Influence of mass asymmetry on nuclear reaction dynamics

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Dedicated

To

My Parents

CERTIFICATE

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Abstract

The present work deals with the theoretical study of multifragmentation and its associated phenomena in heavy –ion collision at intermediate energies. We present a complete systematic theoretical study of multifragmentation for asymmetric colliding nuclei for heavy-ion reactions in the energy range between 50 MeV/nucleon and 1000 MeV/nucleon by using soft equations of state. This study is performed within an isospin dependent quantum molecular dynamics (IQMD) model. We envision an interesting outcome for asymmetric colliding nuclei. Although nearly symmetric nuclei depict a well-known trend for rising and falling for the production of intermediate mass products, this trend, however, is completely missing for large asymmetric nuclei. Also the effect of isospin independent cross section has been studied. We have found the pronounced effect different cross section and mass asymmetry on the nuclear reaction dynamics.

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Chapter 1

1.1 INTRODUCTION

Traditional nuclear physics describes nuclear properties in terms of protons and neutrons. Most of the nuclei are well described, as nucleons interact either through empirical interaction in the shell model, or through a force derived from nucleon-nucleon scattering.

Modern nuclear physics has much greater ambitions. New insights are gained into conventional descriptions by studying nuclei with much larger neutron, or proton excesses, and by investigating nuclei with high spin. Reactions with intermediate-energy mesons and electromagnetic probes provide insight into the quark substructure of the individual composite particles, the high momentum structure of nuclei, and the transition between current-quark, constituent-quark, and meson-baryon degrees of freedom. Relativistic-heavy-ion experiments will soon attempt to recreate the quark-gluon plasma, not present since the first few seconds after the creation of the universe many billions of years ago.

Based on the energy domain nuclear physics can be categorized under three branches:

1. Low energy nuclear physics

2. Intermediate nuclear physics

3. High energy nuclear physics

The nuclear physics (at low/intermediate/high energies) is one the most extensively studied field. After many decades, the nuclear physics has reached a moment or critical differentiation. In last two decades, lots of efforts have been made experimentally as well as theoretically to understand the nuclear physics at intermediate energies which ranges between 50 MeV/nucleon and 1000 MeV/nucleon [1].

The study of nucleon – nucleon collisions between heavy ions at above three energy ranges involves different phenomena’s.

Low energy nuclear physics concentrates mainly on structure of nuclei and low energy nuclear reactions. It gives us information about nuclear medium, high-spin physics, and super deformation and halo nuclei [2]. At low energies, the time dependent hatree fork (TDHF) theory [3] provides a powerful tool for describing single particle observables. The reaction cross-section at low energies composed of three types i.e. the fusion, quasi-elastic and deep inelastic scattering. This process depends on the projectile-target combinations. Due to large efforts in low energies heavy ion collisions, the understanding of different phenomena is quite rich. At low energies the available free phase space is very small, therefore 98% of attempted collisions are blocked, as the whole dynamics at low energies is due to the mean field, and nucleon-nucleon collisions are negligible.

At high energies, nucleon - nucleon collisions dominate the dynamics and the intranuclear cascade (INC) models are applicable. At relativistic energies (≥2GeV/nucleon) there is a presence of large free phase space, so only 4% of attempted collisions are blocked and the dynamics is termed as cascade approach.

In the present work, my aim is to study heavy ion collisions and its related phenomenon's at intermediate energy. At intermediate energy, the available phase space is enlarged and the residual interactions are important, producing collisions between the nucleons. At intermediate energies, both the cascade picture as well the mean field is taken into consideration Different theory is required to study collisions at intermediate energy. Phenomena related at this energy can be multifragmentation collective flow, directed flow and elliptical flow [4,5,6].

With the passage of time, one was able to accelerate the heavy-ion with bombarding energies comparable to its rest mass. This opened up new dimensions which are termed as intermediate and relativistic energy heavy-ion physics. Due to the formation of compressed and hot piece of nuclear matter at intermediate and relativistic energies, it gives possibilities to study the properties of nuclear matter at extreme conditions.

The only way to get on earth to densities well above normal nuclear density is high energy heavy ion collisions. The challenge there is to identify those observables which carry information on the density and on the compressional energy which is obtained during the reaction and then to extract the robust conclusions.

1.2 Heavy Ion Physics:

The heavy ion means nuclei heavier than the helium nucleus. For nuclei with A>4, the internal structure becomes sufficiently complex that when two heavy ions scatter off each, many new reaction channels become open ,such as the transfer of clusters of nucleons and large amounts of angular momentum. With improvements in accelerator to higher and higher energies, it is now technically feasible to bring heavy nuclei to energies far in excess of their rest mass energies. In the case of heavy ions, because of the large amount of kinetic energy, angular momentum and nucleons involved, highly excited nuclear states and exotic nuclei very far away from the valley of stability may be made in the process.

Relativistic heavy ion physics is a fascinating field. In a collision of two nuclei occurring at very high energy, whether in a fixed-target or in a collider mode, thousands of new particles are produced. Their identity and kinematical characteristics go beyond that what could be expected from a simple superposition of elementary nucleon-nucleon collisions, indicating the presence of some new phenomena. Relativistic heavy ion collisions can overcome the strong repulsive force associated with the hard core of the nucleons.

Heavy-ion collisions can be considered as an excellent tool to explore the nuclear equation of state (EOS) of nuclear matter in laboratory controlled conditions. With the availability of radioactive beam facilities, the isospin is being extensively explored. One of the goals of these studies is to provide a better knowledge of the symmetry term of the EOS. In particular, stable and radioactive beams over a wide range of N/Z asymmetries allow to explore the asymmetric nuclear EOS and the density dependence of the symmetry energy.

Symmetry energy and its density dependence determine several properties of neutron stars as well as features (binding energy and rms radii) of exotic nuclear systems as neutron halo nuclei.

Study of heavy-ion collisions at intermediate energies has now become important tool to investigate reaction mechanism behind collective expansion and origin of fragments. Apart from this, it also becomes possible to infer nuclear matter equation of state (EOS)

The study of heavy-ion collisions at intermediate energies ($50 \leq E \leq 1000$ MeV/nucleon) provides a rich source of information for many rare phenomena such as multifragmentation, collective flow as well as particle production. These investigations include the production of secondary particles, the properties of particles in a (dense) nuclear medium, the compression and expansion of dense nuclear matter, its equilibration during the reaction and its decay into fragments and free nucleons. On a macroscopic level the total energy of a dense nuclear system and its decomposition into thermal and compressional parts is related to the concept of the nuclear equation of state. Since a consistent derivation of the nuclear equation of state, e.g. the energy per nucleon as a function of density and temperature is only possible in the low density limit (Bruckner theory). On the other hand this quantity is of interest for many astrophysical questions and therefore its knowledge is highly desirable. Heavy ion reactions in combination with corresponding simulations using a variety of parameterizations of the equation of state are presently the only possible approach to study this quantity.

One can also shed light on the mechanism behind the fragmentation in highly excited nuclear systems. In this energy region, multifragmentation appears to be a dominant de-excitation channel.

1.3 Isospin Physics:

The term isospin refers to the pair of similar particles, e.g. protons and neutrons, which are almost identical in the nuclear matter when electric charge difference is ignored. In many transport simulations, the nuclear interactions difference between protons and neutrons are simply ignored. In other words, these simulations explore the reactions in symmetric nuclear matter limit only [7].

Heavy ion collisions offer the possibility to probe nuclear matter under different conditions of densities and temperature. At high excitation energies and temperature, the nuclei may break up into many intermediate mass fragments, the so called multifragmentation.

Isospin physics with heavy ion reactions is a fast growing field. There are many interesting studies in the literature.

The rapid progress in producing energetic radioactive beams has offered an excellent opportunity to investigate various isospin effects in the dynamics of nuclear reactions. This study has made it possible to obtain crucial information about the nuclear equation of state of isospin asymmetric nuclear matter and about the isospin dependent nucleon-nucleon cross-section. This information is important for understanding both novel properties of neutron or proton-rich nuclei as well as explosion mechanisms of supernovae and the cooling rates of proton-neutron stars.

1.4 Multifragmentation:

Heavy-ion collisions offer the possibility to probe nuclear matter under different conditions of densities and temperatures. At high excitation energies the nuclei may break-up into many intermediate-mass fragments, the so called multifragmentation. In multifragmentation, nuclear matter at low densities and, more generally, modes of disintegration of dynamically unstable systems are probed [8, 9, 10].

Multifragmentation is by essence associated to the emission of several fragments. Any study of the phenomenon requires a coincident and efficient detection of these fragments and of the associated particles ($Z \leq 2$). This is why, in the recent years, multifragmentation studies were performed with 4π detectors.

According to the currently most believable scenario, during the overlapping stage of heavy-ion collisions (typical time $\simeq$ 100 fm/c) matter can undergo compression, leading to large excitation energies. As a consequence, the blob of nuclear matter starts to expand and can go on expanding down to sub-saturation densities ($\simeq$ 0.1 - 0.3ρ_0, where ρ_0 is the normal nuclear matter density) and reach temperatures $\simeq$ 3 - 8 MeV, where it becomes unstable and breaks up into multiple fragments [8].

Multifragmentation is a universal phenomenon occurring when a large amount of energy is deposited in a nucleus. It has been observed in nearly all types of high energy nuclear reactions induced by hadrons, photons, and heavy ions. At low excitation energies, the produced nuclear system can be treated as a compound nucleus which decays via evaporation of light particles or fission. However, at high excitation energy, possibly accompanied by compression during the initial dynamical stage of the reaction, the system will expand to sub-saturation densities, thereby becoming unstable, and will break up into many fragments. The excitation energy is indeed related to the mass asymmetry ($\eta = (A_T - A_P)/(A_T + A_P)$): in case of symmetric central reactions the compression is responsible of the high excitation energy, whereas in case of asymmetric reactions only a partial compression can occur and a large part of the excitation energy appears in the form of thermal energy [8]. Multifragmentation has been shown to be a fast process with characteristic times around 200fm/c or less. Nevertheless, as evident from numerous analyses of experimental data, a high degree of equilibration can be reached in these reactions. In particular, chemical equilibrium among the produced fragments is very likely while kinetic equilibration may not be reached. Statistical models were found very suitable for describing the measured fragment yields. Even though equilibration may not occur within the individual system during the primary reaction stage the processes are, apparently, of such complexity that dynamical constraints beyond the conservation laws do not restrict the statistical population of the available partition space.

