CHAPTER I

Introduction to High Energy Heavy-Ion Physics

1.1 The introductory remarks

The discovery of the presence of high energy nuclei in the primary cosmic rays by Frier et al.[1] in 1948 motivated experimental studies of heavy-ion collisions at high energies. Significant contributions have been made by Jain et al.[2], Tsuzuki et al.[3], Anderson et al.[4] and Abraham et al.[5] in this area by investigating the characteristics of relativistic charged particles produced in the interactions of nuclei of cosmic ray with nuclear emulsion. However, the basic limitation of these studies was that despite their valuable contributions[6], they suffer from serious deficiency of sufficient experimental knowledge which could improve the reliability of the results yielded by these studies. It was rather difficult to glean significant information regarding the mechanism of multiparticle production in high energy nuclear collisions, because cosmic rays provide low statistics and the nature and energy of the primary nuclei taking part in the collisions could be known only approximately.

Advent of heavy-ion accelerators enabled the high energy physicists to investigate the mechanism of multiparticle production in more detail. Systematic and well focussed study of the physics of relativistic nuclear collisions became possible with the advancement in accelerator technology. Possibility of studying ultra-relativistic heavy-ion collisions at Brookhaven[7] and CERN[8] since 1986 has led to the emergence of a new interdisciplinary field from the traditional domains of particle physics and nuclear physics[9]. The Alternating Gradient Synchrotron(AGS) at Brookhaven was transformed into a heavy-ion accelerator in 1986; it has been running since then on a regular basis, several weeks per year with beams up to $^{28}\text{Si}$ at 14.5 GeV/nucleon.
energy[10]. Initiated by a proposal of Stock and Gutbroad[11] in 1982, the Super Proton Synchrotron (SPS) at CERN started accelerating $^{16}\text{O}$ nuclei at 60 and 200 GeV/nucleon energies in 1986 and $^{32}\text{S}$ at 200 GeV/nucleon energy in 1987. After the initial short runs of two weeks each, a new, long term programme of heavy-ion physics, was started at CERN in 1990 with several weeks of $^{32}\text{S}$ beam runs. The early, so called 'exploratory' phase of heavy-ion collisions (1986-1990) is characterized by the fact that dedicated machines were not used, but rather existing accelerators were upgraded involving modest financial support. Likewise, the experiments made extensive re-use of existing high-energy physics equipments.

1.2 Experimental facilities

Table 1.1 Existing and Future heavy-ion accelerators[9]

<table>
<thead>
<tr>
<th>Machine</th>
<th>AGS</th>
<th>SPS</th>
<th>AGS</th>
<th>SPS</th>
<th>RHIC</th>
<th>LHC</th>
<th>GSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projectile</td>
<td>$^{28}\text{Si}$</td>
<td>$^{16}\text{O}$, $^{32}\text{S}$</td>
<td>$^{197}\text{Au}$</td>
<td>$^{208}\text{Pb}$</td>
<td>$^{197}\text{Au}$</td>
<td>$^{208}\text{Pb}$</td>
<td>$^{238}\text{U}$</td>
</tr>
<tr>
<td>$\sqrt{s}$ (GeV)</td>
<td>3.5</td>
<td>17.5</td>
<td>3</td>
<td>15.5</td>
<td>200</td>
<td>6300</td>
<td>50-100</td>
</tr>
<tr>
<td>Rapidity range, $\Delta y$</td>
<td>$\pm 1.7$</td>
<td>$\pm 3$</td>
<td>$\pm 1.6$</td>
<td>$\pm 2.9$</td>
<td>$\pm 5.5$</td>
<td>$\pm 8.8$</td>
<td>$\pm 4.3$</td>
</tr>
<tr>
<td>Luminosity ($\text{cm}^{-2}\text{s}^{-1}$)</td>
<td>$\approx 10^{31}$</td>
<td>$\approx 10^{28}$</td>
<td>$\approx 10^{30}$</td>
<td>$\approx 10^{29}$</td>
<td>$\approx 10^{26}$</td>
<td>$\approx 10^{27}$</td>
<td>$&gt;&gt; 10^{26}$</td>
</tr>
<tr>
<td>Duration of Operation (weeks/year)</td>
<td>4-6</td>
<td>0-6</td>
<td>8-10</td>
<td>&gt; 6</td>
<td>$\approx 40$</td>
<td>$\approx 4$</td>
<td>$\approx 40$</td>
</tr>
</tbody>
</table>

Table 1.1 summarizes the existing and planned heavy-ion accelerators and provides some information on the scope of their scientific programmes.

