Chapter 1

Introduction

"A theory can be proved by experiments, but no path leads from experiments to the birth of a theory." — Albert Einstein.

The heavy-ion collisions provide unique possibility to understand the different observables and phenomena which emerge at different incident energies and impact parameters. The colliding nuclei at low incident energies cannot compress each other, therefore one has studied the physics of sub-density phenomena. The low energy heavy-ion reactions ($E_{\text{incident}} \leq 20 \text{ MeV/nucleon}$) look for the nuclear interactions as well as fusion-fission, cluster-radioactivity, formation of super heavy nuclei, etc. [1]. The low energy physics has been explored by studying variety of experiments which involves both the symmetric as well as very asymmetric nuclei [1]. The heavy-ion collisions at intermediate energies ($20 \text{ MeV/nucleon} \leq E_{\text{incident}} \leq 2000 \text{ MeV/nucleon}$) produce a piece of hot and dense nuclear matter. In addition, several rare phenomena like the multifragmentation, collective flow and subthreshold particle production are also observed [2, 3].

The outcome of intermediate energy heavy-ion collisions is not only important for nuclear physics, but is also useful for astrophysics as well as for cosmology. The understanding of celestial objects such as supernova and neutron stars may need the knowledge of hot and dense nuclear matter that depends on the temperature and density of the environment.
Fig. 1.1 shows the phase diagram of nuclear matter in temperature-density plane. Like all other materials, the properties of nuclear matter are also influenced by the pressure, density and temperature. The hadronic matter (a generic name for all strongly interacting particles) may have a rich structure in the domain of high excitation energies and compressions. From Fig. 1.1, one can see the nuclear liquid-vapor phase-transition at low temperature and sub-nucleonic densities. At very high density and temperature, one may also have the quark-gluon-plasma [2, 3, 4] whereas at moderate temperatures, the hadron-gas can occur which can be studied through intermediate energy heavy-ion collisions. It is relevant to mention that the properties of hadrons at high densities and temperatures are not only of interest for nuclear physicists, but are also of great interest for astrophysicists and cosmologists who have to deal with the dense objects. Let us examine the other possible candidates for higher temperatures and densities. Table 1.1 gives the list of different possible candidates that can produce high densities and temperatures. From Table 1.1, we see that the finite nuclei (through breathing mode) can generate a...
Table 1.1: Candidates for high densities and temperatures.

<table>
<thead>
<tr>
<th>Candidate</th>
<th>Max. Density</th>
<th>Max. Temp.</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Finite Nucleus (monopole)</td>
<td>ρ/ρ₀ ≈ 1</td>
<td>T ≈ 0 MeV</td>
<td>Very small range of density is available</td>
</tr>
<tr>
<td>Neutron Star</td>
<td>ρ/ρ₀ ≈ 6</td>
<td>T ≈ 0 MeV</td>
<td>Rare in time and remote in space</td>
</tr>
<tr>
<td>Supernova</td>
<td>ρ/ρ₀ ≈ 4</td>
<td>T ≈ 10 MeV</td>
<td></td>
</tr>
<tr>
<td>Heavy Ion Collisions @ Intermediate energies</td>
<td>ρ/ρ₀ ≈ 2 – 3</td>
<td>T ≈ 100 MeV</td>
<td>Give unique possibility to study the matter at high density and temperature.</td>
</tr>
</tbody>
</table>

Small fluctuation in the density and therefore, cannot be used to study the matter at the extremes of densities and temperatures. The next two candidates, namely, the neutron star and supernova explosion, are remote in space and rare in time, therefore, provide a limited possibility to extract the information about the matter at high temperature and density. The last candidate i.e. the heavy ion collision at intermediate energies provides unique possibility to study the properties of hadrons over a wide range of temperature and density [2, 3]. In addition, one can also examine the properties of hadrons in medium. Note that the experimental measurements are done at the end of the reaction where matter is cold and well separated. In other words, one cannot study the hot and dense matter directly in experiments. One has to rely on indirect methods to extract the information about the hot and dense matter. It is worth mentioning that the hot and dense nuclear matter produced in the collision of heavy nuclei (at intermediate energies) remains for very short span of the time (≈ 20 fm/c) [2,3,4]. This hot and dense piece of nuclear matter gives rise to various phenomena like the flow of nucleons, subthreshold particle production, multifragmentation, etc.

