CHAPTER II

EXPERIMENTAL DETAILS

2.1 Introduction

The main emphasis in the present experiment is the study of target and projectile related fragments in nucleus-nucleus interactions. Various experiments dealing with nucleus-nucleus interactions at relativistic energies were listed in chapter I (Table 1.1). Most of these experiments use highly sophisticated electronic counters of various types. The main goal of these experiments is to study the general characteristics of heavy ion interactions and to look for specific signals of Quark-Gluon Plasma formation. Only a few of these experiments (EMU11, EMU12, EMU13, EMU14, EMU15, EMU19, WA80, WA98, E910, NA52) are equipped to study projectile and target fragmentation [1-6]. Electronic detectors have the great advantage of accumulating data at a very fast rate as compared to nuclear emulsions but they also have their own weak points. For example, the WA80 experiment, with its famous plastic ball detector was limited to the detection of slow target related particles within a restricted angular interval only. Despite certain drawbacks the nuclear emulsions still possess certain characteristics which make them very useful for the study of target and projectile fragmentation. A mention of these characteristics is given in the next section. This is followed by a brief description of the composition of emulsions, preparation of stacks and chambers, methods of irradiation, processing and scanning for events. In sections 2.6 and 2.7 we describe the methods of classification of tracks and events. Various methods of measurement like ionization, range, multiple coulomb scattering etc. are given in subsequent sections of this chapter. These measurements are basically designed to isolate, identify and measure the characteristics of target and projectile related fragments. A study of target related fragments has been mainly confined to S-Em collisions at 200 A GeV, whereas a study of helium projectile fragments has been done in the case of Au-Em interactions at 10.7 A GeV. Details of the later study are given in chapter V.
2.2 Nuclear Emulsion as a Charged Particle Detector

The use of nuclear emulsion as a detector, as well as an analyser, was first made in 1946 for the study of cosmic ray events. No doubt, many versatile detectors, such as plastic ball, streamer chamber and other sophisticated electronic devices have been employed since then, but the unsurpassed spatial resolution and compactness of nuclear emulsion, together with its capacity to retain a permanent record of events, has made it a unique detector which is favoured in many front ranking high energy physics experiments. One of the most prestigious high energy experiments, which is presently in operation at CERN, is the CHORUS experiment which uses nuclear emulsion to detect events related to neutrino oscillations [7].

The nuclear emulsion technique is well suited for precise measurements of multiplicity and angular distributions of produced particles. The number and direction of charged particles can be conveniently studied using emulsions. Due to its permanent character, events once recorded, can be studied at any later time.

Owing to high stopping power of nuclear emulsion, a large fraction of slow particles comes to rest in emulsion before decay. Their ranges and rates of ionisation loss can then be measured in order to identify the particles. Even neutral particles can be detected in emulsion from their decay mode. Good lifetime measurements of many unstable elementary particles have been made in emulsion. Nuclear emulsion has been used to measure lifetimes as small as ~10^{-16} seconds.

In addition to the above mentioned advantages, it has its own weak points also. One of these is that its composition cannot be changed arbitrarily. So interactions studied in emulsions are limited to those with nuclei present in it or to those nuclei with which emulsion may be loaded. The presence of several different types of nuclei in emulsion makes it difficult and often impossible to determine the nucleus involved in a specific interaction. Sometimes it is only possible to identify the group of nuclei (Ag, Br, I), (C, N, O) involved in the interaction. However, it is possible to place thin targets of specific materials before the emulsion and study the produced particle tracks in emulsion. Another disadvantage relates to the smallness of volume in which a phenomenon is analysed. Because of the limited size of the microscope field of view, it is difficult to correlate events which are situated at distances greater than one field of view.
2.3 Composition of Emulsion

The basic constituents of nuclear emulsion are H, C, N, O and AgBr. The AgBr crystals, with a small admixture of iodine, are embedded in gelatine [8,9]. The main function of gelatine is to provide a three dimensional network which serves to isolate the halide crystals. Gelatine is a complex substance which has the capacity to absorb large amounts of water. This is of fundamental importance for recording the tracks of charged particles in emulsions. The gelatine also prevents the migration of halide crystals during development and fixing stages. The ratio of AgBr to gelatine is 1:1 by weight. The physical properties of various types of emulsion are shown in Table 2.1. Out of the different makes of nuclear emulsion, the most widely used is the Ilford G-5 emulsion. Table 2.2 gives the standard composition of Ilford G-5 emulsion at a density of 3.815 gm/cm$^3$, corresponding relative humidity of 61% [10].

2.4 Preparation of Stacks/Chambers and Procedures for Irradiation and Processing

In a typical high energy experiment, using nuclear emulsions, one goes through the following major steps:

Freshly made emulsion gel is melted by heating to about 30$^\circ$C and is poured on flat, specially prepared glass sheets using a digital syringe. The gel is allowed to set at about 18$^\circ$C, resulting in a thin sheet of emulsion. This sheet is then peeled off from the glass. It is called a pellicle and has a typical thickness of about 600 $\mu$. An emulsion stack is made up of several tens of emulsion pellicles, arranged like the pages of a book. This stack is clamped tightly between two metal plates so that it behaves like a single block of emulsion.