Attempts were made to produce beams of heavier and heavier ions of as much
high energy as possible in order to improve the experimental research findings. In the series of these attempts, in 1992 Gold ions of 10 GeV/nucleon energy and in 1994 Gold and Lead ions of 170 GeV/nucleon energy were produced by AGS and SPS respectively\cite{10,11}. A big collider known as Relativistic Heavy-ion Collider (RHIC) at BNL started functioning in 2000\cite{12}. By using RHIC to collide ions travelling at relativistic speeds, physicists have been able to study the primordial form of matter that is believed to have existed in the Universe shortly after the Big Bang\cite{13}.

Another gigantic and state-of-the-art collider, Large Hadron Collider (LHC), is being constructed at CERN and is expected to be commissioned in 2008\cite{14}. It is expected that the LHC will provide heavy ions of significantly higher energies once completed, significantly superseding RHIC energies. LHC will collide protons at the centre of mass energy, $\sqrt{s}=14$ TeV. Besides protons, the LHC will also accelerate and collide beams of Lead nuclei at the centre of mass energy $\sqrt{s}=5.5$ TeV/nucleon. However, RHIC will likely remain unique in various fields which the LHC in the present form will not cover. Unlike RHIC, LHC is unable to accelerate spin polarized protons, which would leave RHIC remaining as the World’s highest energy accelerator for studying spin-polarized proton structure\cite{15}.

The main goal of the LHC and its related experiments include investigation of possible new physics aspects such as the Higgs boson and Supersymmetry, role of chiral symmetry in the generation of mass in composite particles (hadrons) and CP-symmetry violating processes. Five experiments with huge detectors will explore particle/heavy-ion collisions at the LHC; these experiments are: ATLAS (A Toroidal LHC Apparatus), CMS (Compact Muon Solenoid), LHCb (The Large Hadron Collider Beauty Experiment), ALICE (A Large Ion Collider Experiment) and TOTEM (Total Elastic and Diffractive Cross Section Measurement).
1.3 Space-time evolution of heavy-ion collisions

Nuclei are extended objects, therefore, their geometry plays an important role in heavy-ion collisions.

![Space-time diagram for the time evolution of the colliding system](image)

**Fig. 1.1** Space-time diagram for the time evolution of the colliding system

The expected space-time evolution of a central ($b=0$) heavy-ion collision at a very high energy is sketched in Fig. 1.1.

The two nuclei collide at time $t=0$. Almost immediately afterwards, $\sim 1\text{fm/c}$, a superdense and hot state of quark-gluon matter may be created at energy density $\sim 3\text{GeV/fm}^3$, approximately 20 times the normal nuclear matter density, and at a temperature of $T \sim 200\text{ MeV}$. It may not be out of place to mention that this temperature is more than 5 orders of magnitude higher than the temperature of the interior of the Sun\[12-14\].

This leads to a rapid expansion of the system along the longitudinal direction. In the ongoing process, its temperature falls down and reaches the critical transition
temperature $T_c$ after $\tau \simeq 3-5$ fm/c[15]. In the mixed phase, the matter sustains its condition for a longer time, i.e., $(\tau > 10 \text{ fm/c})$, especially if the transition is of the first order[16]. It then rearranges many degrees of freedom of the QGP into smaller number available in the hadron phase with a large associated release of latent heat. Finally, in the hadronic phase $(\tau \gg 10 \text{ fm/c})$, the expansion of interacting matters continues in an ordered motion. This expansion is likely to get more pronounced (to a relatively large dimensions, $V > 10^4 - 10^5 \text{ fm}^3$) before the particles freeze out. In this stage, interaction ceases and the particles stream out freely away to be detected in experiments.

In Fig. 1.1 time-evolution of the created 'fireball' is shown in the plane transverse to the direction of the collision. In this direction, all the expansion is due to the pressure gradients in the "fire ball". At this moment, when the system is in the state of decoupling from the strong interactions, it expands with a velocity equal to half of the velocity of light in vacuum and reaches a size which is twice as large as the projectile.

