which a very large number of silver-halide crystals are embedded. It differs from ordinary photographic emulsion by a higher silver-halide content, a smaller average-crystal diameter, a narrow spread of crystal-diameter and increased thickness. These differences are shown in Table 2.1.

Table 2.1: Difference between nuclear and ordinary photographic emulsion.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Nuclear Emulsion</th>
<th>Ordinary Emulsion</th>
</tr>
</thead>
<tbody>
<tr>
<td>AgBr/Gelatine</td>
<td>53/17</td>
<td>50/50</td>
</tr>
<tr>
<td>% by weight</td>
<td></td>
<td></td>
</tr>
<tr>
<td>AgBr/Gelatine</td>
<td>50/50</td>
<td>17/83</td>
</tr>
<tr>
<td>% by volume</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crystal-diameter</td>
<td>0.07-0.3 micron</td>
<td>0.5-3.0 micron</td>
</tr>
<tr>
<td>Emulsion-thickness</td>
<td>400-600 micron</td>
<td>10 micron</td>
</tr>
</tbody>
</table>

The atomic composition of a given emulsion depends on absolute water-content. Ilford has reported the average composition of 40 batches of GE emulsion in equilibrium with air at 58 % R.H., as shown below in Table 2.2.
Table 2.2: "ecn composition of Ilford GE emulsion.

<table>
<thead>
<tr>
<th>Elements</th>
<th>g/cu.cm(Ref.64)</th>
<th>Atoms/cu.cm x 10^{22}(Ref.65)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ag</td>
<td>1.817±0.029</td>
<td>1.0101</td>
</tr>
<tr>
<td>Br</td>
<td>1.338±0.020</td>
<td>1.0041</td>
</tr>
<tr>
<td>I</td>
<td>0.0120±0.0002</td>
<td>0.00565</td>
</tr>
<tr>
<td>S</td>
<td>0.0072±0.0002</td>
<td>0.0135</td>
</tr>
<tr>
<td>O</td>
<td>0.249±0.005</td>
<td>0.9497</td>
</tr>
<tr>
<td>N</td>
<td>0.074±0.002</td>
<td>0.3168</td>
</tr>
<tr>
<td>C</td>
<td>0.277±0.006</td>
<td>1.3850</td>
</tr>
<tr>
<td>H</td>
<td>0.0534±0.0012</td>
<td>3.2156</td>
</tr>
</tbody>
</table>

Average density of emulsion = 3.828±0.036 g/cm³.

Total number of atoms/cm³ = 7.8948 x 10^{22}.

2.1.3 Properties of emulsion: its various types.

When an ionizing particle passes through an emulsion some of its halide grains are modified in such a way that on developing the plate they turn into grains of silver and appear black.

For recording the tracks of all particles Ilford has first manufactured three types of nuclear emulsion designated by GF, F6 and L4 having silver-bromide crystal-diameters respectively 0.27, 0.20 and 0.14 microns approximately. These emulsions have constant properties in respect of sensitivity and atomic composition.
HIKFI Institute of Moscow, U.S.S.R. later manufactured emulsions of type R whose properties are similar to those of G5. HIKFI emulsions have uniform grain-size obtained by lamellar centrifugation. Grain-diameters of different HIKFI emulsions are 0.98, 0.18, 0.16 and 0.08 microns approximately. The fog or the single-grain background is low in these emulsions. Other important types of emulsions are Kodak HTE 3, Gevart NUC 7.15, and FUJI FT 7A. Grain-diameters of these emulsions are respectively 0.26, 0.15 and 0.27 microns approximately. Processed sensitivity obtainable in the case of a relativistic track ranges from nearly 20 to 30 grains per 100 microns. Less sensitized emulsions such as Ilford K2, LP, K1, PO; HIKFI T-1, T-2, A-1 and A-2; Kodak HP 2, HP, NTA and Gevart NUC 3.07 can record the tracks of low speed particles. In a supersensitized emulsion as many as 50 to 100 blobs per 100 microns are developable along a relativistic track.

2.2 Experimental details: Measurement procedures.

2.2.1 Exposure: The following emulsion stacks are used for the purpose of study.

a) Ten collieles of HIKFI-Br 4 emulsion each of size (10 x 20) cm² x 600 micron exposed to a separated beam of 50 GeV/c negative pions at the Institute of High Energy Physics (I.H.E.P.), Serpukhov, U.S.S.R.
b) Ten pellicles of NIKFI-Br 2 each of size (10 x 80) cm² x 600 micron irradiated by 69 ± 1 GeV/c proton beam at I.H.E.P., Serpukhov, U.S.S.R.

c) Four pellicles of NIKFI-Br 3 each of dimension (10 x 80) cm² x 400 micron irradiated by 69 ± 1 GeV/c proton beam from I.H.E.P. accelerator, Serpukhov, U.S.S.R.

d) Two pellicles of Ilford G5 emulsion each of size (10 x 12) cm² x 400 micron exposed to 200 GeV/c proton beam at Fermi National Accelerator Laboratory (FNAL), Chicago-Patavia, U.S.A. in Sept. in 1972.