For irradiation this stack is placed on a precisely levelled table and placed in the path of the desired beam of particles for a sufficient duration till we get adequate number of beam particles to pass through the emulsion stack. Next, a reference grid is printed on one of the surfaces of each of the pellicles.

The pellicles are again mounted on specially treated glass plates and are developed using the wet hot stage technique. Subsequently the plates are fixed, washed and dried, using procedures which are specially designed to minimise distortions in the processed
Table 2.1: Physical properties of various emulsions sensitive to singly charged relativistic particles.

<table>
<thead>
<tr>
<th>Type of emulsion</th>
<th>Emulsion density (gm/cm³)</th>
<th>Diameter of the undeveloped grain (μm)</th>
<th>Diameter of the developed grain (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ilford - L4</td>
<td>3.815 ± 0.035</td>
<td>0.14</td>
<td>0.30</td>
</tr>
<tr>
<td>Ilford - K5</td>
<td>3.828 ± 0.035</td>
<td>0.20</td>
<td>0.40</td>
</tr>
<tr>
<td>Ilford - G5</td>
<td>3.828 ± 0.035</td>
<td>0.27</td>
<td>0.60</td>
</tr>
<tr>
<td>Nikfi</td>
<td>3.815 ± 0.035</td>
<td>0.28</td>
<td>0.28</td>
</tr>
</tbody>
</table>

Table 2.2: Chemical composition of standard nuclear emulsion at ρ = 3.815 gm/cm³ (Ilford - G5).

<table>
<thead>
<tr>
<th>Element</th>
<th>Density (gm/cm³)</th>
<th>No. of atoms/cm³ N_i (10²⁰)</th>
<th>Charge Z_i</th>
<th>N_i Z_i (10²²) atoms/cm³</th>
</tr>
</thead>
<tbody>
<tr>
<td>H</td>
<td>0.0538</td>
<td>321.560</td>
<td>1</td>
<td>3.216</td>
</tr>
<tr>
<td>C</td>
<td>0.2757</td>
<td>138.300</td>
<td>6</td>
<td>8.292</td>
</tr>
<tr>
<td>N</td>
<td>0.0737</td>
<td>31.680</td>
<td>7</td>
<td>2.218</td>
</tr>
<tr>
<td>O</td>
<td>0.2522</td>
<td>94.970</td>
<td>8</td>
<td>7.597</td>
</tr>
<tr>
<td>S</td>
<td>0.0072</td>
<td>1.353</td>
<td>32</td>
<td>0.216</td>
</tr>
<tr>
<td>Br</td>
<td>1.3319</td>
<td>100.410</td>
<td>35</td>
<td>35.143</td>
</tr>
<tr>
<td>Ag</td>
<td>1.8088</td>
<td>101.010</td>
<td>47</td>
<td>47.476</td>
</tr>
<tr>
<td>I</td>
<td>0.0119</td>
<td>0.565</td>
<td>53</td>
<td>0.299</td>
</tr>
<tr>
<td>Total</td>
<td>3.815</td>
<td>Σ N_i = 789.8 x 10²⁰</td>
<td></td>
<td>Σ N_i = 105.063 x 10²²</td>
</tr>
</tbody>
</table>
emulsion. The dried plates are cleaned by rubbing with cotton wool soaked in alcohol. The plates are then ready for observation under an optical microscope.

A radically different design for using nuclear emulsions has been pioneered by EMU01 collaboration. This is called the *emulsion chamber* and is described in more detail in section 5.3. In this set up we use emulsion layers attached to both surfaces of thin polystyrene plates. Several of these plates are used in an emulsion chamber and are separated by appropriate spacers. The emulsion chamber is exposed to the beam particles in such a way that the beam passes normally through the plates. This kind of arrangement has been found to be very useful for performing high precision measurements of emission angles of tracks emanating from a nuclear interaction. It has also an added advantage that one can place a target of any desired material in contact with the chamber in order to study the interactions produced in that material.

In the present experiment we have used two emulsion stacks, designated as stack A and stack B. Stack A (No. 32) consists of 12 pellicles exposed to 200 A GeV $^{32}$S ions at the CERN SPS in 1988. Stack B (No. 50) consists of 13 pellicles exposed to $^{32}$S beam in 1991. For our study of He projectile fragments we have used a stack exposed to 10.7 A GeV $^{197}$Au beam at the BNL-AGS.

### 2.5 Scanning Procedures

Two standard methods are used to locate events of interest in nuclear emulsions:

(i) Line scanning

(ii) Area scanning

These two methods are discussed below:

**(i) Line scanning**: This technique is used in conventional stacks where ion beams are incident parallel to the plane of emulsion pellicles. In this method a track is, first of all, followed up to the exposed edge of emulsion plate to ensure that it is not coming out of an interaction. Only those primary tracks which lie at distances greater than 50 $\mu$m from air and glass surfaces are selected for line scanning.