1.4 Formation of Quark-Gluon Plasma and its important signatures

Interest in the study of ultra-relativistic heavy-ion interactions has considerably grown recently due to the possibility of occurrence of a new phase transition from a colour insulating medium to the colour conducting medium, referred to as quark-gluon plasma, which is the densest and the hottest form of matter. Quark-gluon plasma is a new state of matter, the occurrence of which has also been predicted by Quantum Chromodynamics(QCD). It is believed to be formed when quark matter made up of baryons is either compressed or heated to a high temperature as depicted in Fig. 1.2. In quark-gluon plasma, quarks and gluons are envisaged to behave as
if these were almost free objects. QGP is envisaged to be formed at a temperature \( \sim 170 \) MeV. On the other hand, cold QGP may be formed at high energy densities, about 20 times the normal nuclear density without heating[9].

![Phase transition diagram](image)

**Fig. 1.2 Phase transition originated by a high temperature and/or a high baryonic number density**

A predicted phase diagram of the strongly interacting matter is exhibited in Fig. 1.3. In the context of Standard Model, study of this phase diagram is not only of interest in exploring and testing QCD on its natural scale, that is, in the non-perturbative sector, but it might also shed light on such fundamental questions as the nature of confinement itself and on the process of spontaneous symmetry breaking, which is thought to be responsible for the origin of the ‘effective’ quark masses.

As already stated quark-gluon plasma is believed to have existed in the early Universe. It is also believed to exist in the core of neutron stars. These two sources of QGP production are quite impossible as one cannot expect occurrence of another Big Bang conditions and the neutron stars are very far away.

The only possibility left for the production of QGP is by creating the so called Little Bang in the laboratory by colliding two heavy nuclei at ultra-relativistic energies.
Thus, in the laboratory nucleus-nucleus collisions at very high energies is envisaged to produce this de-confined state of nuclear matter. Conclusive evidence about QGP formation is expected to be obtained at the LHC energies, (5.5 TeV/nucleon).

Nearly conclusive evidences are mounting at RHIC on the creation of QGP[17], that is, (i) it is dense hadronic matter which gives large energy losses and modifications of jet correlations for hadrons, (ii) appears to be thermalized very early and to exhibit maximal flow as predicted by hydrodynamics models, (iii) also causes large energy loss and flow for heavy quarks and (iv) causes strong suppression, beyond that expected from cold nuclear matter effects, for instance $J/\psi$.

As already mentioned, search for the formation of QGP is a challenging task. The reason for this is the fact that even if QGP is formed, it will exist only for a fraction of the total evolution time and it will thus be difficult to discern its formation. It is a transient state as it survives for a very short time and is not directly observable. It will only leave its 'finger prints'.

For this reason, a number of signatures have been proposed which by and large
give valuable information about the various characteristics of the particles that arise due to interaction between the constituents of the plasma. Some of the most promising signals of QGP formation are briefly discussed below.

### 1.4.1 Direct Photon production in QGP

An electromagnetic interaction between the constituents of plasma is responsible for the emission of photons from the QGP environment. These are called direct photons and their multiplicity in the plasma rises as the square of the total number of charged particles produced. Direct photons are considered to be one of the cleanest signals of the QGP formation as they respond only to electromagnetic process and are not affected by the intervening hadronic medium. Annihilation of quark-antiquark pair in the plasma is the dominant process for the production of direct photons.

$$ q + ar{q} \rightarrow \gamma + \gamma $$  \hspace{1cm} (1.1)

QCD Compton scattering also produces direct photons.

$$ q + g \rightarrow q + \gamma $$ \hspace{1cm} (1.2)

$$ \bar{q} + g \rightarrow \bar{q} + \gamma $$ \hspace{1cm} (1.3)

The photon production rate and the photon momentum distribution depend on the momentum distribution of the quarks, antiquarks and gluons in the plasma, which govern the thermodynamical condition of the plasma. Photons produced in the QGP may, therefore, carry vital information about the thermodynamical state of the medium at the time of their production\cite{16, 18-20}.

### 1.4.2 $J/\psi$ suppression in QGP

$J/\psi$ is a bound state of charm quark and anticharm quark. The suppression of $J/\psi$ production in QGP is regarded\cite{21} as one of the most significant signatures of
deconfinement of quarks at high temperatures. In QGP the color charge of a quark is screened due to the presence of other quarks, anti-quarks and gluons in the plasma. This phenomenon is called Debye screening. The Debye screening will weaken the interaction between $c$ and $\bar{c}$ quarks.