2.2.2 Processing technique:

a) Pre-soaking: Exposed emulsion after being mounted on a glass plate is pre-soaked in distilled water having temperature 5°-7°C for about three hours before being placed in a developing solution.

b) Developing: Dilworth et al. introduced the method of temperature development in which process the developer is allowed to penetrate the emulsion at low temperature and subsequently warmed to allow the main development to proceed. This process allows quick and uniform development throughout the volume of emulsion. The developing solution contains Amidols 3g, anhydrous sodium sulphate 6.7g, sodium bisulphate 0.77g in 930 cc water. Emulsion is first immersed in a solution at 5°-7°C for about three hours. Next emulsion is separated from the solution and
is kept at a temperature about 27°c for about an hour. To stop the development a stop bath is used containing 0.5% solution of acetic acid.

c) **Fixation**: During fixation the unsensitized silver-halide is removed from emulsion. A fixer solution contains sodium thiosulphate (hypo) 400g and sodium metasilicate 30g in one litre of distilled water.

d) **Washing and drying**: When all surplus silver-halide has been removed the fixer solution is washed out by using cold water. This follows alcohol drying procedure using glycerolene and alcohol.

### 2.5.3 Scanning Procedure:

Emulsion plates were area scanned by Cooke, Troughton and Simms M4006 microscope using 16x eyepiece and 46x objective (total magnification being about 1000x) and events with Nh > 1 were recorded. The scanning efficiency checked by the method of repeated scanning is found to be about 94%. Interaction stars lying within 5mm at each edge were excluded. All interactions lying at a depth of 20 micron from top and bottom surfaces of the pellicles were recorded. In order to collect the primary stars each of the observed stars were looked at under 16x eyepiece and 96x objective (total magnification nearly 2000x). The pellicles were mounted on the stage of the microscope such that the primary beam was nearly allined.
to the $x$-motion of the microscope and the primaries of the scanned events were followed backward 1000 micron on $x$-axis from the centre of the interaction. The $x$-coordinates were measured both at the centre of the star and at the point $x=1000$ micron. The dip angle $\delta$ of the primary was thus measured. Also the inclination $\theta$ of the primary with the mean beam direction was measured with the help of the circular scale attached with the eyepiece. The tracks having $\delta \pm 0.25^\circ$ and $\theta \pm 0.25^\circ$ were taken to be the primaries belonging to the beam. The stars having primaries originated from the other interactions in the same pellicle were nearly removed from the sample. The stars lying in the region of distortion were also excluded.

Final samples accepted for analysis consists of 839 stars at 60 GeV/c negative pion interactions, 312 stars at 70 GeV/c proton interactions and 263 stars at 800 GeV/c proton interactions with emulsion nuclei.

2.2.4 Determination of grain density.

Grain density, $g$, is defined as the number of grains developed per 100 micron-length along a track. It is commonly found that there is a variation of degree of development of grains with type of the emulsion. Therefore the normalized grain density, $g^*$, is determined which is independent of degree of development. Normalized grain density is the ratio of observed grain density in any track to the grain density of primary or
any other relativistic track, $g_p$, called plateau value of grain density.

Thus $g = g/g_p$

Blob density, $B$: It is the number of individually resolved grains or cluster of grain per 100 micron of a track.

Grain density of primaries:

Grain density is also found to vary with depth of emulsion.

The average grain density of 20 primaries lying at a depth 80 micron from either surfaces is measured. The primary track is aligned along $x$-axis of the stage. In each track 1000 grains are counted and corresponding length of the track is measured by noting $x_1$ and $x_2$ respectively the initial and final values of $x$-coordinate.

Thus $g_p = 1000 \times 100 / (x_2-x_1)$ micron.

Grain density of a relativistic track produced by the secondary particles may be measured by the same procedure adopted for a primary track. Grain density of a highly ionising track may be determined from the estimates of blob density, $B$, and gap density, $H$. $H$ is the number of gaps in a track having gap length longer than a suitably selected value, I. Fowler and Perkins estimated $g$ from the determination of $B$ and $H$ as given below:

$$g = \frac{1}{L} \log_2 \frac{B}{H}.$$
2.2.6 Classification of shower, grey and black tracks:

Since ionization or blob development is inversely proportional to the velocity of a charged particle, the separation of shower tracks formed by relativistic particles, grey tracks formed by fast cascade particles and black tracks formed by slow evaporated particles can be done by determining the grain density of each track of any particular star.