In the present experiment, scanning was done on Zeiss and Leitz microscopes using 50x oil immersion objectives and 15x eyepieces. This was to ensure that all types of events were picked up with high efficiency. All the plates have 1mm x 1mm grid printed on the top (air) surface. The grid is very useful as it acts like a built in co-ordinate system. With
the help of the grid, one can easily record the position of a track as well as that of its interaction. The line following was done up to a distance of 5 cm or up to the point of interaction, whichever happened first.

In case of Electromagnetic Dissociation (ED) events (section 2.7.4), it is difficult to detect the vertex. Therefore, these events were carefully scrutinized using 100x oil objective. The interaction point was noted along with the following features: (i) The number of black tracks, \( N_b \) and number of grey tracks, \( N_g \) (ii) Alpha tracks and \( Z > 2 \) projectile fragments in the forward cone and (iii) Number of minimum ionizing, \( Z = 1 \) particles in the forward cone, \( N_i \) (section 2.6).

At ultra-relativistic energies, a sulphur ion can also produce high energy knock-on electrons. The cross-section for the production of direct \( e^+e^- \) pairs is also significant. In appearance these events look like \( N_e = 1 \) and \( N_e = 2 \) events in which the shower particles are emitted at angles \( \geq 1^\circ \). In order to filter out such spurious events from the genuine interactions we removed all \( N_e = 1 \) and \( N_e = 2 \) events in which the shower particles were emitted at angles \( \geq 1^\circ \). As a check, we followed the shower tracks from many such events and found that in all the cases, the tracks showed considerable scattering - a characteristic of electrons.

\( \text{(ii) Area scanning} \) : Events occurring in the emulsion chambers are collected by area scanning. In this method, the circular spot exposed to ions (radius~ 3cm) is divided into small strips (Fig.2.1). The width of each strip is equal to side of the square inscribed in the microscope field of view. The volume of emulsion present in one strip is scrutinized carefully for any interaction. In this way, the whole volume of spot is scanned through a field by field scrutiny.

In the present experiment, emulsion chambers, vertically exposed to 10.7 A GeV \(^{197}\)Au ion beam, were area scanned on Zeiss microscope using 22x oil objective and 15x eyepieces. The 22x objectives needed for this work were specially made to order. These objectives have the following advantages:

(i) The field of view is quite large.
(ii) The image quality is extremely good.
(iii) The working distance is very large (~2200 cm) so that one can look at a particular event in both the emulsion layers in a chamber plate.
Fig. 2.1: Method of area scanning.
2.6 **Classification of Secondary Tracks**

The passage of a charged particle through nuclear emulsion leaves behind a trail of ionisation produced in AgBr crystals. On development, the AgBr crystals are reduced to specks of metallic silver which are visible under a high magnification microscope as grains of diameter ~ 0.6 μm. The number of such grains per unit length of the track is known as *grain density*. The tracks of the produced particles (i.e., secondary tracks) are classified on the basis of grain density. A singly charged particle moving at relativistic velocity is called a minimum ionizing particle (MIP). In the present experiment, proton tracks emitted in Electromagnetic Dissociation events have been used to determine the grain density (gmin) produced by a MIP.

In the case of the two sulphur stacks used in the present experiment, we find gmin as 35 ± 3 grains/100 μm and 26 ± 3 grains/100 μm, respectively. The secondary particles are classified as follows:

(i) **Shower tracks**: These are the tracks with g.d < 1.4 gmin, corresponding to singly charged particles with β > 0.7. These are mostly due to relativistic pions. Protons with energy >400 MeV also appear as shower tracks. The number of shower tracks in a given interaction is denoted as Ns.

(ii) **Grey tracks**: Tracks produced by particles having 1.4 gmin < g.d ≤ 9 gmin are termed as grey tracks. These are predominantly protons with energy 30 MeV ≤ Ep < 400 MeV. A 30 MeV proton has a range of 3mm in emulsion. So a grey track must have a range greater than 3mm. The number of grey tracks is denoted as Ng.

(iii) **Black tracks**: These tracks have ranges from 10 μm to 3 mm and g.d > 9 gmin. These are either protons with energy <30 MeV or slow multiply charged particles. Black tracks are produced due to evaporation of the excited residual target nucleus. The number of black tracks is written as Nb.

Grey and black tracks are collectively termed as heavy tracks. Their number is denoted by Nh (=Nb + Ng).

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**(iv) Projectile fragments**: These are confined to a narrow forward cone defined by a certain angular cut depending on the beam momentum. They can be singly or multiply charged particles. The projectile fragments with charge $Z=2$ ($q.d \equiv 4 \ g_{\text{min}}$) are taken as alpha ($\alpha$) tracks and others with $Z > 2$ are denoted as fragments, $f$.

### 2.7 Classification of Events

Geometry of collision in heavy ion interactions plays a very important role in understanding the collision dynamics. Nuclear interactions are generally classified into three categories, depending upon the impact parameter "$b$" [11,12] (i.e. the transverse distance between centre of mass of projectile and that of the target nucleus).