Debye screening length is inversely proportional to temperature. Thus, we can impose a lower limit on the value of temperature, called critical temperature, above which $c$ and $\bar{c}$ cannot form a bound system. Due to very high temperature of QGP medium, the bound state of $c$ and $\bar{c}$ forming $J/\psi$ will be weakened and hence as the temperature rises above the critical temperature, it will not be easy for $c$ and $\bar{c}$ to form bound states. This will result in the suppression of $J/\psi$ production in the QGP phase[21,22].

### 1.4.3 Strangeness enhancement

Enhancement in the production of strange particles containing strange quarks in comparison to light quarks ($u$ and $d$) has been proposed as a possible signal of QGP formation in the ultra-relativistic heavy-ion collisions[23,24]. Within the de-confined QGP medium, high temperature will surely overcome the difference of mass among $s$, $u$ and $d$ quarks and $s\bar{s}$ pair production is described well in terms of the following two lowest order QCD processes[25,26]. Firstly, a gluon pair in the plasma annihilates to create a $s\bar{s}$ pair through the reaction

$$g + g \rightarrow s + \bar{s} \quad (1.4)$$

Secondly, strange quarks and anti-quarks may be produced in the collisions of light quarks and antiquarks through the reactions:

$$u + \bar{u} \rightarrow s + \bar{s} \quad (1.5)$$

$$d + \bar{d} \rightarrow s + \bar{s} \quad (1.6)$$
The production of $s$ and $\bar{s}$ will be energetically more favourable in QGP. The densities of $u$ and $d$ are greater than the densities of $\bar{u}$ and $\bar{d}$ in a QGP medium with non-zero chemical potential $\mu_{u,d}$. So, it is more likely for the $\bar{s}$ to combine with a $u$ or $d$ quark to form $k^+(us)$ or $k^0(ds)$ than it is for the $s$ to combine with a $\bar{u}$ or a $\bar{d}$ to form $\bar{k}^0(\bar{us})$ and $k^-(\bar{ds})$. For the strange quark $s$, a more likely outcome is for it to combine with $u$ and $d$ quarks to form $\Lambda(uds)$, $\Sigma^+(uus)$, $\Sigma^0(uds)$, $\Sigma^-(dds)$ instead of combining with $\bar{u}$ and $\bar{d}$ to produce $\bar{k}^0$ and $k^-$. Hence, it will result in the enhancement of strange particle production, such as: $k^+$, $k^0$, $\Lambda$, $\Sigma^+$, $\Sigma^0$ and $\Sigma^-$. 

1.4.4 Dilepton production in QGP

The measurement of dileptons has been emphasized as the most relevant probe to study the dynamics of relativistic heavy-ion collisions. In the QGP lepton pairs are produced through the interaction of quark and an anti-quarks via the mediator, a virtual photons, $\gamma^*$s.

$$q + \bar{q} \rightarrow \gamma^* \rightarrow l^+l^- \quad (1.7)$$

The produced pair $l^+l^-$ is known as lepton pair or dilepton. These electromagnetically interacting pairs, while passing through the intervening hadronic medium, leave the dense and hot reaction zone almost unaffected and carry information about the thermodynamical state of the matter at the time of their creations. However, QGP may not be the only source of dilepton production in high energy heavy-ion collisions. There are other processes as well which contribute to the dilepton production. One of the other main sources of dilepton production is Drell-Yan process[27,28] in which a quark of a nucleon of one of the colliding nuclei can interact with an anti-quark of a nucleon of the other colliding nuclei to form a virtual photon which would subsequently decay into a $l^+l^-$ pair. Furthermore, the interaction of charged hadrons with
their antiparticles, like $\pi^+ + \pi^- \rightarrow l^+ l^-$ and the decay of hadron resonances such as $\rho^0, \omega^0, \phi^0$ and $J/\psi$ would contribute to dilepton production. It is worth mentioning that lepton pairs originating from quark-gluon plasma are identifiable only for the invariant masses above 1-1.5 GeV[29-31].