The true multifragmentation events were confined to central collisions only. The multifragmentation therefore exhibits a complex picture which is quite sensitive to the entrance channels characteristics that is to the impact parameter beam energy as well as to the total mass of the target and projectile.

Multifragmentation is expected to bring information and constraints on the phase diagram of nuclear matter through measured fragment properties.

Fig 1.1 shows the collision between two nuclei at peripheral impact parameter. (a) shows the two nuclei after collision i.e. when they are far apart. No collision is going to take place when they are far apart. (b) Two colliding nuclei come near to each other and (c) compression zone is formed i.e. formation of compound nucleus takes place. And in (d) multifragmentation takes place i.e. compound nucleus expands and breaks into fragments.

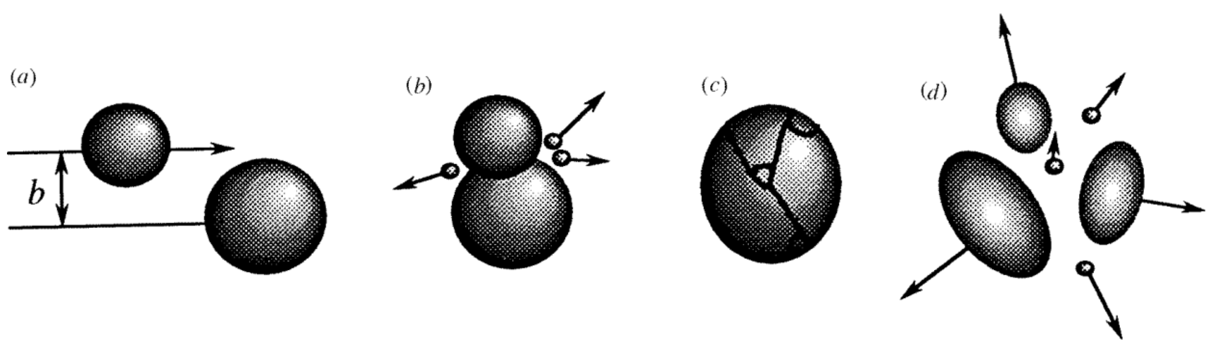

Figure 1.1 Schematic representation of a multifragmentation event following a collision, (a) with impact parameter b, between projectile and target nuclei. The violence of the shock is responsible for the rapid ejection of light particles at the start of the collision process (b). The mass (and charge) ejected in this ‘pre-equilibrium emission’ process plays no further role in the multifragmentation mechanism. The remaining nucleons form a hot and compressed composite nucleus (c) which expands and fragments. The arrows (d) represent (mainly) outward-directed velocities due to Coulomb forces and random thermal motion

1.5 Mass Asymmetry:

The outcome of a reaction depends on the incident energy, the impact parameter, as well as on the mass asymmetry of the colliding partners [11, 12, 13]. For symmetrically heavy colliding nuclei at central impact parameters, two primary fragments are formed: one that is the projectile like fragment and the other that is the target like fragment. These excited fragments deexcite through various exit channels: evaporation of light particles and emission of intermediate- mass fragments (IMFs) [11, 12, 13]. The excitation energy deposited in the system at low incident energies is too small to allow the break up of the nuclei into fragments. With an increase in the incident energy, colliding nuclei may break into dozens of fragments consisting of light, medium, and heavy fragments. The size of the fragments and physics behind their formation differs in different physical conditions. No such fragments will survive at extremely high incident energies.

A careful analysis of experimental efforts reveals either that one has studied the collision of symmetric nuclei (e.g., $_{79}Au^{197}$ + $_{79}Au^{197}$) [4] or that one has studied asymmetric colliding nuclei (e.g., $_{20}Ar^{40}$+$_{21}Sc^{45}$, $_{20}Ar^{40}$+$_{79}$ $Au^{197,}$ $_{6}C^{12}$+$_{79}Au^{197}$, $_{20}Ca^{40}$ +$_{79}$ Au^{197}) [13]. Although the dynamics for symmetrically heavy nuclei is prominently exposed in experimental and theoretical studies, little attention is paid to the collision of asymmetric nuclei. We, at the same time, know that the symmetry and the isospin play decisive roles in a reaction. We want to discover the fragmentation of asymmetrically colliding pairs.

The mass asymmetry of a reaction can be defined by the asymmetry parameter $\eta = |(A_T - A_P)/(A_T + A_P)|$; where A_T and A_P are the masses of the target and projectile, respectively. The $\eta = 0$ corresponds to the symmetric reactions, whereas non-zero values of η define different asymmetries of a reaction. As noted by FOPI group, the reaction dynamics in a symmetric reaction ($\eta = 0$) can be quite different compared to an asymmetric reaction ($\eta \neq 0$). This is valid both at low and intermediate energies. This difference emerges due to the different deposition of the excitation energy (‘in form of compressional and thermal energies) in symmetric and asymmetric reactions.

In recent years, it has become possible to do exclusive measurements of multifragmentation process. This has been done with streamer chamber detectors, electronic detectors, and 4π detectors. ALADIN [14, 15, 16] group has reported that the mean multiplicity of IMF’s < NIMF >

was found to be same for all targets ranging from Beryllium to Lead and for E/A ranging from 400 to 1000 MeV/nucleon. De Souza et al., [17] observed a linear increase in the multifragmentation of IMF's for central collisions with incident energies varying between 35 and 110 MeV/nucleon.

1.6 Experimental View of multifragmentation:

The nuclear multifragmentation phenomenon was predicted and studied since the early 80's. It is however only with the advent of powerful 4π detectors [18] that real advances were made. Such arrays allow the detection of a large amount of the many fragments and light particles produced in nuclear collisions at intermediate and high energies. Indeed it now appears that further progresses are linked to the knowledge of many observables and the possibility to study correlations inside the multifragment events.

Some of the important experiments performed in recent years are as follow. The first experiments were done at Berkley. The motive behind these experiments was to get the theoreticians and experimentalists aware of the problems and pitfall of the way from medium energy heavy ion collision to equation of state. Later on, several accelerators were built at Michigan state university (USA), GANIL (France), and at GSI (Germany). The SIS (heavy ion synchrotron) accelerator at GSI is specially designed to study the heavy-ion collisions at intermediate energies. The MSU group at Michigan state university is very active in studying the fragment's spectra at lower side of the bombarding energies. Similarly efforts are also made by INDRA group at GANIL. The ALADIN group at GSI has provided complete spectra of the fragments.

The main interest of INDRA collaboration at GANIL is to study the collisions where large multiplicities of the nucleons are observed in the exit channel and they have studied the influence of different parameters on multifragmentation including role of size of system in entrance channel, Coulomb instabilities etc. In particular, the size effects are studied in symmetric collisions of ^{36}Ar+KCl , ^{58}Ni+^{58}Ni, ^{129}Xe+^{118}Sn [19], ^{181}Ta+^{197}Au and ^{238}U+^{238}U. On the other hand the entrance channel effects are studied by keeping the total mass equal to 250 units. Naturally, for studying the gentle compression and Coulomb instabilities, one has to go to heavy fragments. A detailed theoretical study of INDRA experimental findings was carried out by Aichelin and coworkers [20]

The Berkley group has concentrated mainly on the asymmetric reactions like $^{197}Au + ^{27}Al$, ^{51}V, and ^{64}Cu at 60 MeV/nucleon [12]. $^{56}Fe + ^{197}Au$ at 50 and 100 MeV/nucleon etc. Their main motive was to look for probabilities which include the excitation energy, angular distribution and velocity distribution etc. Another symmetric reactions studied were carried out using AMPHORA detector at SARA (France). The MSU group studied reactions like $^{36}Ar+^{197}Au$, $^{129}Xe+^{197}Au$ at 50-110 MeV/nucleon, $^{40}Ar+^{45}Sc$ etc.

Like Berkeley group, National Superconducting Cyclotron Laboratory (NSCL) of Michigan State University (MSU) focus on the asymmetric reactions like $Xe^{129} + C^{12}$, A^{127},V^{51}, Cu^{64}, Y^{89} (50 MeV/nucleon), $Ar^{36} + Au^{197}$, $Xe^{129} + Au^{197}$ (50-110 MeV/nucleon), $Ar^{40} + Cu^{64}$, Ag^{108}, Au^{197} (at 17-115 MeV/nucleon) [13]. The average multiplicity as well as mass of the heaviest fragments is investigated. Apart from asymmetric reactions, nearly symmetric channels $Ne^{20} + A^{127}$, $Ar^{40} + Sc^{45}$, $Kr^{84} + Nb^{93}$, $Xe^{129} + La^{139}$ (15-135 MeV/nucleon) are also investigated[13]. In the experiment of Cd^{114} ion with Mo^{92} at E = 50 MeV/nucleon, the charge correlations, average relative velocities for mid-velocity fragments emission and the size, density, N/Z, E^*/A, E_{flow}/A of the emitted source on the measured isotope ratio was explored [13].

The FOPI and ALADIN groups at GSI are studying the variety of reactions giving nearly all kind of possibilities. It ranges from ^{12}C to ^{208}Pb, and with incident energy between 100 to 1000 MeV/nucleon[21]. A lot of physical conclusions are also drawn from these studies.

Therefore, in the past years a very active program has developed at many places. SIS at GSI has replaced Bevalac as the main accelerator in what is now called intermediate energy (500 MeV/nucleon up to 2 GeV/nucleon). This facility has made a big impact with three new second generation experiments, FOPI, ALADIN and KAOS.

At present, several experimental groups are engaged in extracting information of nuclear EOS from multifragmentation and nuclear flow/fragment flow. Many body nuclear dynamics group at INDIANA University Bloomington, USA studied the role of nuclear equation of state (EOS) in particular how the density dependence of the symmetry energy affects the properties of nuclear matter [22]. TAPS collaboration studied the role of nuclear incompressibility in the production of hard photons in heavy ion collisions [23]. Recently E802 collaboration studied mid rapidity energy distribution [24].