(i) **Central Collisions**: $0 \leq b \leq |R_p - R_T|$

(ii) **Quasi Central Collisions**: $|R_p - R_T| < b < |R_p + R_T|$

(iii) **Peripheral Collisions**: $b \sim |R_p + R_T|$

where $R_p$ and $R_T$ are radii of projectile and target nucleus, respectively. Fig. 2.2 shows the geometry of these three types of collisions. Actual microphotographs of the three types of interactions in the case of S-Em collisions are given in Fig. 2.3.

#### 2.7.1 Central Collisions

As seen from the diagram, the impact parameter in the case of central collisions is small and lies in the range $0 \leq b \leq |R_p - R_T|$. If the two nuclei have different radii, the smaller nucleus makes a tunnel in the larger one and all nucleons of the smaller nucleus can, in principle, participate in an interaction. A large amount of energy is transferred from the projectile nucleus to the target nucleus. The number of projectile and target nucleons participating in the collision is large. In this case the larger nucleus has some spectator nucleons at the edge. If the projectile nucleus is smaller, it is completely destroyed, i.e. no projectile fragments with $Z \geq 2$ are seen in the forward cone.

#### 2.7.2 Quasi Central Collisions

In such collisions, there is relatively less involvement of the projectile nucleus. In this type of interactions, $Z \geq 2$ projectile fragments can also be emitted in the forward cone.
(i) Central collision
\[ 0 \leq b < |R_p - R_T| \]

(ii) Quasi-central collision
\[ |R_p - R_T| \leq b < |R_p + R_T| \]

(iii) Peripheral collision
\[ b \sim |R_p + R_T| \]

Fig. 2.2: Participant spectator picture of nucleus-nucleus collisions as a function of impact parameter.
Fig. 2.3: Micro-photographs of three types of S-Em interactions at 200 $A$ GeV.
2.7.3 Peripheral Collisions

Here, due to large impact parameter the transfer of momentum involved is less. The two nuclei graze each other with an impact parameter, \( b \), which is roughly equal to the sum of the two radii. A few nucleons of both nuclei do participate in the interaction while the remaining act as spectators, as shown in Fig.2.2. Since the energy and momentum transfer is relatively small in these interactions, therefore, projectile spectator part will emit fragments in a very narrow forward cone of angle \( \theta_c \). The reason for this is as follows: the projectile fragments continue to move at a velocity nearly equal to that of beam velocity \([12,13,14]\). On the other hand, the target evaporation fragments are isotropically emitted. In the center of mass system of the projectile these fragments carry momenta which are characteristic of Fermi motion of nucleons inside the nucleus \([15-17]\). Taking Fermi momentum \( \approx 200 \text{ MeV/c} \) per nucleon the angle of the forward cone \( \theta_c \) in which the projectile fragments are emitted is given by

\[
\theta_c \approx \frac{0.2}{P_b}
\]  

(2.1)

where \( P_b \) is the beam momentum per nucleon in GeV/c. In the case of S-Em collisions at 200 A GeV, \( \theta_c \approx 1 \text{ mrad} \) whereas in the case of 10.7 A GeV Au interactions \( \theta_c \approx 18.7 \text{ mrad} \).

2.7.4 Electromagnetic Dissociation (ED) Events

In addition to the nuclear interactions, a different category of events, namely the Electromagnetic Dissociation (ED) events, are also observed. These events correspond to values of impact parameter larger than \( (R_p+R_T) \). During the time of collision the electric field of the target is seen by the projectile as a flux of virtual quanta, one or more of which can excite the projectile by absorption in the giant resonance region. The projectile then dissociates into fragments with a small energy release in the c.m. system. In the lab frame, the projectile is seen to split into very closely spaced fragments with typical separation of the order of fraction of a mrad at beam energy of 200 A GeV. These ED events are further classified into three types, depending upon whether projectile or target or both nuclei have dissociated.

(i) ED of projectile: In this category of electromagnetic dissociation events, there is no target fragment \( (N_t=0) \) and no shower track outside the fragmentation cone, defined by the cut-off angle, \( \theta_c \). The total charge of the fragments, \( Q_c \), inside the fragmentation cone
(θc) is equal to the charge of the projectile, Zp. Fig. 2.4 (a) shows micro-photograph of such an event for 200 A GeV $^{32}$S projectile.

(ii) ED of target: In this type of events, only the target dissociates into more than one fragment. Due to the limited excitation energy the number of target fragments ($N_h$) is usually less than 8. Similarly, the number of grey tracks ($N_g$) does not exceed 2. Projectile nucleus moves along its trajectory with its initial velocity without any change i.e., the deflection angle of projectile remains within the fragmentation cone. Micro-photograph of a typical event of this kind is shown in Fig 2.4 (b).

(iii) Double ED in nucleus-nucleus collisions: Double ED occurs when both the above mentioned processes take place simultaneously. In such events we have $N_h \leq 8$, $N_g \leq 2$ and $Q_c = Z_p$ where $Q_c$ is the sum of the charges of all particles emitted in a cone of angle $\leq \theta_c$. All the relativistic particles should lie within the fragmentation cone, $\theta_c$. Fig.2.4 (c) shows a photograph of a typical example of this type of ED event.