It is well known that the colliding nuclei (at intermediate energies) shatter into several small and medium size pieces and lot of nucleons are also emitted. This branch is dubbed as multi-fragmentation. One is struggling to find the answer of typical questions like why do nuclei break into several fragments? How and when are these fragments
formed? How does the medium affect the clusterization? What is the mechanism behind the multi-fragmentation? Why does a nucleus shatter into several (up to a dozen) fragments if hit by a projectile? Is this a statistical process, making new micro-canonical phase-space models the proper tool for its description or is this a dynamical process etc. etc.? During last two decades, extensive efforts have been made experimentally as well as theoretically to find the possible answer of all these questions. The present thesis also deals with multifragmentation. We shall attempt to extract the information about several model ingredients by comparing our theoretical results with experimental data.

In the following, we shall first present a brief survey of experimental status and then, a brief discussion of various theoretical methods will be made. The detailed discussion on different theoretical tools is given in chapter 2.

1.1 Review of experimental attempts for multifragmentation

Until seventies, it was not possible to accelerate the heavy nuclei and therefore, one could accelerate the light ions and particles only. The field of heavy-ion physics was dominated by shooting light particles on heavy targets. In other words, the study of nuclear physics was confined to fusion, fission, particle transfer etc. At present, one is able to accelerate the nuclei up to several hundreds of GeV/nucleon that has opened new vistas in the field of intermediate and high energy heavy-ion reactions.

In 1974, the BEVALAC accelerator at Lawrence Berkley Laboratory (LBL) became capable of accelerating heavy nuclei such as iron upto incident energies of 2.1 GeV/nucleon. This was the beginning of new era in accelerator based heavy-ion physics. Since a piece of hot and compressed nuclear matter can be produced in heavy-ion collisions, these experiments were aimed to determine the nuclear equation of state [2]. As stated above, the equation of state is not only of importance for nuclear physics, but is also essential for astrophysics and cosmology.
After the first Berkeley experiments (which served mainly to get the experimentalists and theoreticians aware of the problems and pitfalls of the way from medium energy heavy-ion collisions to the equation of state), several accelerators were built at Michigan state university (MSU) (USA), GANIL (France), and at GSI/Darmstadt (Germany). The SIS (heavy-ion synchrotron) accelerator at GSI is specifically designed to study the heavy-ion collisions at intermediate energies. The experimental group at MSU is very active in studying the fragment's spectra at lower side of the bombarding energy. Similar efforts are also made by the INDRA collaboration at GANIL and by the ALADiN/FOPI collaboration at GSI. These measurements provide a complete spectra of fragments over wide range of incident energies and impact parameters which include the fusion, fission, multifragmentation as well as total disassembly of the nuclear matter at higher incident energies.

The emulsion experiments (O+Br/Ag) of Jakobsson et al. [5] were among the first attempts which have thrown light on the complex picture of heavy-ion collision at intermediate energies. These experiments provide valuable information on the onset of multifragmentation as well as on vaporization in heavy-ion collisions. One has also investigated the associated properties of fragments which include the collective flow [5, 6], energy spectra as well as rapidity distribution. The incident energy range of emulsion experiments (between 25 MeV/nucleon and 200 MeV/nucleon) provides unique possibility to look for the complete and partial fusion at low incident energies as well as the multifragmentation and vaporization at intermediate energies. The emulsion experiments have, however, few limitations that will be discussed in chapters 3 & 4.

The Berkley group focuses mainly on asymmetric reactions like $^{197}$Au + $^{27}$Al, $^{51}$V, $^{64}$Cu (at 60 MeV/nucleon), $^{36}$Ar + $^{197}$Au (at 50 and 110 MeV/nucleon), $^{56}$Fe + $^{197}$Au (at 50 and 100 MeV/nucleon), $^{139}$La + $^{12}$C (at 50, 80 and 100 MeV/nucleon) and $^{139}$La + $^{27}$Al, $^{40}$Ca, $^{64}$Cu, $^{139}$La (at 35, 40, 45 and 55 MeV/nucleon) [7], etc. Their main aim was to investigate the role of entrance-channel mass asymmetry on reaction dynamics.
They emphasized on different probabilities which include the excitation energy, angular distribution, cross sections as well as the velocity distribution. The MSU group also focussed on asymmetric reactions like $^{36}Ar + ^{197}Au$, $^{129}Xe + ^{197}Au$ (at 50-110 MeV/nucleon), $^{129}Xe + ^{12}C$, $^{27}Al$, $^{64}Cu$, $^{89}Y$ (at 50 MeV/nucleon), $^{40}Ar + ^{65}Sc$, $^{40}Ar + ^{197}Au$ (at 35, 50, 80 and 110 MeV/nucleon) [8], etc. Some attempts were also made for symmetric reactions like $^{197}Au + ^{197}Au$ (at 100-400 MeV/nucleon) etc. In most of the above mentioned experiments of MSU group, the geometrical coverage was about 87-90% of $4\pi$. The underlying physical processes were explored by employing several statistical and dynamical models. The theoretical calculations were filtered through experimental acceptance which is the software replica of experimental device that takes into account the energy thresholds, angular acceptance and double hit probabilities. They emphasized on the collective expansion, kinetic energy spectra, angular and charge distribution and velocity correlations [8].