1.4.5 Dynamical fluctuations as a probe of QGP production

Any physical quantity measured in an experiment is subject to fluctuations. In general, these fluctuations depend on the properties of the system under study and may reveal important information about the system. The most efficient way to address fluctuations relating to a system created in a heavy-ion collision is by studying event-by-event fluctuations, where a particular observable is measured on an E-by-E basis and the fluctuations are studied over the whole ensemble. An E-by-E analysis, successfully used from the very beginning in high energy physics (bubble/streamer chamber experiments) was recently proposed[32] and applied[33] to nucleus-nucleus collisions at SPS energy. In the field of heavy-ion physics, search for "unusual" events, i.e., events having a particularly high variation of some observable from its average value is, especially important due to the possibility of non-trivial dynamical fluctuations caused by the formation of quark-gluon plasma bubbles and/or other exotic phenomena, such as disoriented chiral condensate (DCC)[34], jet quenching[35], color fluctuations in the early stages of the collision[36], etc. An E-by-E analysis of fluctuations would surely help separate dynamical and statistical fluctuations. It is interesting to point out that experimental and theoretical knowledge are merging together to relate the fluctuations with phase transition of the confined hadronic matter to QGP.
1.5 Models of high-energy nucleus-nucleus interactions

Several models have been proposed to explain the experimental data on heavy-ion collisions at relativistic energies. They differ in their basic assumptions but have the same common goal of explaining multiparticle production in these interactions. Besides, some event generators (Monte Carlo simulations for nucleus-nucleus collisions) have also been introduced. Salient features of some of the most important models and event generators are briefly described in the following sections.

1.5.1 Hydrodynamical Model

Hydrodynamical model was proposed by Landau [37] as an improvement over the Fermi Statistical Model [38] for explaining multiple particle production phenomenon in high energy nuclear collisions. Since then the model has been developed progressively with the availability of accelerator data on multiparticle production. According to this model, the two Lorentz contracted (in the c.m. frame) nuclei collide and it assumes [39,40] that mean free path of an interacting particle is small in comparison to the size of the system. This model envisages that when two nuclei collide, a hot and dense matter is created after a complex process involving microscopic collisions of nuclear constituents. The resulting matter will be in local thermal equilibrium. This hot and dense state of matter is specified by some appropriate initial conditions in terms of distribution of fluid velocity and thermodynamical quantities followed by hydrodynamical expansion, described by the hydrodynamical equation \( \frac{\partial T^{\mu \nu}}{\partial x^\rho} = 0 \), where \( T^{\mu \nu} \) is the energy-momentum tensor. This equation indicates conservation of energy-momentum, baryon number and other conserved numbers such as strangeness, isotopic spin, etc.

As the expansion proceeds, the fluid becomes cooler and cooler and more rarefied, leading finally to decoupling of the constituent particles. The observable quantities
such as $\frac{dN}{dy}$, $\frac{d\sigma}{dm_T}$ and $<v>$, where $m_T$ and $<v>$ represent respectively the transverse mass and the average velocity of the fluid, are computed by using these decoupled or free particles.

### 1.5.2 Wounded Nucleon Model

Bialas[41] introduced the concept of wounded nucleons, that is, nucleons that are involved in at least one inelastic collision. The Wounded Nucleon Model[41] as usual started from the experimental observations in high energy hadron-nucleus interactions. The Wounded Nucleon Model[41] helps understand the mechanism of multiparticle production in relativistic nucleus-nucleus(A-A) collisions[42]. This model visualizes that the number of relativistic charged particles created in a A-A collision should be identical to the mean number of wounded nucleons, $W$. The average particle multiplicity in A-A collisions at a given projectile energy is:

$$n_{AA}(E) = \frac{1}{2}Wn_{pp}(E)$$

(1.8)

where $n_{pp}(E)$ is the multiplicity in a p-p collision at the same energy; $W$ is the number of wounded nucleons, which depends on the impact parameter[41], density and nuclear radius.

The multiplicity per participating nucleon, $M(=n_{AA}/W)$, is a convenient parameter for comparing the multiplicities observed in colliding systems of different sizes as in the framework of wounded nucleon model; $M$ is envisaged[42] to depend only on the dynamics of the collisions and not on the impact parameter, $b$. On the other hand, $W$ depends on the nuclear radius, density and impact parameter.

The number of wounded nucleons in a nuclear collision is estimated[41] using the following expression:

$$W = A_T\frac{\sigma_{NP}}{\sigma_{PT}} + A_P\frac{\sigma_{NT}}{\sigma_{PT}} = W_T + W_P$$

(1.9)
where $\sigma_{PT}$ is the total inelastic cross-section for a projectile nucleus interacting with the target nucleus, $\sigma_{NP}$ and $\sigma_{NT}$ are the inelastic cross-sections for the interactions of a nucleon with projectile and target nuclei respectively; $A_p$ and $A_T$ are the mass numbers of the projectile and the target nuclei respectively and $W_T$ and $W_P$ are the numbers of the wounded nucleons of the target and the projectile nuclei respectively.