2.8 Methods of Measurements

A charged particle, in traversing nuclear emulsion, loses energy by interactions with the atoms along its path. As a result of the energy transfers in these interactions, a large number of atoms are ionized. The ionization, thus caused, renders some of the grains in the emulsion developable and after development, the track of the particle is seen as a series of grains.

The number of grains per unit length (i.e., grain density) can provide an estimate of the ionization produced by the particle. However, the grain counting can only be done on tracks of fast particles. In electron sensitive emulsions, tracks of even singly charged particles of moderate energy are somewhat clogged, that is, the grains coalesce to form continuous blobs. A measure of the ionization may then be obtained from the gap and blob densities.

While part of the energy loss of a particle traversing emulsion is in the form of ionization along the track, part of the energy loss is in the form of distinguishable electrons which has resulted from knock on processes. The particle sometimes projects electrons with energies sufficient to give observable tracks. These are known as delta rays. The delta
Fig. 2.4: Micro-photographs of three types of Electromagnetic Dissociation events observed in S-Em collisions at 200 A GeV.
ray density can be measured and used to provide information similar to that obtained from ionization measurements. For a particle of charge $Z$, the delta ray density along its trajectory is proportional to $Z^2$. The measurement of delta ray density is one of the techniques for determining the charge of multiply charged particles traversing nuclear emulsions.

If, as a result of large number of collisions and the consequent loss of energy, a charged particle is finally brought to rest in the emulsion, its visible track terminates. The track length, $R$, of the particle is the distance along the trajectory from its point of origin to the last developed grain. Very energetic particles may have ranges so great that their tracks do not end in the emulsion stack of small dimensions. In both the cases, whether the particles stop in emulsion or not, energy determinations may be carried out by making scattering measurements on their tracks, provided the particle energy is less than a few GeV per nucleon. In case when the particle track terminates in emulsion, the particle identification can be made quite easily by a suitable combination of scattering, ionization and range measurements. From the measured range of a particle its energy can be accurately found by using the range energy relation [18]. For non-stopping particles of known identity, the multiple scattering measurements can be used to estimate their energies.

Measurements that may be made on the track of a particle in photographic emulsion are:

(i) Range

(ii) Ionization- estimated from: (a) grain density or (b) blob density or (c) blob and gap density or (d) integral gap length or (e) mean gap length or (f) delta rays or (g) track width

(iii) Scattering, by employing: (a) constant cell method or (b) constant sagitta method

In the present work we have divided the flat grey tracks into two categories:

(A) those which are due to fast particles which do not stop in the emulsion stack and

(B) those which stop inside the stack.

We have determined the mass and energy of fast (non stopping) charged particles by a combination of measurements of ionization and multiple scattering ($\alpha$, $g^*$). Mass measurements of particles stopping in emulsion has been done by two different methods:

(a) Range vs. Ionization ($R$, $g^*$) method and
(b) By constant sagitta method

In the following, we describe the experimental procedures for measurement of the above mentioned parameters needed for the determination of mass and energy of grey tracks and their emission angles.

2.8.1 Range

When a charged particle traverses matter, it loses energy because of its interactions with the constituent particles of the medium. If the particle has initial kinetic energy $E_0$ and the rate at which it loses energy in the medium is $-dE/dx$, then the distance it is expected to traverse before coming to rest is termed as range, $R$, and is given by

$$ R = \int_{0}^{R_0} \frac{dE}{-dE/dx} \quad (2.2) $$

The measured range of a charged particle is the distance to which it penetrates through the original unprocessed emulsion, and is given by

$$ R = \int (dx^2 + dy^2 + dz^2)^{1/2} \quad (2.3) $$

where the integration is to be carried out along the locus of the latent image of the particle track in the unprocessed emulsion. In the course of processing, the emulsion shrinks in the $z$ direction (normal to the emulsion surface) by a factor $S$. The range may then be calculated from the following formula:

$$ R = \sum_{i=1}^{n} \left( \Delta x_i^2 + \Delta y_i^2 + S^2 \Delta z_i^2 \right)^{1/2} \quad (2.4) $$

In the co-ordinate method of range measurement, the co-ordinates of the points connecting the successive track segments with approximate straight lines are measured. Suppose they are $(x_0, y_0, z_0), (x_1, y_1, z_1), \ldots, (x_n, y_n, z_n)$ then

$$ R = \sum_{i=1}^{n} \left[ (x_i - x_{i-1})^2 + (y_i - y_{i-1})^2 + S^2 (z_i - z_{i-1})^2 \right]^{1/2} \quad (2.5) $$

In emulsion work, all the ranges are referred to the standard emulsion which has a density of 3.815 gm/ml [19].

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2.8.2 Fowler-Perkins Parameter (g*)

In the present investigation, we deal with particles having specific ionization as high as 10 times that of the minimum ionising particle. The basic requirement to measure such ionization values would be to choose a parameter having the following characteristics:

(i) It should show little or no saturation effects for $I/I_0$ values upto 10.

(ii) It should be reproducible and have small subjective errors.