Moreover NA49 collaboration has recently performed a series of measurements of $^{208}_{82}Pb + ^{208}_{82}Pb$ collisions at 20, 30, 40, 80 and 158 MeV/nucleon [25].

With the advent of powerful multidetectors dedicated to the study of multifragmentation, which allow in particular the detection of more complete events, important improvements have been realized in the sorting of data and the construction of global observables. New correlation methods were developed (higher order charge correlations, fragment-particle) to investigate fragment formation mechanism and primary fragment excitation energy. Yield scaling as well as various fluctuation properties were also studied in relation with phase transition. Detailed and instructive comparisons with dynamical and statistical models have been reported.

1.7 Review Of Theoretical Models Used To Study Heavy Ion Collisions at Intermediate Energy:

The study of intermediate energy heavy-ion collision needs correct treatment of nuclear interactions. Naturally if projectile and target are comparatively same (symmetric) then reaction leads to high compression of the system whereas, asymmetric reactions lead to the heat or thermal energies. In theoretical treatment there are many parameters before and after the collision in time scale on which theory can be proposed like incident energies, type of target and projectile, density and impact parameter etc before and flow, rapidity, balance energy and many fluctuation and correlations etc. after the collision. In literature every model is capable of explaining the reaction dynamics to some extent.

The theoretical models for the processes at intermediate energies can be divided into two categories: Statistical and Dynamical model. Example of statistical models include multi-particle phase space models, such as the Statistical Multifragmentation Model (SMM) [18] and the Berlin Multifragmentation Model [26], which can incorporate specific nuclear properties directly. But this model was failed in the study because of its limitations which are as:

1. The situation at the start of reaction is based on some assumption for the degree of thermalization.
2. The statistical models give a better description only of the later/final stage of the reaction.

Hence due to these limitations statistical models were neglected. Therefore this study is possible by the dynamical models only.

In the dynamical approach, the Vlasov equation was coupled with nucleon-nucleon collisions and thus, a new realization, named as Boltzmann-Uehling - Uhlenback equation (BUU) [27], was developed to study the large deviation problems of low, intermediate and relativistic heavy-ion collisions. The BUU equation was solved by test particle method. The one body distribution function is described as a collection of NA test particles, where A is the mass number and N is event number. All possible collisions between the test particles are considered, i.e., there is no division of test particles. In other words, N parallel runs communicate with each other, therefore, event by event correlation cannot be analyzed.

Keeping in mind the requirement of intermediate energy region, one would like to have those methods where correlations and fluctuations among nucleon can be preserved. The Classical Molecular Dynamics (CMD) [28] approach (or the equation of motion), in principle, is capable of predicting the both compression and fragments production. It also incorporates the complete classical N-body dynamics which is necessary to describe the formation of the fragments. The simple Classical Molecular Dynamics models, however, needs major refinements (including 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 and Stocker [11]. This new approach, which explicitly incorporates the N-body correlations as well as nuclear matter equation of state and important quantum features (like the Pauli principle, Stochastic scattering and particle production), was dubbed as Quantum Molecular Dynamics (QMD) model [11].

As discussed above, the dynamical evolution of the nucleus-nucleus collisions is simulated by quantum molecular dynamics (QMD) and the Boltzmann-Uehling-Uhlenbeck (BUU)[27] models as well as their relativistic extensions. With the development of radioactive ion-beam physics, several rather comprehensive isospin-dependent, but mostly semi-classical transport models such as IBUU [29], SMF [30] and IQMD [32] have been successfully developed in recent years to describe nuclear reactions induced by neutron-rich nuclei at intermediate energies [13].

Isospin dependent Quantum Molecular Dynamics (IQMD) [32] model in heavy ion collisions is used for studying the isospin effects on nuclear transverse collective flow, on nuclear radial flow and nuclear fragmentation. The dynamics in the formation of the transient state is mainly governed by three components, namely, the mean field, two body collisions, and Pauli blocking. For an isospin dependent reaction dynamics algorithm, it is essential that all the three components should reasonably include isospin degrees of freedom. In addition, it is also important that, the initialization of projectile and target nuclei, the samples of neutrons and protons in phase space should be treated separately since there exist a large difference between neutron and proton density distributions for nuclei. IQMD model is developed just on above basis. It has been shown that the IQMD can be used with large success for studying the effects of isospin in heavy ion collisions at intermediate energies

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Chapter 2

METHODOLOGY

When we study the heavy ion collisions at non relativistic energies, Multifragmentation can be observed for the central ones, in a range of projectile ion bombarding energies from 50 MeV/nucleon to 1000MeV/nucleon, depending on the properties of the nuclei under consideration.

On the theoretical side heavy ion collisions can be investigated with nuclear fluid dynamics and microscopic transport models. One of the most successful microscopic transport models is the quantum Molecular Dynamics (QMD) model and its extension to relativistic energies, the Isospin dependent Quantum Molecular Dynamics (IQMD). The model we consider for our work is isospin dependent quantum molecular dynamics (IQMD) [1].

2.1 Isospin-dependent Quantum Molecular Dynamics model (IQMD):

The model involves three steps to stimulate the nuclear reactions. These steps are as under:

2.1.1 Initialization:

In the IQMD model, the neutrons and protons are distinguished from each other in the initialization of projectile and target nuclei. The neutron and proton density for the initial projectile and target nuclei are determined by Skyrme-Hartree-Fock method [2]. The IQMD model treats different charge states of nucleons, deltas, and pions explicitly [3]. In this model the baryons are represented by Gaussian –shaped density distributions

$$f_i\,(\vec{r},\vec{p},t)=\frac{1}{\pi^2\hbar^2}\,e^{-[\vec{r}-\vec{r}_i(t)]^2\frac{1}{2L}}e^{-[\vec{p}-\vec{p}_i(t)]^2\frac{2L}{\hbar^2}} \tag{2.1}$$

In IQMD model the centroid of the Gaussians in a nucleus are randomly distributed in a phase space sphere ($r \leq R \; and \; p \leq p_F$) with R =1.12$A^{1/3}$fm corresponding to a ground state density of

ρ_o=0.17fm$^{-3.}$ The Fermi momentum p_F depends upon the ground state density. For ρ_o =0.17fm^{-3}, the value of $p_F \approx$ 268 MeV/c. The momenta are uniformly distributed within a momentum sphere without any local constraints. Therefore the nucleons near the surface, because of low potential energy, are unbound initially. This possibility however gives a reduced binding energy per nucleon as compared to Weizsacker mass formula. So the initialized nuclei are less stable against spurious particle evaporation compared to oriented QMD model.

2.1.1.1 Interaction range:

Recently studies have been done to see the effect of width of the Gaussian wave packet on fragmentation using QMD model [4]. It was observed that the variation of the width *(L)* has a sizable effect on the clusterization. A broader Gaussian binds more nucleons into a fragment. As a result the fragment turns much heavier. The interaction range parameter L influences the interaction density for finite systems. For (homogeneous) infinite nuclear matter the density (and thus the potential energy) does not depend anymore on the extension of the Gaussian wave packets. Thus, the equation of state of infinite nuclear matter is independent of L. In finite matter $E=A$ also depends on L. Thus even two parameterizations which yield the same EOS may produce different results for the reaction of two heavy ions. Therefore we have to adjust L to have reasonable surface properties. In order to allow a physical interpretation L should be in the order of the size one expects for the range of the nuclear interaction. There exists a range of values for L, which allows fixing these properties. Larger values of L increase the effective range of the interaction and thus lead to some smearing of fluctuations, which are stronger for more located wave packets (small values of L). The Gaussian width can be regarded as a description of the interaction range of a particle. Its influence disappears for infinite nuclear matter whereas for finite systems it may play a non negligible role. In IQMD the Gaussian width can be used as an optional input parameter. The system dependence of L in IQMD has been introduced in order to obtain maximum stability of the nucleonic density profiles. As an example for Au + Au a value of L = 8.66 fm^2 is chosen, for Ca + Ca and lighter nuclei L = 4.33 fm^2.

2.1.1.2 Two body collisions

In IQMD model, two different parameterizations of *N-N* cross sections may be used optionally. One of the parameterization which is the isospin independent and the other is the experimental parameterization σ_{exp} which is isospin dependent. It is shown that for experimental parameterization at energies lower than 300 MeV/nucleon, the neutron-proton cross section is about three times larger than the neutron-neutron or proton-proton cross section [6].

2.1.1.3 Pauli blocking

Whenever a collision occur, in the phase space we assume that each nucleon occupies a six dimensional sphere with a volume of $h^3/2$ and then calculate the phase volume V, of the scattered nucleons being occupied by the rest nucleons with the same isospin as that of the scattered ones. Then we compare $2V/h^3$ with a random number and decide whether the collision is blocked or not. So the Pauli blocking is isospin dependent. Pauli blocking of neutron and proton is treated separately.

2.1.2 Propagation

The successfully initialized nuclei are then boosted towards each other with a proper center of mass velocity using relativistic kinematics. The nucleons of target and projectile interact via two and three body Skyrme forces and the Yukawa potential. The isospin degree of freedom is treated explicitly by employing a symmetry potential and explicit Coulomb forces between the protons of colliding target and projectile. All this provide us a correct distribution of protons and neutrons within the nucleus.