The INDRA collaboration at GANIL [9] is involved in studying the collisions with large nucleonic multiplicities. They have undertaken an ambitious program where influence of different parameters on multi-fragmentation is analyzed. These parameters include the role of system-size in entrance channel as well as in Coulomb instabilities. In addition, system-size effects are studied in a variety of symmetric collisions [like $^{36}Ar + ^{12}C$] (at 32, 40, 52 and 74 MeV/nucleon) [9], $^{58}Ni + ^{58}Ni$ (at 32, 40, 52, 63, 74, 82 and 90 MeV/nucleon) [9], $^{129}Xe + ^{118}Sn$ (at 25, 32, 40, 45 and 50 MeV/nucleon) [10], $^{181}Ta + ^{197}Au$ (at 33 and 39 MeV/nucleon) and $^{238}U + ^{238}U$ (24 MeV/nucleon) [9]. On the other hand, the entrance channel effects are studied by keeping the total mass equal to 250 units. The gentle compression and Coulomb instabilities were studied for heavy fragments. Recently, the detailed theoretical study of INDRA experimental findings was carried out by Aichelin & coworkers [11].

The FOPI and ALADiN groups at GSI are studying variety of reactions with all kind of possible physics. The target/projectile ranges from $^{12}C$ to $^{208}Pb$ over wide range of incident energy between 100 and 1000 MeV/nucleon [12, 13, 14]. The ALADiN group
These reported a target independence above 600 MeV/nucleon if fragment multiplicities are plotted against $Z_{\text{bound}}$ (= the sum of the charges of all fragments with $Z \geq 2$). This is valid if incident energy is above 600 MeV/nucleon and projectile is kept fixed. For different projectiles, one has to rescale the quantities with the charge of the projectile. These experiments also established the relation between the impact parameter and emission of charged particles. A larger multiplicity (of the charged particles) indicates the central collisions which decreases with increase in the impact parameter [8, 12]. Note that the polar angle coverage in ALADIN experiments is $\approx 19-30\%$ with full azimuthal coverage. In recent attempts, the FOPI collaboration [13, 14] is focussing on the mass-dependence in multifragmentation. This study is carried out by using symmetric reactions like Ni+Ni, Ru+Ru, Xe+CsI, and Au+Au. The above analysis of mass dependence was based on the participant-spectator model where yields are analyzed separately for the participant and spectator fragments [13]. The universality in the production of spectator fragments was achieved in the above study which confirms the results of ALADIN experiments [12]. However, a strong mass dependence was seen for the participant fragments [13, 14].

1.2 Review of theoretical models used for multifragmentation

Before looking for different theoretical models and algorithms suitable at intermediate (and relativistic) energies, we have to keep in mind the dynamics involved at these energies. At low incident energy, the possibility of nucleon-nucleon collision and nucleonic degree of freedom is very small, therefore, nuclear dynamics can be understood by studying the real part of the potential only. On the other hand, the frequent nucleon-nucleon collisions at relativistic energies needs imaginary part of the potential (which is proportional to the nucleon-nucleon cross section). At intermediate energy, both the real and imaginary parts of the potential are comparable. Two different schools of thought have been put forward to understand the dynamics at intermediate energies:

(i) In one case, one assumes that the dynamics of the reaction does not play any
role and, therefore, can be ignored. In this case, the final state is decided by the statistical methods. Varieties of statistical and static models [15, 16, 17] exist in the literature that are quite successful in explaining the experimental data. These models are widely used to understand various observables. One has even tried to look for the liquid-gas-phase transition in heavy-ion collisions within these models. The crucial input in these models is the excitation energy and density of the system at freeze-out time. In earlier calculations, one has assumed these inputs parameters, whereas recent calculations estimate these parameters from the freeze-out phase space generated by dynamical models [18].