Fowler-Perkins parameter, $g^*$, was found to fulfill these requirements [20]. According to Fowler and Perkins, this parameter $g^*$ is defined by

$$g^* = \frac{1}{L} \log_e \frac{B}{H} \tag{2.6}$$

where $B$ is the blob density and $H$ is the number of gaps with length greater than $L$. The statistical error in $g^*$ is given by

$$\frac{dg^*}{g^*} = \frac{1}{\sqrt{H \log_e \frac{B}{H}}} \tag{2.7}$$

In order that this error be minimum, $d/dH(\sqrt{H} \log_e \frac{B}{H}) = 0$. This gives the condition that $\log_e \frac{B}{H} = 2$ or $B/H = 7.4$. Equation (2.7) is in fact a slight over estimate of the error but is sufficiently accurate in practice provided $B/H > 4$. We, therefore, so chose the gap length, $L$, that $B/H$ ratio was always between 4 and 7 for every track measured.

Accurate determination of particle masses depends critically on precise estimation of the ionization produced by it. In the present work we used the Fowler-Perkins parameter ($g^*$) for the estimation of ionization. Since the measurements have to be carried out on tracks lying at various depths in nuclear emulsion and also in different plates of the stack it is extremely important to carefully study the depth and plate to plate variation of $g^*$ corresponding to tracks of fixed value of ionization. For this purpose we used the He fragment tracks having the same energy per nucleon as the beam tracks, i.e., 200 AGeV. We performed $g^*$ measurements on long, flat He fragments at various depths in different emulsion plates of the stack. The depth variation in a typical plate is shown in Fig.2.5. We confined all our $g^*$ measurements in the middle 60% layer of an emulsion pellicle. In this layer the level of $g^*$ varies by about $\pm$ 6%. Therefore, we normalized all $g^*$ values w.r.t the $g^*$ level at the centre of each plate. We also carried out measurement of $g^*$ levels in all the plates of the stack and found the level to vary by about $\pm$ 9% from plate to plate. Therefore
Fig. 2.5: Variation of $g^*$ as a function of depth in an emulsion pellicle.
all the $g^*$ values were normalized with respect to one plate (plate no. 9 in stack no. 32 and plate no. 5 in stack no. 50) in the centre of the stack. Such plate to plate and depth wise correction is essential for precise estimation of the ionization produced by a given pellicle.

For estimation of ionization value corresponding to a given $g^*$ measurement it is necessary to have a calibration of $g^*$ value as a function of ionization. We selected tracks of known ionization and performed high statistics $g^*$ measurements on them. A plot between $g^*$ and ionization in the two stacks, used by us, is shown in Fig.2.6(a) and 2.6(b). Such a plot is called a calibration curve. It is seen that the $g^*$ varies in a linear fashion with ionization for $I/I_{\text{min}} < 16$. The calibration curve was used to determine the ionization of a track corresponding to its measured $g^*$ value.

2.8.3 Multiple Coulomb Scattering and its Measurements

When a charged particle passes through a material medium, it deviates from its original direction of motion as a result of transverse impulses received by it from the atomic nuclei near its line of motion. The average angle of deviation in a given path length is inversely proportional to the $p\beta$ of the particle. Generally, the co-ordinate method [21] is used to determine the angle between successive chords by measurement of the track co-ordinates. The average angular deviation of a particle of charge $Ze$ traversing a path of length $t$ is given by

$$\bar{\alpha}_{100,\mu} (\text{degrees}) = \frac{KZ}{p\beta} \left( \frac{t}{100} \right)^{1/2}$$

(2.8)

where $Z$ is charge on moving particle in units of electron charge

$p$ is momentum of the particle

$\beta = v/c$ is ratio of velocity of particle to that of light

$K$ is the scattering constant which is a slowly varying function of velocity of the particle and of cell length $t$

If the mean absolute second difference, corrected for noise and measured in microns, is $\bar{D}$ then

$$p\beta (\text{MeV} / c) = \frac{1}{573} \frac{KZt^{3/2}}{\bar{D}}$$

(2.9)

Important contributions to the multiple scattering theory were made by Moliere [22], Wentzel [23], Bothe [24], Williams [25], Synder and Scott [26], Goudsmit and Saunderson [27], and others. The best known theory of multiple scattering is that of
Fig. 2.6: Calibration curve for (a) sulphur stack no. 32 and (b) sulphur stack no. 50.
Moliere [16]. We have used the value of the scattering constant, $K$ for emulsion on the basis of Moliere’s theory.