The Hamilton equations of motion for the propagation of hadrons are

$$\frac{dr_i}{dt} = \frac{d\langle H\rangle}{d\,p_i}; \qquad (2.2)$$

$$\frac{dp_i}{dt} = -\frac{d\langle H\rangle}{d\,r_i} \qquad (2.3)$$

2.1.2.1 Potentials used in IQMD

A total Hamiltonian function with a kinetic energy T and a potential energy V is given by

$$\langle H\rangle = \langle T\rangle + \langle V\rangle$$

$$= \sum_i \frac{{p_i}^2}{2m_i} + \sum_i \sum_{j>i} \int f_i(\vec{r}, \vec{p}, t) V^{ij}\left(\overrightarrow{r'}, \vec{r}\right)$$

$$\times f_j(\overrightarrow{r'}, \overrightarrow{p'}, t) d\vec{r} d\vec{r}' d\vec{p} d\vec{p}' \quad (2.4)$$

The potential in equation (2.4) is the sum of the following specific elementary potentials,

$$V = V_{Sky} + V_{Yuk} + V_{Coul} + V_{mdi} + V_{loc} \quad (2.5)$$

With a local hard core repulsion,

$$V_{loc} = \sum_i \sum_{j>i} t_1 \delta(\vec{r}_i - \vec{r}_j)$$

$$+ \sum_i \sum_{j>i} \sum_{k>j} t_2 \delta\left(\vec{r}_i - \vec{r}_j\right) \delta(\vec{r}_i - \vec{r}_k), \quad (2.6)$$

The Yukawa short-range term,

$$V_{Yuk} = \sum_i \sum_{j>i} t_3 \frac{\exp\left(\left|\vec{r}_i - \vec{r}_j\right|/\mu\right)}{\left(\left|\vec{r}_i - \vec{r}_j\right|/\mu\right)} \quad (2.7)$$

The Yukawa potential V_{Yuk} in IQMD is very short ranged and weak ($\mu = 0.4$ fm). Additional attractive Yukawa forces hence modify the EOS. Yukawa potential stabilize the nuclei because of the increase of the interaction range as compared to a δ-like Skyrme potential. Thus nucleons notice earlier that they will arrive at the surface and are more effectively deaccelerated without this potential. In addition the fluctuations are reduced.

And the momentum dependent interaction

$$V_{mdi} = \sum_i \sum_{j>i} t_4 \ln(1 + t_5 (\vec{p}_i - \vec{p}_j)^2) \delta(\vec{r}_i - \vec{r}_j) \quad (2.8)$$

The IQMD-model offers rather stable density distributions and good energy conservation, however for the price of nucleon evaporation and improper binding energies (E_{bind} ≈ 4-5 MeV/nucleon for heavy nuclei instead of 8 MeV/nucleon). In addition to the potential used in QMD, a symmetry potential between protons and neutrons corresponding to the Bethe-Weizsacker mass formula has been included

$$V_{Sym}^{ij} = t_6 \frac{1}{\rho_o} T_3^i T_3^j \delta\left(\vec{r}_i' - \vec{r}_j\right) \qquad (2.9)$$

Where T_3^i and T_3^j denote the isospin projections of particles i and j. Other baryonic potentials like V_{Sym}^{ij} and V_{mdi} are defined isospin-independent like in all other flavors. The parameters are propagated under the total interaction calculated by the Hamiltonian equations of motion (2.2) and (2.3)

Parameters used in equation (2.6) to (2.9) are shown in table below:

IQMD parameters	
t_3	15 MeV
t_4	1.57 MeV
t_5	5.10^{-4} MeV^{-2}
t_6	25 MeV
μ	0.4 fm

Table 2.2: IQMD parameters used in equation (2.6) to (2.9)

2.1.3 Collision

During the propagation, two nucleons are supposed to suffer a binary collision if the distance between their centroids is

$$|r_i - r_j| \leq \sqrt{\frac{\sigma_{tot}}{\pi}}\ , \sigma_{tot} = \sigma(\sqrt{s}, type), \tag{2.10}$$

'$type$' denotes the ingoing collision parameter (*N-N, N-*Δ*, N-*π*, etc.)*. And $\sqrt{s}$ is the c.m. energy in GeV. Pions are formed model via the decay of delta resonances. The colliding particles can scatter elastically as well as inelastically. The main processes include:

$$\text{Elastic}\begin{cases} N + N \rightarrow N + N & (a) \\ N + \Delta \rightarrow N + \Delta & (b) \\ \Delta + \Delta \rightarrow \Delta + \Delta & (c) \end{cases}$$

$$\text{Inelastic}\begin{cases} N + N \rightarrow N + \Delta & (d) \\ N + \Delta \rightarrow N + N & (e) \end{cases}$$

Experimental cross sections are used for the processes *(a)* and *(d)*. The cross section for *(e)* is obtained by the detailed balance method. The cross section for processes *(b)* and *(c)* are taken to be same as that of process *(a)*.

In addition to this the Pauli blocking of baryons is also taken into account by checking the phase space densities in the final state. The final phase space fractions P_i and P_j , which are already occupied by other nucleons, are determined for each of the scattering baryons. For each collision the phase space densities in the final state are checked in order to assure that the final distribution in phase space is in agreement with the Pauli principle ($P \leq 1$). The collision is then blocked with a possibility

$$P_{block} = 1-(1-P_i)(1-P_j) \tag{2.11}$$

Where P_i and P_j are the already occupied phase space fractions by other nucleons.

2.2 Method of clusterization:

Minimum spanning tree method (MST)

One of the most extensively used methods to clusterize the nucleons is Minimum Spanning Tree (MST) method [7, 8]. According to this method two nucleons share the same fragment if their centroids are closer than a distance d_{min},

$$\left|\vec{r}_i - \vec{r}_j\right| \leq d_{min}$$

Where $\vec{r}_i$ and $\vec{r}_j$ are the spatial positions of both nucleons. The value of d_{min} can vary between 2-4 fm. It has small effect on multifragmentation [9, 10]. However, this method can not address the question of time scale as it will give a big fragment at the time of highest density when the interactions between the nucleons are still active. This method can only be used to analyze asymptotic configuration in which the fragmenting system can be viewed as a very dilute mixture of free particles and almost equilibrated fragments.

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Chapter 3

PHASE SPACE ANALYSIS

3.1 Introduction:

In the previous chapters, we have discussed about the heavy ion reactions at intermediate energies and the related models. Heavy ion collisions have always played a fascinating role in exploring various aspects of nuclear dynamics such as fusion-fission, multifragmentation and particle production. At low incident energies fusion is dominating the dynamics. At high energies evaporation of the nuclear matter takes place. At intermediate energies multifragmentation plays an important role.

In this chapter, the phase space simulations of heavy ion collisions for different symmetric and asymmetric systems are presented. Influences of different cross section have been discussed for analyzing the phase space generated using IQMD model.

3.2 Time Evolution of a Heavy Ion Collision:

Figure 3.1, sketches schematically a typical heavy-ion reaction. When two nuclei approach each other, their orientation in space and the initial beam direction define the reaction plane. The impact parameter (b) vector beam is located in the reaction plane.

(1) Initial Phase: When the two matter distributions approach each other and start to overlap, the properties of the nucleon nucleon (NN) interaction in free space will be visible in the scattering process. Nucleons at the surfaces will reflect the Lorentz-force-like behavior of the NN interaction most directly. They will be deflected outward and, because of symmetry for finite impact parameter, will show an enhancement in the reaction plane [1-5].

(2) High Density Phase: Once the matter distributions of the projectile and target overlap, the properties of the NN interaction are not well known. At incident beam energies, that exceed the velocity of sound in nuclear matter at ground-state nuclear-matter density (ρ_s= 2) [6], the nucleons cannot escape fast enough and a zone of high density is formed. Many-body effects that are present even at normal nuclear-matter densities can occur, as well as modifications of the properties of the constituents (medium effects)[6].

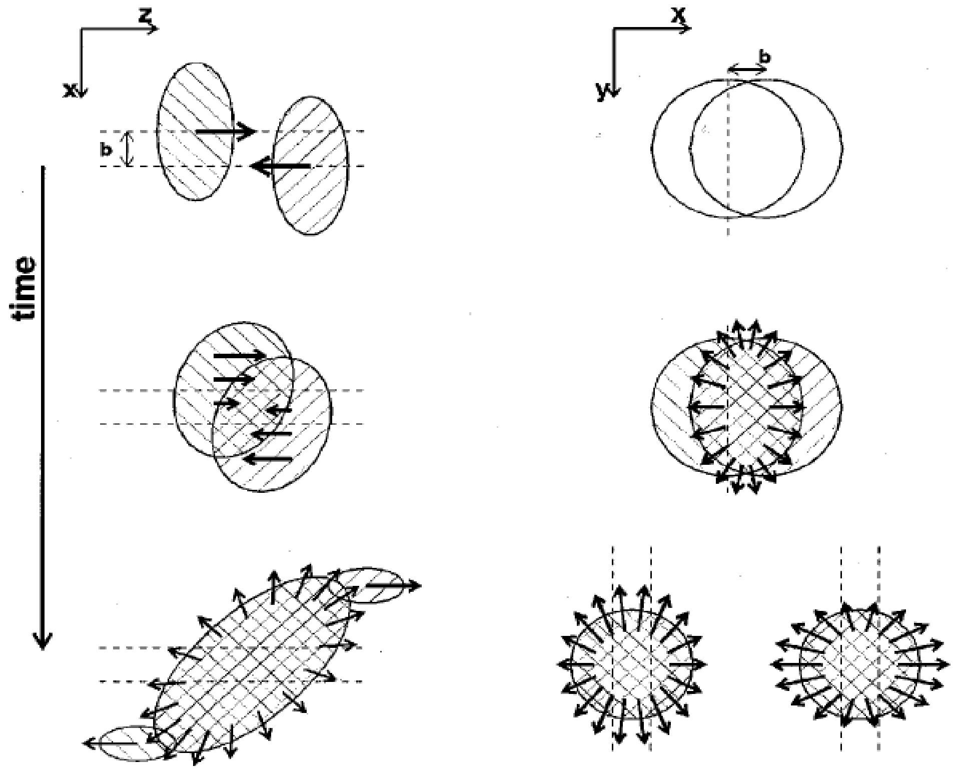

Figure 3.1: Schematic view of the time evolution of a heavy-ion collision.

(3) Expansion: The next stage in the reaction scenario is the relaxation of the energy density. The central system is undergoing expansion, thereby reducing its temperature and density. For symmetric collisions, the expansion is azimuthally symmetric for central collisions. For reactions with finite impact parameter, where an oriented velocity field might have survived the compression phase, the situation is much more complicated. The expansion now has a directed velocity field superimposed. The system always expands into the direction of the largest gradients in density and temperature. In transverse direction, the initial expansion is largest in the direction of the reaction plane. In longitudinal direction, the expansion scenario depends on the degree of stopping. For a high degree of stopping and given the fact that the nuclei are Lorentz contracted in this direction, the pressure gradient is largest along the beam direction; therefore, the system relaxes predominantly longitudinally.

(4) Freeze-Out: The reaction stops at a point commonly referred to as freeze-out. At this point the densities are small enough that during a typical path length, no further interaction will occur.