Powell et al. classify the tracks according to the following rules:

Shower tracks: These are mainly due to pions (about 95%). There may be a small percentage of protons. For these tracks \( g < 1.4 \, g_p \) and \( p > 0.7 \). This corresponds to an energy >375 MeV for protons and >57 MeV for pions.

Grey tracks: These tracks are largely due to recoiling protons and a smaller percentage of deuterons. For these tracks \( 1.4 \, g_p \leq g \leq 10 \, g_p \) and such protons have energy >26 MeV. Corresponding range of proton is greater than 3 mm.

Black tracks: These are mainly due to evaporated protons and a small percentage of alpha particles. For these tracks \( g > 10 \, g_p \) Energy of such proton is less than 26 MeV.

A sample of 50 stars from each stack were taken and the grain density of light and intermediate ionization tracks were measured carefully. Thus the black, grey and shower tracks were separated for each star and for each emulsion stack. Afterward...
this classification is made by eight. Error involved in such
classification of shower, grey and black tracks were found to be
less than 4/\%.

2.2.6 Separation of Ag Br and CNO interactions:

In a nuclear emulsion the incident particles undergo
approximately 71/\%, 21/\% and 4/\% interactions with Ag Br, CNO
and H nuclei respectively. Several authors suggested following
separation criteria which are based on definite experimental
evidences.

a) Friedlander\textsuperscript{69} assumed that collisions occur with CNO nuclei
if \(N_{\text{H}} < 4\) and with Ag Br nuclei if \(N_{\text{H}} \geq 7\).

b) The existence of Coulomb barrier in heavy nuclei prevents the
emission of low energy particles with a range <6\,\text{micron}. This
range corresponds to proton of energy 2.7\,\text{eV} and alpha particles
of energy 10.7\,\text{MeV}. Accordingly Itoh\textsuperscript{70} assumed that
all interactions having following characteristics belong to Ag Br
nuclei

(i) \(N_{\text{H}} \geq 7\) and

(ii) \(0 < N_{\text{H}} \leq 6\) and no prong having range less than 65
\text{micron}.

c) Goryachikh\textsuperscript{71} assumed that all interactions with heavy nuclei
have any one of the following characteristics.

(i) \(N_{\text{H}} \geq 8\)

(ii) \(N_{\text{H}} \leq 7\) but there is a recoil nucleus and

(iii) \(N_{\text{H}} \leq 7\) there is no recoil nucleus and there is no
short range tracks.
d) For et al.\(^{72}\) assumed that an interaction with C\(^{12}\) nuclei should have all the following three characteristics.

(i) \( N_h < 7 \),

(ii) \( N_g = 0 \) or 1 or at least one track of range less than 65 micron and

(iii) no associated electron track.

e) Delkheshv et al.\(^{73}\) (following the method of Abdo et al.\(^{74}\)) used two types of emulsions viz (i) standard Br-2 emulsions and (ii) Br-2 emulsions soaked with ethylene glycol \((\text{CH}_2\text{OH})_n\) which are enriched and properly normalized for both the types of emulsions. The subtraction of one distribution from the other separates the \( \delta \)-distributions for C\(^{12}\), O and Ag\(^{112}\) nuclei.

In the present work we have assumed that all interactions with \( N_h \geq 7 \) to be due to Ag\(^{112}\) Br and the rest interactions to be due to C\(^{12}\) O nuclei.

2.2.7 Measurement of \( \alpha - \gamma \) angles:

The angle \( \theta \) of a track with respect to primary beam in terms of projected angle \( \psi \) and dip angle \( \delta \) is given by the relation \( \cos \theta = \cos \psi \cos \delta \).

The measurements of dip angle and \( \alpha - \gamma \) angle of black, grey and shower tracks were made by Cooke, Troughton and Simms M 4005 microscope using 15x eyepiece and 95x objective with the help of a goniometer scale attached with the eyepiece. The space angles of all black, grey and shower tracks were evaluated with the help of the above formula. The angular resolution of highly
collimated and overlapping shower tracks were made possible by taking the observations on projected angles at a distance 500 micron to 1000 micron from the centre of the respective stars. Measurements on dip angle were made by taking the observation on Z-coordinate at the origin of a star and at a point about 500 micron away from the star. In the measurement of space angles errors may be introduced due to following reasons:

(i) distortion of emulsion at the point of observation,
(ii) multiple coulomb scattering of the track and
(iii) uncertainty in placing the eyepiece graticule along the track of finite width.

2.2.6 Measurement of shrinkage factor:

The ratio of the thickness of emulsion at the time of exposure to its thickness at the time of measurement is called shrinkage factor, S.