(a) Overlapping Cell Method

Scattering measurements have been performed on a Koristka-R4 microscope employing the ‘constant cell’ method of Fowler [28]. In this method, the track is aligned, as nearly as possible, with the direction of microscope stage motion, so that, if possible, over the entire length of measurements, the track remains within the field of view without disturbing the $y$ motion of the stage. A filar micrometer eyepiece is used to measure the deviations of the track in the $y$ direction. For this purpose the position of the track is noted down at regular intervals of 100 µm with the help of filar micrometer. This gives a series of readings $Y_1$, $Y_2$, $Y_3$, $\ldots$, $Y_n$. Second differences are defined as

$$D_i = (Y_i - Y_{i+1}) - (Y_{i+1} - Y_{i+2}) = Y_i - 2Y_{i+1} + Y_{i+2}$$

Then,

$$\bar{D} = \frac{1}{n} \sum_{i=1}^{n} D_i$$

(2.10)

It is well known that when the energy of the particle is determined from the observed deflections, then both ‘real’ and ‘spurious’ deflections must be taken into account. These two sources of deflection are called ‘signal’ (genuine scattering) and ‘noise’ respectively. Noise arises due to:

(i) non-linearity of the stage motion
(ii) various types of distortions in the emulsion
(iii) reading errors of the observer

Considering the random nature of contributions from multiple coulomb scattering and noise, one can write

$$[D_{\text{observed}}]^2 = [D_{\text{signal}}]^2 + [D_{\text{noise}}]^2$$

(2.11)

For the correct scattering measurements of tracks, elimination of noises is necessary. Further, it is found that due to ‘gross’ distortions and ‘local’ distortions [21], profile of the track changes. Thus an originally straight track mostly assumes a C or S-shaped contour. This type of problem is more serious in the case of steep tracks where a relative displacement of its various segments due to distortions is more pronounced. In these tracks, readings of the track are further reduced, due to smaller available length of the track.
track. Such type of distortions may introduce significant errors in measurements, if they are to be performed by using the standard method of second differences (as C-type distortions cannot be removed by taking second differences).

To remove errors due to C-shaped distortions calculations have been done by using the method of algebraic mean [21]. The number of cells is increased by using the method of overlapping cells.

In a very long track, subject to scattering and noise only, the algebraic mean of the values of the second differences should be zero. In the presence of pure C-shaped distortion, which converts the projection of a straight track into the arc of a circle, the algebraic mean of the second differences will be finite. Such distortions can be eliminated by subtracting the observed algebraic mean from each individual value of $D_n$. The value of $\alpha$ is then deduced from the arithmetic mean of the corrected values of $D_n$. This method gives satisfactory results if observations on steeply dipping tracks show the distortion to be nearly C-shaped and if the contributions to the values of the second difference due to distortion are much less than those due to scattering.

Keeping in view all the above mentioned facts, basic measurements in the present experiment were performed with 50 µm and 100 µm cell lengths. Signals for higher cell lengths upto 200 µm and 400 µm were computed from the observations at 50 µm and 100 µm in order to achieve a signal to noise ratio greater than 3.

To eliminate contributions of various noises from the observed signal and to calculate the required Coulomb signal $\overline{D_c}$, we use the relation

$$\overline{D_c} = \overline{D_{obs}} - \overline{D_{noise}}$$

where $\overline{D_{obs}}$ is the observed mean absolute second difference and $\overline{D_{noise}}$ is the mean contribution due to noise.

(b) Measurement of Noise

In order to measure $\overline{D_{noise}}$ as a function of cell length we performed scattering measurements on tracks of four He fragments of 200 A GeV energy. About 100 readings with $t = 50$ µm were taken for each track and noise was calculated for higher cell lengths from these, using the method of algebraic mean. It was observed that noise increases slowly with cell length. The value of $\overline{D_{noise}}$ for $t = 50$ µm, 100 µm, 150 µm, 200 µm, 250
μm, 300 μm, 350 μm and 400 μm are 0.06, 0.07, 0.07, 0.08, 0.09, 0.1, 0.11 and 0.12 microns, respectively.

**The 4D Cut Off Procedure**

The formula \( p\beta = \frac{KZr}{573D} \) does not take into account the finite probability for the occurrence of single, large angle scatterings. Such single scatterings lead to a higher value of \( D \) and a lower value of energy. All these values, therefore, should be rejected. The normal values of \( D \) follow a gaussian distribution function whereas those due to single scatterings fall beyond the tail of the gaussian. To avoid these, all those values of \( D \) which are greater than \( 4D \) should be rejected. Appropriate values of scattering constant must be used when the 4D cut off procedure is employed.

The value of \( K \), corresponding to the 4D cut off procedure, has been derived from the formula given by Moliere [22]:

\[
K^2 = 675(α + b \log_{10} Ω)
\]

where \( α \) and \( b \) have values

\[
α = 0.090, \quad b = 0.272
\]

Ω in Eq. (2.13) is given as \( Ω = 5 t_i \) where \( t_i \) is the equivalent cell length, defined as

\[
t = \left(0.23 + 0.77 \frac{P^2}{Z^2}\right) t_i
\]

where \( Z \) is the charge of the incident particle. \( Z=1 \) in our case. Table 2.3 shows the variation of \( K \) at different \( β \) and cell lengths, \( t \). Fig.2.7 shows the variation of scattering constant \( K \) with \( β \). This graph shows that \( K \) has a weak dependence on \( β \). In the present experiment, we have used the value of \( K \) corresponding to \( β = 0.5 \) for the calculations of \( p\beta \) of grey tracks.