In the next sections, we will present the analysis of coordinate phase space and momentum phase space of a heavy ion collision at intermediate energy

3.3 Results and Discussion of Phase Space:

For the present study, we have simulated symmetric and asymmetric reactions for a single event. Symmetric reaction taken is $^{208}Pb_{82}$ + $^{208}Pb_{82}$ and asymmetric reaction is $^{12}C_6$ + $^{197}Au_{79}$. These reactions have been stimulated by using Isospin dependent Quantum Molecular Dynamics (IQMD) at incident energy 400 MeV/nucleon. The phase space of symmetric and asymmetric reactions by having the isospin dependent cross section, σ_{iso} ($3\sigma_{nn} = 3\sigma_{pp} = \sigma_{np}$) as well as by having isospin independent cross section, σ_{noiso} ($\sigma_{nn} = \sigma_{pp} = \sigma_{np}$) have been discussed in the following section.

3.3.1 Coordinate Phase Space Analysis:

3.3.1.1 Comparison of Phase Space for Symmetric and Asymmetric Systems:

First of all, we display the coordinate phase space for symmetric system i.e. $^{208}Pb_{82}$ + $^{208}Pb_{82}$ reaction and asymmetric reaction i.e. $^{12}C_6$ + $^{197}Au_{79}$ at 400 MeV/nucleon and at central collision i.e. b = 0 and at various time steps. The panels from top to bottom are representing the position of nucleons of projectile and target at different times. Here fig 3.2 represents the front view (X-Z planes) of the coordinate phase space of symmetric heavy ion reaction.

In the symmetric collision, the nucleons follow the spherical distribution; the asymmetric collisions do not follow any particular kind of distribution. The nucleons in asymmetric collisions are randomly scattered having more concentration around target (i.e. $^{197}Au_{79}$) nuclei.

During the initial stages of a heavy ion reaction, the projectile and target are far apart i.e. whole of the matter is in the form of spectator only. As the projectile and target approach each other and nuclei overlaps, the density of the system increases, which lead to the collision of the two nuclei. For central collisions, almost all the nucleons take part in the collision, while the situation is quite different for highly asymmetric nuclei. After the collision, the two nuclei breaks up into fragments and the formation of various fragments of different masses takes place such as LMF's($2 \leq A \leq 4$), MMF's($5 \leq A \leq 9$) and IMF's($5 \leq A \leq A_{tot}/6$).

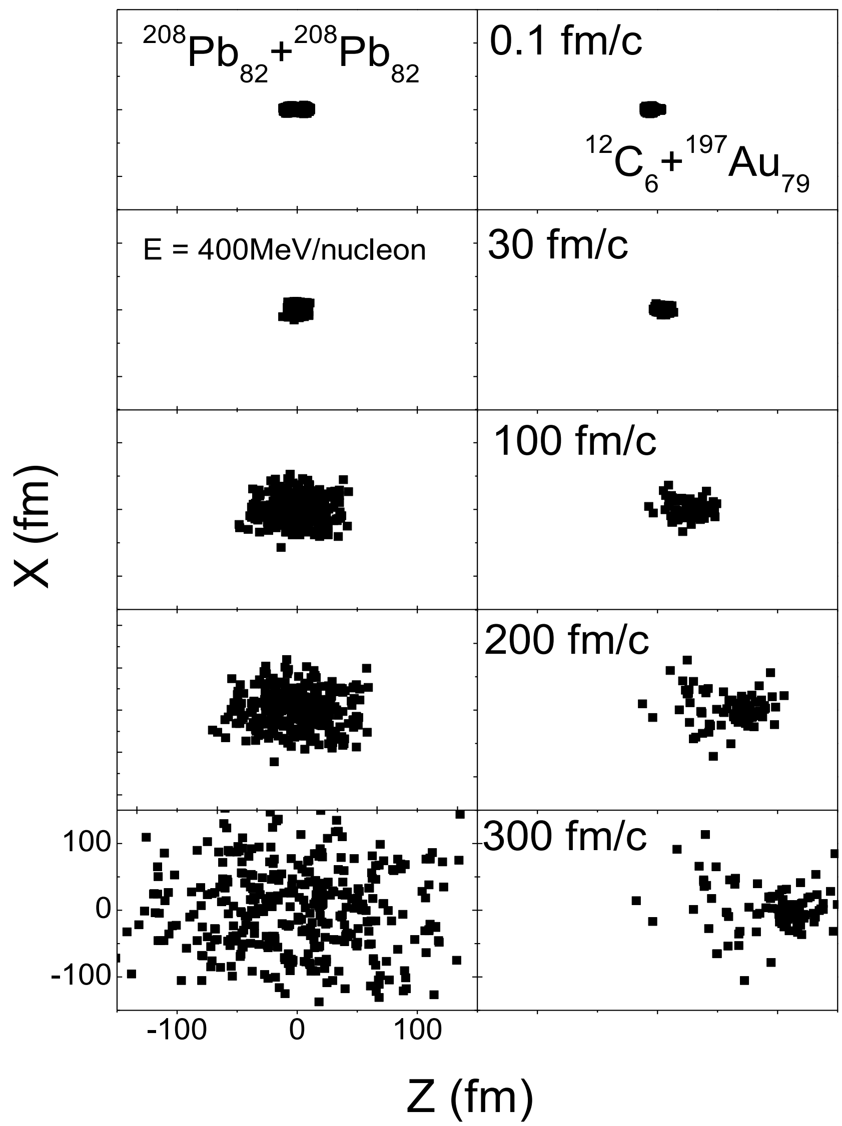

Fig 3.2 Phase space distribution of the projectile and target having symmetric nuclei (left panel) and having asymmetric nuclei (right panel). The symmetric reaction under study is $^{208}Pb_{82}+^{208}Pb_{82}$ and asymmetric reaction under study is $^{12}C_6 +^{197}Au_{79}$ at 400MeV having central impact parameter. The panels from top to bottom are showing the various time steps.

As it can be seen from the figure, that for a symmetric reaction, large number of fragments are formed while for asymmetric reactions quite less number of fragments are formed. Also the phase space is much more scattered for asymmetric system as compared to symmetric system. The reaction dynamics in a symmetric reaction can be quite different compared to asymmetric reactions. This is due to the deposition of excitation energy in the form of compressional energy and thermal energy in symmetric and asymmetric reactions, respectively.

3.3.1.2 Comparison of Phase Space with Cross Section:

Here the phase space for symmetric nuclei with isospin dependent cross section and without isospin dependent cross section has been displayed. In the figure the left panels shows the phase space for symmetric reaction i.e. $^{208}Pb_{82}$+$^{208}Pb_{82}$ at energy equal to 400MeV/nucleon for central impact parameter with isospin dependent cross section,σ_{iso}. And the right panel shows the phase space for the same reaction but with the no isospin dependent cross section, σ_{noiso}. The panels from top to bottom are showing the various time steps.

The role of isospin independent cross section can be clearly seen from the figure 3.3 and figure 3.4. It can be seen from the phase space figure 3.3 that the scattering of the symmetric nuclei with isospin dependent cross section is more as compared to symmetric nuclei with no isospin dependent cross section. This is due to the fact that collision among neutron - protons are attractive, while replusive for proton - proton and neutron-neutron with isospin dependent cross section. The scattering of nucleons takes at a relatively large time for the system having isospin independent cross section (right panel). It has been clearly seen that the system scatters at 100fm/c for isospin dependent cross section while no significant scattering occurs at same time for without isospin independent cross section.

Similarly, from the figure 3.4 it can be seen that for the mass asymmetric collision, $^{12}C_6$+$^{197}Au_{79}$ $_{the}$ scenario is the same as for the symmetric system with the difference that the distribution is not spherical as that is in the case of symmetric nuclei. The scattering in case of asymmetric collision is less for no isospin dependent cross section as compared to isospin dependent cross section.

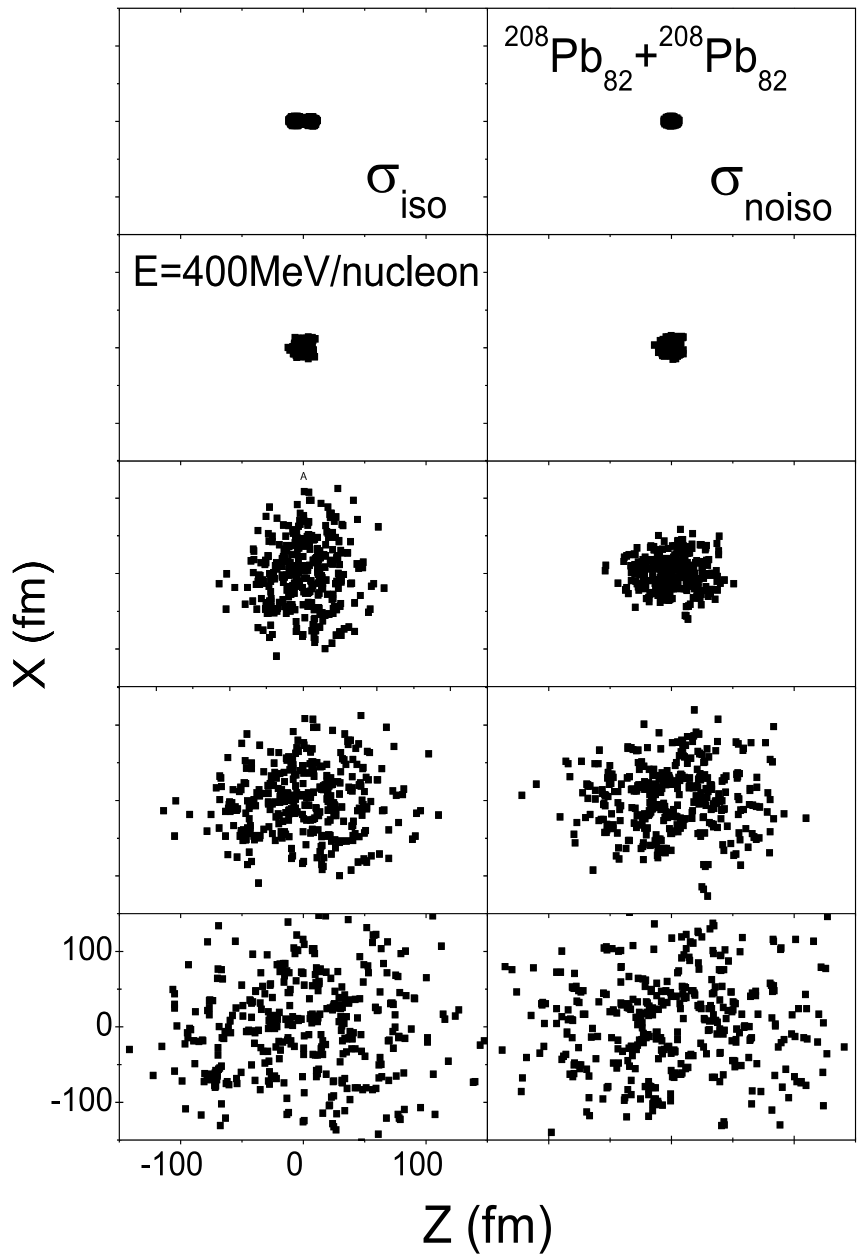

Fig: 3.3: Phase space for symmetric nuclei with (left) and without (right) isospin dependent cross section in the X-Z plane. The panels from top to bottom are showing the increasing time steps(fm/c) as shown in fig 3.2.