According to Glauber model [43] in the central A-A collisions, the maximum impact parameter, $b_{max}$, is used to determine the total number of wounded nucleons from:

$$\sigma_{part} = \pi b_{max}^2 = \frac{N_{central}}{N_{total}} \sigma_{PT}$$

where $N_{central}$ and $N_{total}$ are the numbers of the central and total events respectively.

According to Wounded Nucleon Model the cross-section for the excited nucleons due to collisions should be the same as that for the unexcited ones. The mean numbers of collisions made by the projectile and target nucleons are calculated using the following expressions:

$$\nu_T = A_T \sigma_{NN} / \sigma_{NT}$$

(2.1)

and

$$\nu_P = A_P \sigma_{NN} / \sigma_{NP}$$

(2.2)

The total number of collisions made by the colliding nucleons may be calculated from:

$$\nu = W_P \nu_T = W_T \nu_P$$

(2.3)

It has been reported [41,42,44] that the predictions of the Wounded Nucleon Model are compatible with the results obtained for the experimental as well as FRITIOF data for 200 GeV/c p-Em, 200A GeV/c $^{16}$O- and $^{32}$S-Em interactions and Pb-Pb collisions at 158 GeV per nucleon energy.
1.5.3 Bjorken Model

Bjorken model[12] is used for estimating the initial energy density in A-A collision. In this model the target and projectile nuclei are considered as two thin discs as displayed in Fig. 1.4(a). The longitudinal thickness can be neglected because of high energy involved, so that the longitudinal coordinates of the two colliding nuclei are almost the same.

![Before Collision](a) ![After Collision](b)

Fig. 1.4 The configuration of two colliding nuclei before and after a collision.

Let us consider two nuclei coming towards each other from two extremes of Z axis, i.e., Z =−∞ and Z =+∞ with relativistic velocities. Collision will take place at the point (Z,t) = (0,0) as depicted in Fig. 1.4(b). The quanta which carry the energy deposited in the collision region around Z~ 0 can be in the form of quarks, gluons, or hadrons. The space-time evolution of the collision is shown in Fig. 1.1. It is believed[12] that in a relativistic collision at (Z,t) = (0,0), the energy density will be quite large and quark-gluon plasma is likely to be formed in the central rapidity region. In order to estimate the initial energy density, a longitudinal length ΔZ around Z =0, where the matter is at rest, is taken into consideration. If A is the
overlapping transverse area then volume is given by:

\[ V = A \Delta Z \tag{2.4} \]

The number density in the given volume at \( Z = 0 \) and at the proper time \( \tau_0 \) is given by:

\[ \frac{\Delta N}{A \Delta Z} = \frac{dN}{Adydz}|_{y = 0} \tag{2.5} \]

where \( y \) is rapidity of the particle and \( \Delta N \) is the number of particles present in the volume \( A \Delta Z \). Average value of the initial energy density covering the transverse area \( A \) at proper time \( \tau_0 \) is given [12] by:

\[ \epsilon_0 = \frac{m_T dN}{\tau_0 Ady}|_{y = 0} \tag{2.6} \]

where \( m_T \) is the transverse mass defined as \( m_T = \sqrt{p_T^2 + m^2} \). Eq. 2.6 can be written in terms of the transverse energy as [12]:

\[ \epsilon_0 = \frac{dE_T}{\tau_0 Ady} \tag{2.7} \]

where \( E_T = \sum_i E_i \sin \theta_i \), \( E_i \) and \( \theta_i \) being the total energy and emission angle of \( i^{th} \) particle respectively.

According to Bjorken model the value of the initial energy density turns out to be \( \epsilon_0 \sim 1.3 \text{ GeV}/\text{fm}^3 \) at AGS energy for which \( \frac{dE}{d\eta} = 200 \text{ GeV} \) in a central Au-Au collision and \( \epsilon_0 \sim 3 \text{ GeV}/\text{fm}^3 \) at the SPS energy having \( \frac{dE}{d\eta} \sim 450 \text{ GeV} \) for central Pb-Pb collisions [12].

### 1.5.4 Participant Spectator Model

The Participant-Spectator Model [45] of heavy-ion collisions is illustrated in Fig. 1.5. The participating nucleons from the overlapping nuclear part create a region of high temperature and density, while the spectators continue their initial motion.
almost undisturbed. The impact parameter, ‘b’, determines the centrality of the collision and it is not directly measurable.