**2.8.4 Constant Sagitta Method**

The mass of particles, which come to rest in emulsion, can also be determined by the constant sagitta method [29] which gives good mass resolution on tracks larger than 3mm. The method consists of performing multiple scattering measurements along the trajectory of a track by continually varying the cell length in such a way that the mean deviation, \( D \), remains constant with residual range. The set of cells, thus defined, can be
Table 2.3: Values of $K$ at different $\beta$ and cell lengths ($t$).

<table>
<thead>
<tr>
<th>$\beta$</th>
<th>$t$ (100 $\mu$m)</th>
<th>$t$ (200 $\mu$m)</th>
<th>$t$ (300 $\mu$m)</th>
<th>$t$ (400 $\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>25.7</td>
<td>26.7</td>
<td>27.3</td>
<td>27.7</td>
</tr>
<tr>
<td>0.2</td>
<td>25.5</td>
<td>26.6</td>
<td>27.2</td>
<td>27.6</td>
</tr>
<tr>
<td>0.3</td>
<td>25.4</td>
<td>26.4</td>
<td>27.0</td>
<td>27.4</td>
</tr>
<tr>
<td>0.4</td>
<td>25.1</td>
<td>26.2</td>
<td>26.8</td>
<td>27.2</td>
</tr>
<tr>
<td>0.5</td>
<td>24.9</td>
<td>26.9</td>
<td>26.6</td>
<td>27.0</td>
</tr>
<tr>
<td>0.6</td>
<td>24.6</td>
<td>25.7</td>
<td>26.3</td>
<td>26.7</td>
</tr>
<tr>
<td>0.7</td>
<td>24.3</td>
<td>25.4</td>
<td>26.0</td>
<td>26.5</td>
</tr>
<tr>
<td>0.8</td>
<td>24.0</td>
<td>25.2</td>
<td>25.8</td>
<td>26.2</td>
</tr>
<tr>
<td>0.9</td>
<td>23.8</td>
<td>24.9</td>
<td>25.6</td>
<td>26.0</td>
</tr>
</tbody>
</table>
Fig. 2.7: Variation of scattering constant $K$ with $\beta$. 
constructed from a consideration of the empirical range energy relation [30]. As suggested by Biswas et al [29], the mass \( m_x \) of any unknown particle coming to rest in emulsion can be determined by making the scattering measurements using either the \( P_{1.0} \) cell scheme or the \( \Pi_{1.6} \) cell scheme. In the \( P_{1.0} \) cell scheme the cell sizes are so adjusted that the expected value of \( D_c \) is 1.0 \( \mu \)m, independent of residual range, for a proton track. In the case of \( \Pi_{1.6} \) cell scheme, the expected \( D_c \) for a pion track is 1.6 \( \mu \)m.

According to \( P_{1.0} \) scheme [29]:

\[
m_x = m_p \left( \frac{1.0}{D_c} \right)^{2.276} \cdot (\sec \theta)^{2.221}
\]

and according to \( \Pi_{1.6} \) scheme

\[
m_x = m_p \left( \frac{1.6}{D_c} \right)^{2.276} \cdot (\sec \theta)^{2.221}
\]

where \( \theta \) is the average dip angle of the measured track in the unprocessed emulsion. The statistical accuracy of the measured scattering value and, therefore, of the particle’s mass depends, for a track of a given length, on the number of available cells and, therefore, on the choice of the scattering scheme. The choice is essentially limited by the condition that the measured sagitta value must be significantly larger than the noise level.

The constant cell method proved to be very useful in identifying stopping tracks with small ranges. In such tracks it was not possible to do \( g^* \) measurements with good statistics because of the small available track length. In all, identification of 134 stopping grey tracks was done using the constant sagitta method. The mass histogram obtained by this method is shown in Fig. 4.3.

### 2.8.5 Measurement of Emission Angles of Grey Tracks

Angular distribution of grey tracks is a very important parameter studied in the present investigation. Therefore, great care was exercised in performing these measurements. The emission angle (\( \theta \)) of a grey track was determined from the relation

\[
\theta = \cos^{-1} \left( \cos \delta \cdot \cos \theta_p \right)
\]

where \( \delta \) is the dip angle and \( \theta_p \) is the projected angle of emission.
All the angle measurements were performed on a Koristka R-4 microscope. \( \theta_p \) was measured with a goniometer having a least count of 0.1°. The dip angle (\( \delta \)) was calculated from the formula

\[
\delta = \tan^{-1}\left( \frac{\Delta Z \times S}{L} \right)
\]

(2.18)

where \( \Delta Z \) is the change in depth of the track over a projected length \( L \). \( S \) is the shrinkage factor of emulsion defined as

\[
S = \frac{\text{Original Thickness}}{\text{Present Thickness}}
\]

(2.19)

All \( Z \) measurements were performed relative to the emulsion glass interface. Least count of the \( Z \) motion screw was 0.2 \( \mu m \). The overall accuracy in the determination of emission angle \( \theta \) was thus of the order of 0.2°. Angular distributions of grey tracks, obtained from these measurements, will be presented in chapter IV.
References

18. UCRL - 2426 Vol. II (1966 Rev.)