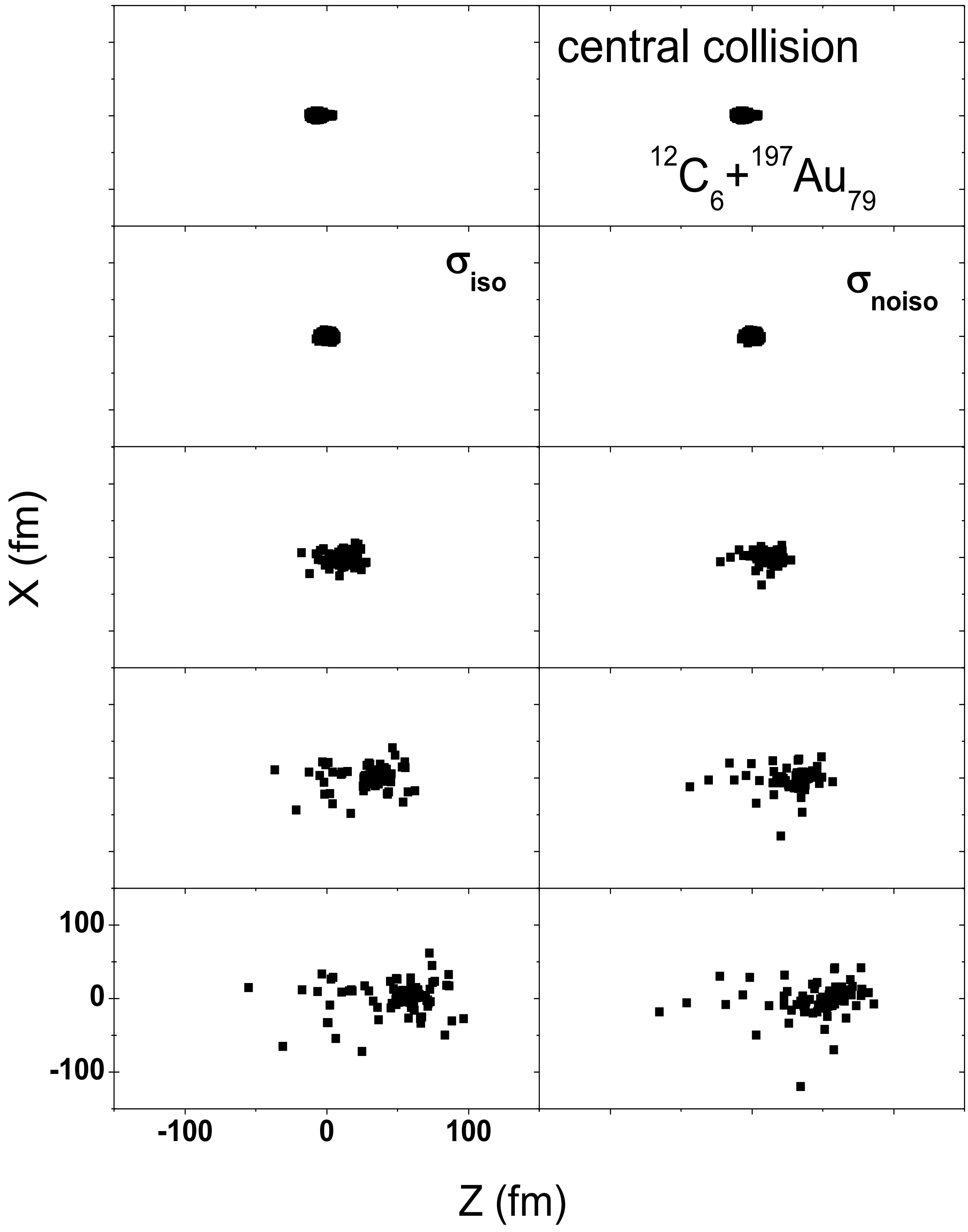

Fig 3.4: Same as fig.3.3 but for asymmetric system, $^{12}C_6$ + $^{197}Au_{79}$

3.4 Momentum Phase Space

3.4.1 Effect of Cross Section on Momentum Phase Space:

In this section the time evolution of symmetric reaction and mass asymmetric reaction at 400Mev/nucleon and b = 0 fm in momentum phase space (p_x vs p_z) have been displayed. It has seen in the last section that for the coordinate phase space, after the collision, the formation of light particles and heavy residual can be seen.

It has been observed that in contrast to coordinate phase space, the momentum phase space is less affected. In case of mass asymmetric system the momentum phase space is concentrated in small region with isospin dependent cross section compared to isospin independent cross section.

3.5 Summary:

From the above discussions of various coordinate and momentum phase space figures, it is concluded that multifragmentation is also dependent on mass asymmetry and cross section in addition to its dependence on impact parameter, incident energy and equation of state. The distribution of the nucleons is not the same for the symmetric and mass asymmetric collisions.

In the next chapter, the discussion will be on the effect of cross section and mass asymmetry in comparison to symmetric collisions on various parameters like time evolution of density, time evolution of number of number of allowed collisions and also on the multiplicity of fragments formed.

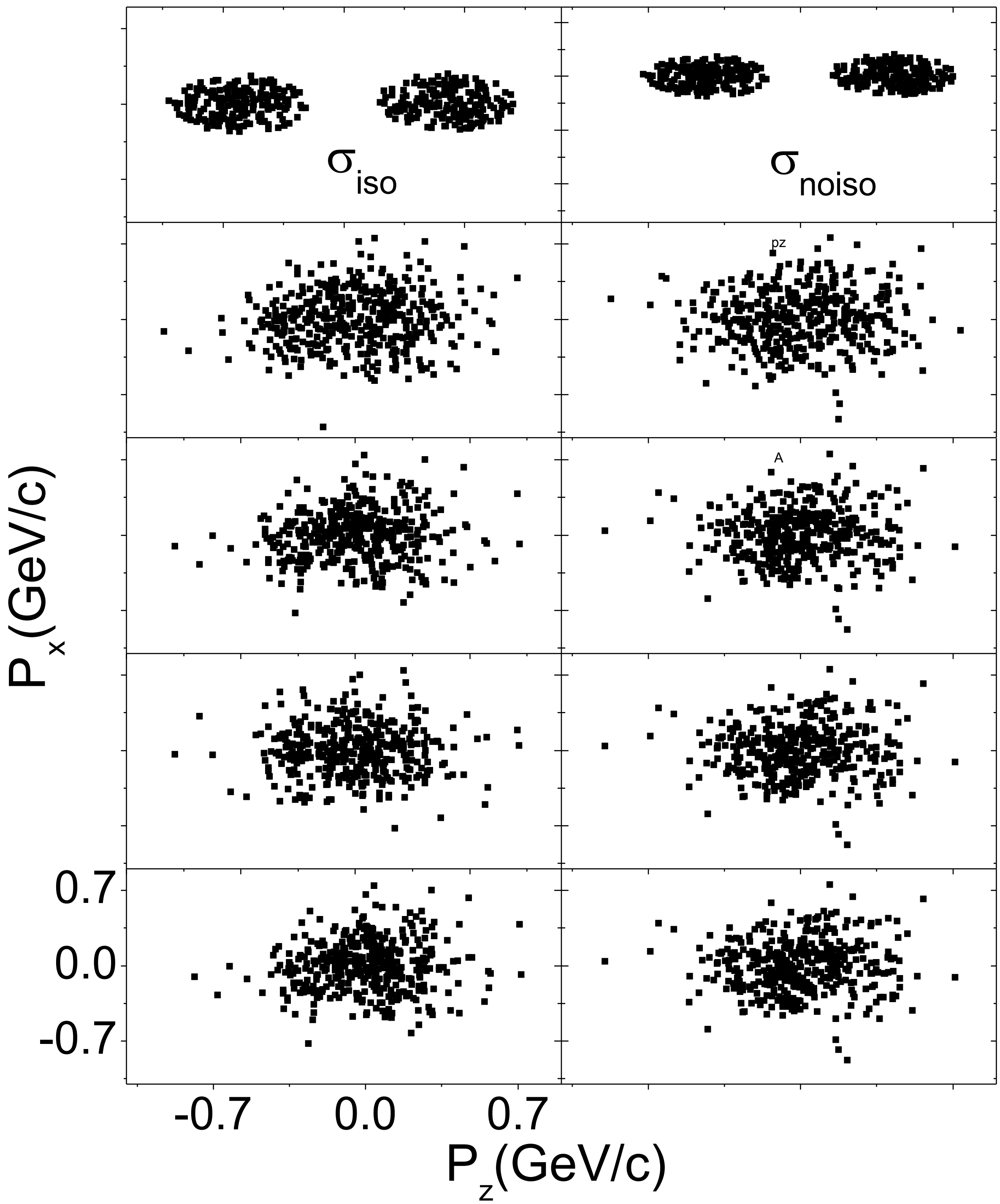

Fig: 3.4: Same as fig 3.2 but for momentum phase space.