(ii) In other thought, importance is attached to the dynamics of the reaction. Here one starts from two (well defined) nuclei and follow the dynamics of the collision within dynamical model. These dynamical models, therefore, are capable of studying the detailed reaction phenomena which have many body features. Naturally, the situation at the start of the reaction is non-equilibrated and therefore, theoretical model should not assume global (or local) equilibrium [2, 3]. As we want to study the role of dynamical ingredients in multifragmentation, we shall concentrate on dynamical models only.

A nucleus-nucleus collision at intermediate energy can be viewed as composed of three stages [2, 3]: (i) The first one is the initial stage where the target and projectile are prepared and boosted towards each other with proper centre-of-mass energy. (ii) In the second stage, reaction happens and matter is compressed. One may obtain a piece of hot and dense nuclear matter. This is called as the compressional stage. (iii) The compressed (and hot) nuclear matter expands to sub-nucleonic densities which will eventually break the matter into large number of entities consisting of emitted nucleons as well as light and medium mass fragments. The size (and multiplicity) of various fragments depends crucially on the incident energy as well as on the impact parameter of the reaction which will be discussed in detail in following chapters.

It is worth mentioning that all dynamical models follow the evolution of single nucleons only. No dynamical model simulates directly the clusters production. One,
therefore, needs sophisticated algorithms to identify the clusters. In other words, the study of multifragmentation (in a dynamical model) can be divided into two parts: (i) the calculation of the phase space of nucleons and (ii) the clusterization of the calculated phase space using cluster recognition algorithms. The dynamical model used to simulate a heavy ion reaction (and generate the phase space of nucleons) can be termed as "primary model". The primary model is an essential part of the dynamics as its merit defines the success of a theoretical approach. The cluster recognition algorithms are dubbed as "secondary algorithms". We shall first discuss the primary models and then shall present the secondary algorithms.

1.2.1 Primary models

The mean field theories {such as the Time Dependent Hartree-Fock (TDHF) theory [2, 19] or its semi-classical version the so-called Vlasov equation (in phase-space) [20,21,22]} are suitable approaches at low incident energies where nucleon-nucleon collisions are negligible. However, a suitable and reasonable approach for intermediate energy heavy-ion physics should treat the nucleon-nucleon collisions and mean field on equal footing. Some attempts were made in the literature to extend the TDHF theory to take care of the residual nucleon-nucleon (NN) interactions which are responsible for the two body collisions (this was dubbed as Extended Time Dependent Hartree-Fock (ETDHF) theory) [23]. However, its numerical implementation prohibited its use for large scale investigations of the heavy-ion collisions.

In the first attempt towards reasonable theory for intermediate energies, the semi-classical version of ETDHF theory (i.e., Vlasov equation) [20, 21, 24] was coupled with nucleon-nucleon collisions and thus, a new realization (named as Boltzmann-Uehling-Uhlenbeck equation (BUU) \(^1\) was developed to study the large deviating problems of low, intermediate and relativistic heavy-ion collisions. The solution of the BUU equation provides the time evolution of one-body distribution function in six dimensional

\[^1\text{Many more names like the Landau-Vlasov (LV) equation [24] or Vlasov-Uehling-Uhlenbeck (VUU) [22] or Boltzmann-Nordheim equation [25] also exist for the same realization.}\]
phase-space. In actual calculations, one does not solve the Boltzmann-Uehling-Uhlenbeck (BUU) [20,21,22,24,25,26] equation directly, instead one solves the classical Hamiltonian equations of motion for the propagation of particles in mean field. The two-body collisions (and the Pauli principle) are treated in a rather phenomenological way by employing the Monte-Carlo techniques. Due to one body nature, the BUU model cannot describe correctly, for example, the multi-fragmentation phenomenon which involves the correlations between nucleons. Recently, some attempts were made to extend the BUU equation by including stochastic two-body correlations so that the N-body phenomena like multi-fragmentation can also be studied [27].