A large number of alpha tracks due to thorium stars were recorded. The maximum range, R, of 50 flat alpha tracks were measured. The maximum projected range, P of 50 inclined alpha tracks, having nearly same dip d, were also measured. The shrinkage factor, S, was estimated from the following relation

\[ R^2 = p^2 + S^2 d^2. \]
A charged particle produces a visible track across its path and gradually slows down by losing energy. When its energy is less than a few keV, it ceases to ionize and its visible track terminates. The total length of the track is called range. The true range, $R$, of a linear track in an unprocessed emulsion is estimated from the measurement of projected range, $P$, and dip angle $\delta$ and using the following relations

$$R = P \cos \delta,$$

and

$$\tan \delta = \frac{d}{P},$$

where $d$ is the difference of depths of the two extreme points of the track and $\varepsilon$ is the shrinkage factor.

There are several factors which limit the accuracy of range measurements. These are:

1) uncertainty in determining the point from which the track originates,

2) frequent scattering of the tracks, and

3) distortion of emulsion during processing.

5.2.10 Energy estimation of charged particles: range-energy relations:

Range of a particle is not proportional to its energy alone. Energy of various ions can be obtained from the range-energy relations given by several authors$^{75-79}$ according to the requirements.
For lighter nuclei, such as protons and alpha particles, the range-straggling is prominent and necessitates corrections in the observed range. For heavy fragments such as hammer tracks, range correction due to tapering is made according to the formulation of Barkes. For alpha particles of energy below 50 MeV, Wilkins curves and for energy greater than 20 MeV, Berkeley curves have been used. For proton, Berkeley curves have been used. For heavy fragments with range greater than 200 micron, range-energy curves have been drawn from the range-energy relations of proton following the instruction given in the same report of Berkeley group. For lower energies, the range-energy curves given by Pepineau have been used. For II nuclei, range-energy relations of Heckmann et al. have been used.

2.2.11 Identification of heavy fragments:

The tracks of charge greater than 3 display following three features which are in marked contrast with those of protons and alpha particles:

1) increased number of delta rays,
2) pronounced thin-down length at the end of the range, and
3) increased width of the solid core of the track.

Delta-ray measurements:

When a charged particle penetrates emulsion, its electric field disturbs the atomic electrons with varying amount of energy transfer. If an electron receives kinetic energy exceeding 2 KeV,
it is likely to have a range long enough to produce an observable track by secondary ionization. Such electron tracks are known as delta-rays.

According to Mott \(^{50}\) the number of delta-rays per unit length, \(N_\delta\), having energy greater than \(E\) produced by a nucleus of charge \(Z_e\) and velocity \(v\) is given by

\[
N_\delta = \frac{2\pi N_e Z_e^2}{m v^2} \left[ \frac{1}{W} - \frac{1}{2mv^2} \right],
\]

where \(N_\delta\) = delta-ray density,

\(W\) = number of electrons per cc. in emulsion

\(m\) = mass of electron.

Because of \(Z^2\) dependence, the delta-ray density of heavy fragments is far greater than that of protons or alpha particles when the velocity of the particles are of the same order of magnitude.

If two particles have velocities in same order of magnitudes, the values \(N_1\) and \(N_2\) of delta-rays produced by them are connected to their charges \(Z_1\) and \(Z_2\) respectively by the relation

\[
\frac{Z_1^2}{Z_2^2} = \frac{N_1}{N_2}.
\]

Tapering length measurements:

If energy transfer is low the range of electron track will be shorter than the mean grain diameter and ionization will be entirely confined to those grains which lie exactly on the trajectory of the particle. This happens at a certain low velocity of
the heavy ion approaching the residual range and the width of
the track becomes maximum. As the speed of the ion is reduced
to that of the orbital electrons of emulsion nuclei, it captures
such electrons in steps and neutralizes its nuclear charges.
Thus the thinning down of the track occurs because of the reduced
ionization of the ionizing particle. The thin-down or tapering
length should be a function of \( Z \); because the process starts
by capturing a K-electron— the velocity of which is proportional
to \( Z \).

Following two relations between charge of an ion, \( Z \), and
tapering length of its track, \( L \), are given by Hoang \(^{81}\) and Perkins \(^{82}\)
on the basis of experimental study:

\[
Z = \frac{L}{10} \quad (\text{Hoang}) \quad (2.1)
\]

\[
Z^2 = \frac{L}{0.7} \quad (\text{Perkins}) \quad (2.2)
\]

Obviously, these relations depend on the development of emulsion
and the technique followed the observer.

Track-width measurements:

Width of a track of heavy nuclei is due to the production
of sufficiently large number of short-range delta-rays which
are commonly retained in the grains lying across the path of
the parent particle. The width of the solid core in a particular
element of a track is due to development of nearly all grains
along the path of the particle. Nakagawa et al. \(^ {83}\) observed that
the maximum width of a track increases proportional to the
square root of charge of the ion.
FIG. 2.1 A photograph of Cooke, Troughton and Simms M4005 microscope used for experimental works.