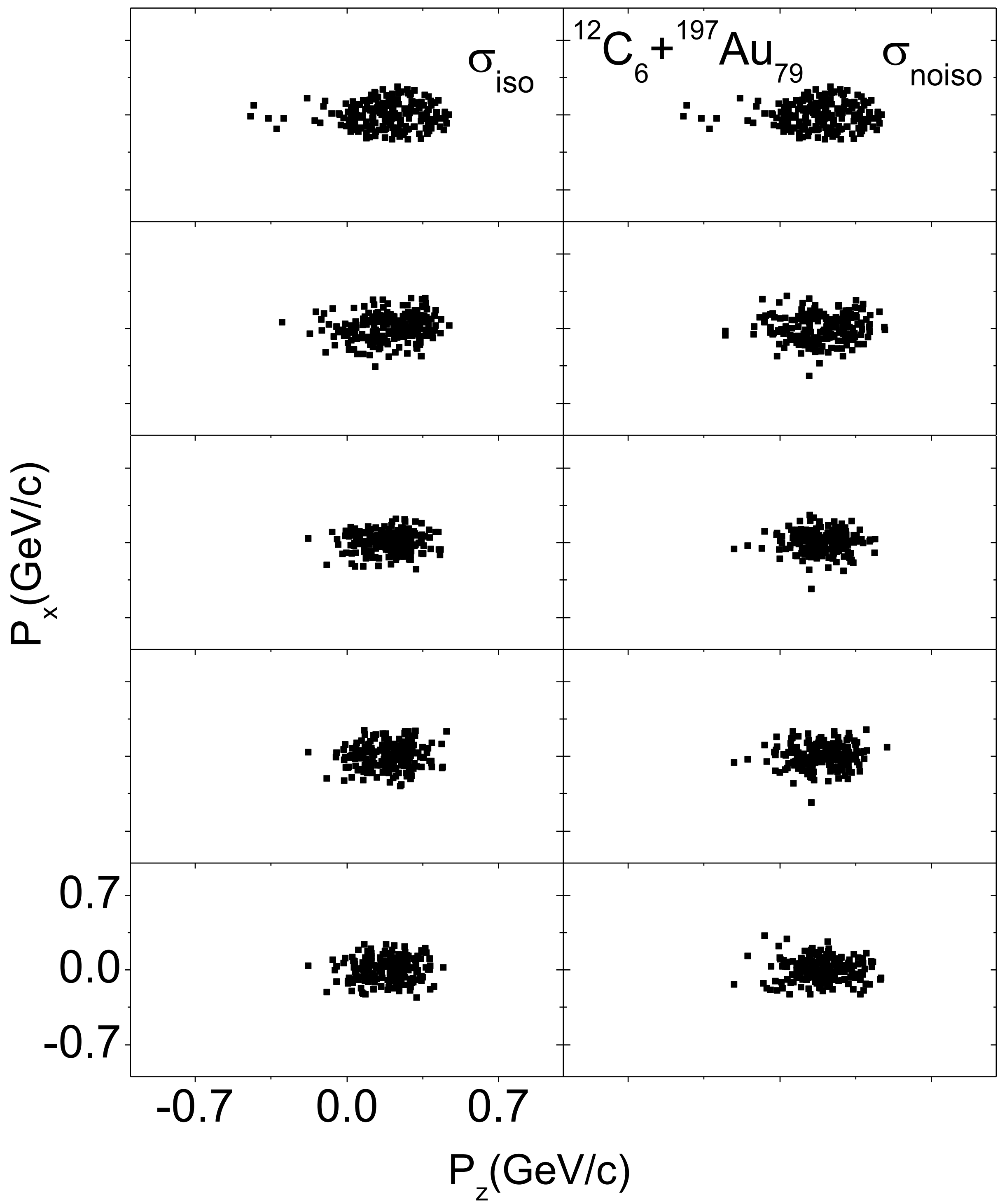

Fig: 3.5: Same as fig3.3 but for momentum phase space. The asymmetric reaction under study is $^{12}C_6 + {}^{197}Au_{79}$.

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Chapter 4:

Influence of Mass Asymmetry on Nuclear Reaction Dynamics:

The mass asymmetry of a reaction can be defined by the asymmetry parameter $\eta = |(A_T - A_P)/(A_T + A_P)|$; [1] where A_T and A_P are the masses of the target and projectile, respectively. The $\eta = 0$ corresponds to the symmetric reactions, whereas non-zero values of η define different asymmetries of a reaction. As noted by FOPI group [2-6], the reaction dynamics in a symmetric reaction ($\eta = 0$) can be quite different compared to an asymmetric reaction ($\eta \neq 0$). This is valid both at low and intermediate energies. This difference emerges due to the different deposition of the excitation energy (in form of compressional and thermal energies) in symmetric and asymmetric reactions.

4.1 Results and Discussion:

For the present study, we have stimulated symmetric and asymmetric reactions for 1000 events. Symmetric reactions include $^{40}Ca_{20} + ^{40}Ca_{20}$ and $^{208}Pb_{82} + ^{208}Pb_{82}$ both having $\eta = 0$. Asymmetric reactions include $^{12}C_6 + ^{197}Au_{79}$ having $\eta = 0.8$ and $^{40}Ca_{20} + ^{208}Pb_{82}$ $\eta = 0.6$. Simulations are carried at incident energies ranging from 50 MeV/nucleon to 1000 MeV/nucleon. The collision geometry is varied from central to non-central/peripheral one. Calculations have been done once by taking the isospin dependent cross section (σ_{iso}) i.e $3\sigma_{nn} = 3\sigma_{pp} = \sigma_{np}$ and once by taking the isospin independent cross section (σ_{noiso}) i.e $\sigma_{nn} = \sigma_{pp} = \sigma_{np}$. During this study the soft nuclear equation of state (NEOS) has been used.

The phase space generated using Isospin Quantum Molecular Dynamics (IQMD) model is analyzed by using Minimum Spanning Tree (MST) clusterization method.

The results obtained are discussed in the following section:

4.2 Time evolution of allowed nucleon-nucleon collisions:

Fig 4.1 and Fig 4.2 shows time evolution of allowed collisions for symmetric and asymmetric reactions by using isospin dependent cross section (σ_{iso}) and isospin independent cross section (σ_{noiso}) respectively at incident energy 50 MeV/nucleon and 400 MeV/nucleon. From the figure it is clear that the number of allowed collisions is more for heavier system. It has been observed that collision rate depends on the participant zone and incident energy. This is due to the fact that higher incident energies destroy most of the initial correlations among nucleons, leading to highly unstable compressed zone, which does not sustain for a longer time and as a result fast emission of nucleons occur. It is also observed experimentally that a little change in fragmentation yield takes place beyond 400 MeV/nucleon [8].

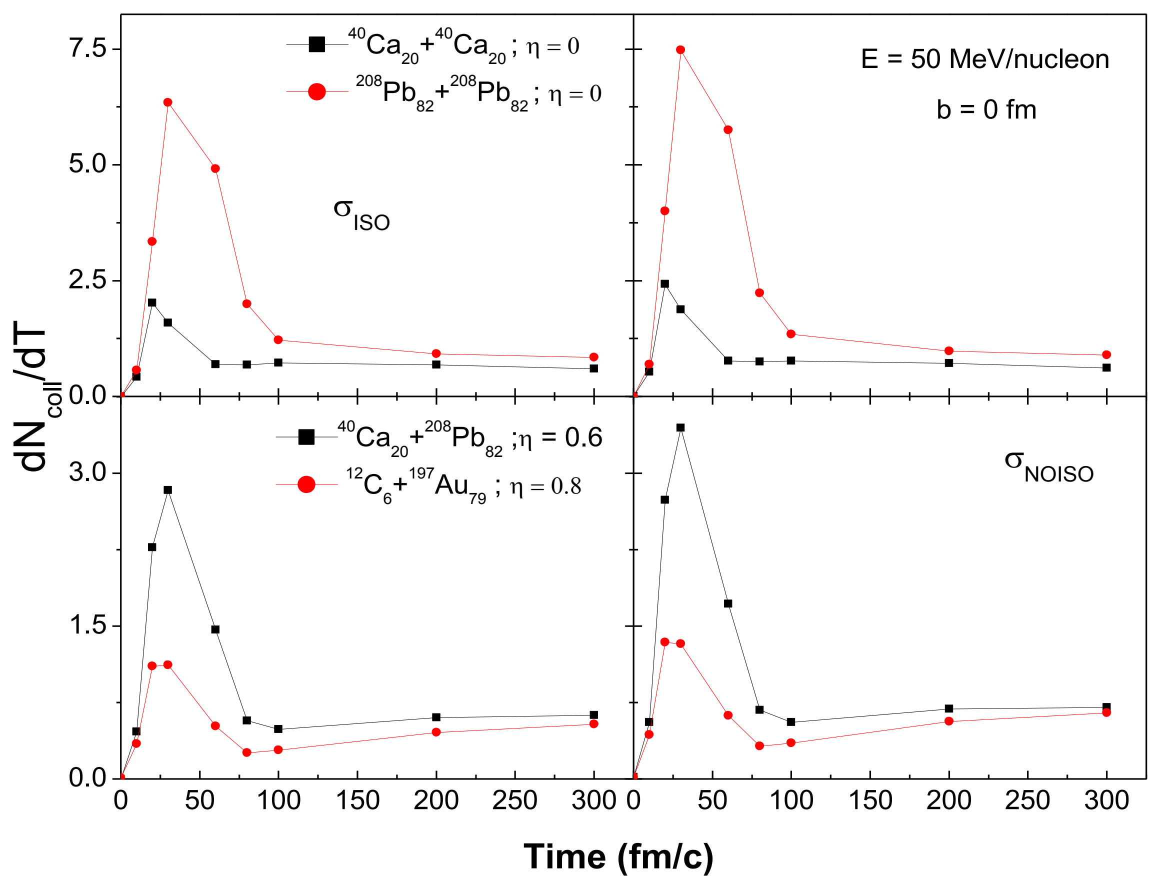

Figure 4.1: Time evolution of allowed collisions.The top panel shows the symmetric reactions and the bottom panel represents the asymmetric reactions for central geometry. The left panel represents the plot at 50MeV/nucleon and right panel represents at 400MeV/nucleon. The figure represents the collision with isospin dependent cross section.