Keeping in mind the requirements of intermediate energy region, one would like to have the methods where correlations and fluctuations among nucleons can be preserved. The classical molecular dynamics (MD) [28, 29] approach (or the equation of motion), in principle, is capable of treating both the compression and fragment formation. The molecular dynamics predicts the collective (sideways) flow in a qualitative agreement with the data. It incorporates the complete classical N-body dynamics which is necessary to describe the formation of the fragments. The simple classical molecular dynamics, however, needs major refinements (including the quantum features). The quantum features play a very important role at low incident energies. The above approach was later extended to incorporate the quantum features by Aichelin & Stöcker [3, 30]. This new approach [which explicitly incorporates the N-body correlations as well as a nuclear equation of state and important quantum features (like the Pauli-principle, stochastic scattering and particle production)] was dubbed as Quantum Molecular Dynamics (QMD) [3, 4, 11, 18, 30, 31, 32, 33, 34, 35] model. In recent years, several refinements and improvements were made over the original QMD model. The new versions were named as IQMD (Isospin-QMD) [35], GQMD (G-matrix-QMD) [34, 36] etc. The crucial quantum features like the antisymmetrization were implemented in approaches like Fermionic Molecular Dynamics (FMD) [37] and Antisymmetric Molecular Dynamics (AMD) [38]. The serious numerical problems have restricted the use of FMD and AMD approaches to light nuclei only. Here it is worth mentioning that the intranuclear cascade (INC) model
developed by Cugnon et al. [39] was one of the pioneering models in the field and has acted as a guideline for the development of the field.

1.2.2 Secondary models

As discussed above, every dynamical model can follow the phase-space of nucleons only and, therefore, one needs methods to define the clusters. These methods are referred as "secondary models". In a very simple picture, nucleons were connected to a cluster using space correlation method. This method binds two nucleons in the same fragment if their centroids are less than certain distance [3]. This method is also called as Minimum Spanning Tree (MST) method [3,12,13,18,21,30,31,35,40]. By default, this method is valid for dilute systems and therefore, cannot address the question of mechanism behind the multi-fragmentation which may happen at relative higher densities. This method is one of the most extensively used methods. Recently, several modified versions of the MST method and some new algorithms were also advanced. Some of these methods are based on the spatial-momentum correlations whereas other needs proper minimization of the energy of the system. Some attempts are also made in the literature to couple statistical model with dynamical model. We shall discuss these methods in detail in chapter 2.

It is worth mentioning that different clusterization algorithms should give same distribution at the end of the reaction where matter is very dilute and clusters are well separated from each other [41].

From the above discussion, it is clear that several primary and secondary models are available to study the reaction dynamics. We shall use the QMD model coupled with minimum spanning tree method for our present study. A comparison of different clusterization algorithms will also be presented. We shall divide our study into symmetric and asymmetric reactions. The symmetric reactions generate high compression whereas asymmetric reactions lead to heat or thermal energies. The collision of heavy target against light projectile leads to target multi-fragmentation whereas the collision of
a heavy projectile against light target gives possibility of projectile fragmentation mechanism. Moreover, the physics at peripheral collisions is dominated by the spectator physics whereas the central collisions have a fire ball dynamics.

Our main interest is to look for the role of model ingredients (such as equation of state, momentum dependent interaction as well as nucleon-nucleon cross section) in multifragmentation. We shall also attempt to present the results of system-size effects in multifragmentation.

It is important to note that the experimental setups are complex in nature and therefore, all experimental groups have developed sophisticated and complicated filters [42, 43, 44, 45]. The experimental results reported in the literature are subjected to various filters which meet the efficiency cuts of these experiments. The theoretical results should also be subjected to the same filters before a comparison with experimental results is made. Unfortunately, these experimental filter routines are not accessible to us, therefore, we have attempted to compare our results with those experiments where effect of experimental cut is very small.
The thesis is organized as follows:

Chapter 2 gives the details of various theoretical models in brief. We shall discuss the QMD, MST and restructured aggregation models (RAM) in detail.

In Chapter 3, we shall discuss the importance of momentum dependent interactions in explaining the multifragmentation [46] in asymmetric reactions by comparing the results with $^{16}$O induced emulsion data [5]. The nuclear dynamics in asymmetric reactions is quite different compared to symmetric reactions. We shall show that the inclusion of momentum dependent forces improves the agreement with the measured atomic charge distribution. The simple static interaction fails to explain the experimental data. We shall also discuss the universal dependence of the effect of momentum dependent interactions on the asymmetry of a reaction.

As noted in Refs. [3, 31, 35, 40], a larger nucleon-nucleon cross section and momentum dependence of the equation of state has a strong role to play if the system is mildly excited. This study was carried out for symmetric collisions only. Now one is interested to see how different forms of the nucleon-nucleon cross section (e.g., the popular energy dependent, in-medium, and constant cross sections) affect the fragmentation if highly asymmetric reactions are studied. As stated above, the asymmetric reaction leads to thermal energy. In addition, up to now, we and others [3, 31, 35, 40], have studied the effect of a larger nucleon-nucleon cross section in the presence of a static equation of state only. One is, naturally, tempted to understand the reaction dynamics in the presence of a larger cross section and momentum dependence of the equation of state at the same time. The point to note here is that both the momentum-dependent interactions and larger nucleon-nucleon cross section tend to destroy the initial correlations among nucleons.