An important aspect of Participant Spectator Model is that it helps select collisions with different impact parameters by selecting events with different number of participant nucleons. This approach owes its experimental origin to Dubna and Berkley[46]. This approach makes use of the geometry of the collisions in heavy-ion interactions for a better understanding of the collision dynamics.

Nuclear interactions are generally classified[47] into the following three categories depending upon the impact parameter, ‘b’:

(i) central collisions: \(0 \leq b \leq |R_p - R_T|\)
(ii) quasi-central collisions: \(|R_p - R_T| < b < |R_p + R_T|\) and
(iii) peripheral collisions: \(b \sim |R_p + R_T|\)
where $R_p$ and $R_T$ are radii of the projectile and target nuclei respectively.

1.5.4.1 Central collisions

As is seen from Fig. 1.5 the impact parameter in the case of the central collisions is zero or close to zero. If the two nuclei have different radii, the smaller nucleus makes a hole in the larger one and all nucleons of the smaller nucleus can in principle participate in an interaction. The numbers of projectile and target nucleons participating in the collision is large. In this case, only the larger nucleus has some spectator nucleons at the edge.

1.5.4.2 Quasi-central collisions

When a nucleon is no longer a spectator, but participates in the reaction, it is scattered into the rapidity space between the projectile fragmentation and target fragmentation regions. Such a collision may be either quasi-central or central one. In both quasi-central and central collisions, therefore, the projectile and target nuclei are close to each other.

1.5.4.3 Peripheral collisions

In a peripheral collision, the two colliding nuclei glance each other, with an impact parameter ‘b’ which can be as large as the sum of the radii of the two nuclei approximately. However, due to large impact parameter the transfer of momentum involved is less. Some nucleons of both the nuclei do participate in the interaction while the remaining ones act as spectators.

1.5.5 Monte Carlo FRITIOF model for nucleus-nucleus collisions

Monte Carlo codes based on string model like VENUS[48], RQMD[49], FRITIOF[50] and HIJING[51] are widely used by experimentalists whenever they want to investigate whether their data exhibit some thing anomalous[52]. All these models are
non-plasma models and have string formation and fragmentation as an important ingredient. These event generators describe the phenomenology of heavy-ion collisions based on extrapolations from known regions of high energy interactions. They might thus be used to disentangle 'new physics' from the 'background' of conventional physics.

It is necessary to have a reliable event generator for comparison with the experimental data and the event generator must have capability to simulate collisions of a particular type. These conditions are nicely fulfilled by the so-called Lund model for high energy A-A interactions and its event-simulator FRITIOF. The Lund nucleus-nucleus model is a generalization of the Lund hadron scattering model[53]. The basic feature of this model is that a hadron is envisaged to behave like a relativistic string with a confined colour field, that is, it consists of a hard core surrounded by an exponentially damped field.

String formation and its fragmentation, the two unique properties of relativistic nuclear collisions, are the two basic features of this model. It may be mentioned that a string is a longitudinally oriented object formed when the nucleons of the projectile come closer than a certain minimum distance, \( d < \sqrt{\frac{E_{NN}}{x}} \). This model envisages the formation of a string as a result of momentum exchange, i.e., longitudinal excitation as shown in Fig. 1.6.
Fig. 1.6 String formation due to longitudinal excitation. All partons in a string originate from one baryon.

The FRITIOF programme is written in FORTRAN 77 and the only nonstandard function needed to run the program is a random number generator, which supplies uniformly distributed random numbers between 0 and 1.

1.6 Need and objective of the present work

One of the possible approaches for examining the dynamics of multiparticle production in relativistic heavy-ion collisions is to investigate the occurrence of fluctuations in particle density distribution of the particles produced in these collisions. These fluctuations may arise due to: (i) statistical reasons or (ii) occurrence of an uneven phenomenon during the collision.

It is worth mentioning that creation of an environment for QGP formation does not necessarily mean that all heavy-ion collisions at ultra-relativistic energies would produce QGP. It is believed that fluctuations in multiplicity distributions of hadrons produced in heavy-ion collisions at high energies may be used to examine whether the quark-gluon system has undergone a phase transition[54,55]. Such anomalous fluctuations in a single event are represented as peaks, often termed as 'spikes', in narrow pseudorapidity intervals. The observed fluctuations have been found to exceed significantly the statistical noise and several experiments[56,57] have confirmed...
these early observations.

In order to disentangle information regarding dynamical fluctuations in particle densities, various methods of analysis like $F_q$ moments, $G_q$ moments, modified $G_q$ moments and Takagi moments, etc., have been proposed. These methods have been used in the present work to investigate the occurrence of fluctuations in the distributions of density of charged particles produced in the collisions of 14.5A GeV $^{28}$Si-nuclei in nuclear emulsion. In each case the experimental results are compared with those obtained for generated events using Lund model FRITIOF[50]. The multifractal specific heat, $c$, is also computed for the experimental and FRITIOF data sets. The study is organized in the following manner.

As already mentioned Chapter I entitled, "Introduction to High Energy Heavy-Ion Physics", is of introductory nature, which briefly sums up the past attempts made to study heavy-ion collisions employing heavy-ion accelerators. The theory of the space-time evolution of heavy-ion collisions is also outlined in this chapter. It is followed by a brief discussion on the formation of QGP along with its important signatures. Results based on the data of A-A collisions involving the ion beams from the accelerators located at DUBNA, BNL and CERN do not yield unambiguous evidence about the formation of quark-gluon plasma. However, physicists have extensively used these data to have a clear understanding of the collision dynamics. In view of this, a number of models for explaining the dynamics of multiparticle production in relativistic heavy-ion collisions have been proposed[58-61]; a few of these have been briefly discussed.

Availability of the event generators, based on the models of multiparticle production, have provided a unique opportunity to compare the findings with the model predictions by generating similar events and carrying out a parallel analysis of the
simulated data. Event generators have also been discussed along with the models of nucleus-nucleus collisions.

In Chapter II, entitled "Nuclear Emulsion Technique and General Features of 14.5A GeV $^{28}$Si-nucleus collisions" a brief description about the scanning procedure, mechanism of track formation, various track parameters, criteria used for selecting events and measurements of emission angles, ionization, etc. has been given. General characteristics of various secondary particles like mean multiplicity, multiplicity distribution, multiplicity correlations amongst the emitted charged particles and pseudorapidity distribution for different $n_\pi$ intervals are also discussed. Salient features of correlations and clusterization of relativistic charged particles produced in 14.5A GeV $^{28}$Si-nucleus collisions are investigated using both the experimental and FRITIOF data. Several approaches are discussed for examining fluctuations in particle density distributions as these are suggested as a probe for gleaning information about the formation of QGP and subsequent phase transition.

Chapter III entitled, "Multifractal Moments in Relativistic Nuclear Collisions" is devoted for presenting a theoretical foundation and mathematical formalism of multifractal moments proposed by Hwa and others[62,63]. $G_q$ moments are systematically studied and results obtained using this method are also presented in this chapter. It may be of interest to mention that the study of the non-statistical fluctuations using the multifractal technique is important as it allows to study the fluctuations for both positive and negative orders of the moments, which further enables to investigate the exact dynamics of multiparticle production.

There is yet another method for investigating the behaviour of dynamical fluctuations in relativistic nuclear collisions, which is called the method of scaled factorial moments, $F_q$, or intermittency proposed by Bialas and Peschanski[56]. The method
of scaled factorial moments allows to test the statistical significance of the observed density fluctuations for examining whether the fluctuations are simply statistical or they have a dynamical origin, leading to an intermittency pattern in multiparticle production. This method (SFM) can not only detect large non-statistical fluctuations but can also investigate the pattern of fluctuations which could lead to physical interpretation of their origin.

In view of this, various aspects of this approach are described in Chapter IV entitled, "Study of Factorial Moments in Relativistic Nuclear Collisions" along with the results obtained using this method for the experimental and FRITIOF data.

The idea of constant specific heat approximation (CSH) is described in Chapter V entitled, "Multifractal Specific Heat in Relativistic Nuclear Collisions" in order to provide a thermodynamical interpretation to the observed behaviour of intermittency and multifractality of the multiplicity fluctuations in 14.5A GeV/c $^{28}$Si-nucleus interactions. For this purpose multifractal specific heat, $c$, has been computed using the approaches of $F_q$ moments, modified $G_q$ moments and Takagi moments for both the experimental and FRITIOF data. At the end of this chapter, a comparison is also made between the results obtained from three approaches.

Summary of the present study and some interesting conclusions are presented in Chapter VI.
References