In Chapter 4, we shall study the relative role of the momentum-dependent interactions and larger nucleon-nucleon cross section in multifragmentation [47]. We shall show that the sensitivity of the larger cross section towards multifragmentation reduces in
the presence of momentum-dependent interactions which makes it difficult to extract the magnitude of nucleon-nucleon cross section from multifragmentation. However, a large effect of different cross sections can be seen if a simple static equation of state is used.

The above two studies are made using minimum spanning tree method.

In Chapter 5, we shall present a systematic comparison of different clusterization methods based on simple spatial correlation, spatial-momentum correlation and energy minimization (simulated annealing clusterization algorithm [SACA]) by simulating the reaction of O+Ag/Br. We shall show that the response of different clusterization algorithms depends on the asymmetry of a reaction [48]. With the inclusion of momentum correlation (in terms of either a momentum cut or energy minimization of the system), the fragments originate between 60-100 fm/c. The response of larger nucleon-nucleon cross section and also of momentum dependent interaction is different in different clusterization algorithms. It is maximum with spatial correlation method whereas it is least with SACA. Interesting feature is that with larger nucleon-nucleon cross section, the evolution of the light and intermediate mass fragments with momentum cut method and energy minimization method is nearly the same. This is true at higher incident energies where the frequency of nucleon-nucleon collisions is very large.

Among the crucial parameters deciding the fate of a reaction, the range of the clusterization and width of Gaussian representing a nucleon are very important. In Chapter 6, we investigate the role of spatial correlations (i.e., the range of clusterization) along with the role of the range of interaction in multifragmentation [49]. We shall show that the effect of different ranges of clusterization and interactions depends on the physical conditions and excitation energy of the system. The impact of different clusterization ranges is more than marginal in the presence of a momentum dependent interaction which is different than the one obtained with a static equation of state.

One of the interesting aspect of physics is that it depends on the size of the system.
Whether it is a fusion at low incident energy or the nucleonic flow, particle production and fragmentation at intermediate incident energy, one has always tempted to understand the system-size effects. Though lot of work has been done in other phenomena to understand the system-size effects, little efforts are made to look for system-size effects in multifragmentation. We shall present a detailed analysis of system-size effects in multifragmentation.

In Chapter 7, we shall analyze the system-size effects in the evolution of different fragments as well in entropy production [50, 51]. This was achieved by studying the symmetric reactions of Ca+Ca, Ni+Ni, Nb+Nb, Xe+Xe, Er+Er, Au+Au and U+U at incident energies between 50 MeV/nucleon and 1 GeV/nucleon. We shall show that the light mass fragments are formed at a very early stage of the reaction. The lighter colliding nuclei generate less density whereas higher density is achieved with heavy nuclei. The relative yields of the light fragments \((d, t, a)\) depend strongly on the impact parameter as well as on the bombarding energy. Similarly the entropy of the system increases with increase in the bombarding energy. The study is further extended to investigate the dependence of the multiplicity of various light fragments (with mass \(\leq 10\)) on the size of the system. Our detailed analysis shows that the triggering of multifragmentation and its saturation is delayed in heavier systems. The striking result, which is independent of the incident energy and impact parameter, is that the mass dependence of the multiplicity of any kind of fragment exhibits a power law behavior \(\propto A_{\text{tot}}^{\tau}\) where "\(A_{\text{tot}}\)" is the mass of the composite system. Similar mass dependencies have already been reported in the literature for the fusion process at low incident energy and for the production of kaon and collective flow (and its disappearance) at intermediate energies. As reported for the production of kaons, the parameter \(\tau\) depends on the colliding geometry as well as on the incident energy. No unique dependence of \(\tau\) (like in the case of disappearance of flow) exists. The value of \(\tau\) in central low energy collisions is close to 2/3 which suggests the dominance of the mean field. On the other hand, a linear dependence occurs at higher incident energies. The rapidity distribution of the various fragments is also affected by the size of the system. The fragments emitted from the heavier system seem to be better
thermalized compared to the one emitted from lighter colliding nuclei. Similar trends can also be seen in the preliminary reports of the FOPI experiments.
Bibliography


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