From the figure 4.1 and 4.2 it is seen that the number of collisions are more with isospin independent cross section as compared to isospin dependent cross section. On the other hand, from the figure 4.2 it is seen that with increase in incident energy, collision rate is found to increase with the probability of break-up of initial correlations among the nucleons. At semi-peripheral geometries, the participant zone decreases and hence decrease is observed in the number of collisions at low as well as high incident energies compared to central geometries [11].

Mass asymmetry plays a significant role. Number of collision for η = 0.6 and η = 0.8 are approximately less than 50% for asymmetric reaction compared to symmetric reaction. Because the number of particles participating in the collision dynamics are very less for asymmetric reactions.

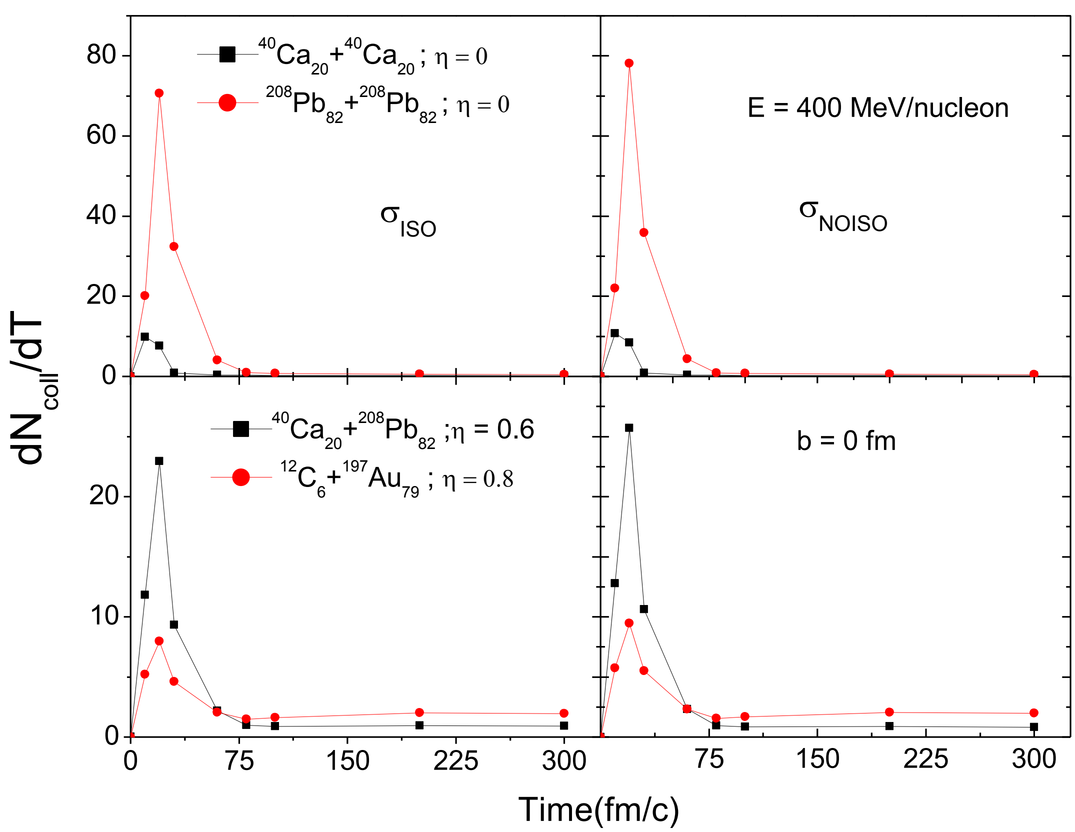

Figure 4.2: Same as figure 4.1 but at 400MeV/nucleon

4.3 Time evolution of various fragments:

In the last section, the time evolution of the allowed collisions is displayed. In this section the time evolution of various fragments formed during multifragmentation have been discussed. Now it is clear from the discussion of above figures that isospin independent cross section and mass asymmetry of the system is having considerable effect on the dynamics of a heavy ion nuclear reaction at intermediate energies. In order to see the effect of isospin independent cross section and mass asymmetry on the fragments formed during multifragmentation, the time evolution of various fragments such as free nucleons($1 \leq A \leq 1$), light mass fragments($2 \leq A \leq 4$) and intermediate mass fragments($5 \leq A \leq A_{tot/6}$) have been displayed in the following figures. These fragments are formed during the collision at central geometry, with soft equation of state and at energy 50 MeV/nucleon. The fragments formed at time 200 fm/c (typical saturation time) have been taken for the present analysis.

First of all the time evolution of free nucleons during the symmetric as well as asymmetric heavy ion collision with isospin dependent and isospin independent cross section have been displayed at b = 0 fm in the fig 4.3. In the figure the left panels show the symmetric systems while the right panels show the asymmetric systems. It can be clearly seen from the fig. 4.3 that there is no change in the multiplicity of free nucleons with time for isospin dependent cross section and isospin independent cross section. This is due to the reason that free nucleons are emitted from the interaction range. Therefore isospin independent cross section does not have much effect on the multiplicity of free nucleons with evolution of time.

At low energies, few nucleons are emitted from the excited compound nucleus which is followed by the emission of the LMF's. In some cases (especially at non central collisions), the excited system decays in two steps:

i. It fissions into two parts (the binary break up) and
ii. These fissioned products emit nucleons/LMF's during the simulations, a group of nucleons can come closer and form a fragment in many cases, these fragments are not properly bound and thus emit nucleons/LMF's before cooling down. In other words, the nucleons/LMF's and the remaining part is a heavy residual fragment [10].

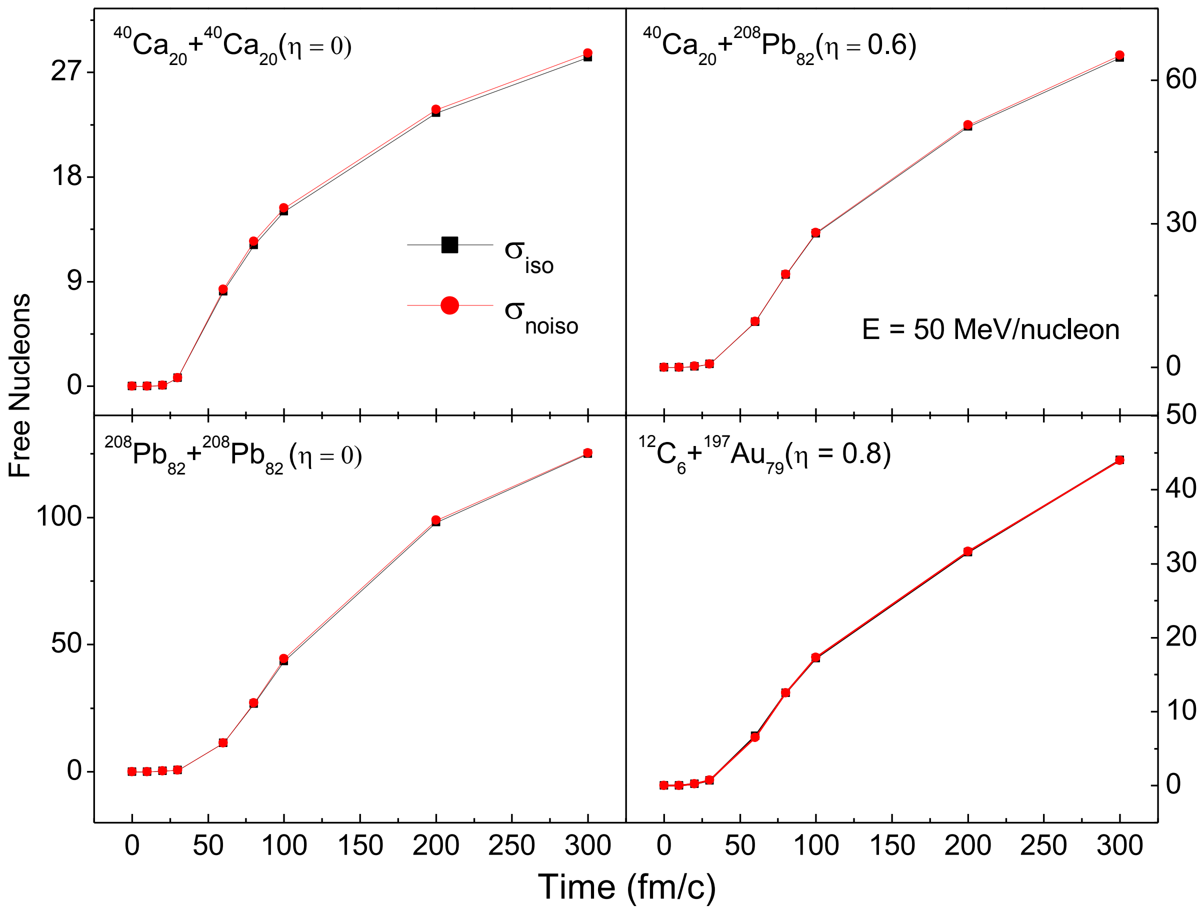

Figure 4.3: Time evolution of free nucleons for different symmetric systems (upper panels) and asymmetric systems (lower panels) at central geometry with isospin dependent cross section (left panel) and isospin independent cross section at 50MeV/nucleon.

Now the time evolution of light mass fragments (LMF'S), 2≤A≤4 at same conditions as the free nucleons have been displayed in the fig 4.4. It can be seen from the figure that the trend for light mass fragments for symmetric as well as for asymmetric colliding nuclei remains the same. More number of LMF's are formed for symmetric systems as compared to mass asymmetric systems at 50MeV/nucleon. At the start of the reaction a minimal number of LMF's are produced but as the time increases the number of light mass fragments goes on increasing. The role of cross section can be clearly seen from the figure. The difference between the two cross sections isospin dependent and isospin independent is more pronounced for asymmetric colliding nuclei than symmetric colliding nuclei. This is because of the reason that the dynamics governing the symmetric and asymmetric reactions are totally different. Also the LMF's are produced from the participant zone, therefore the less number of LMF's will be produced as compared to free nucleons.

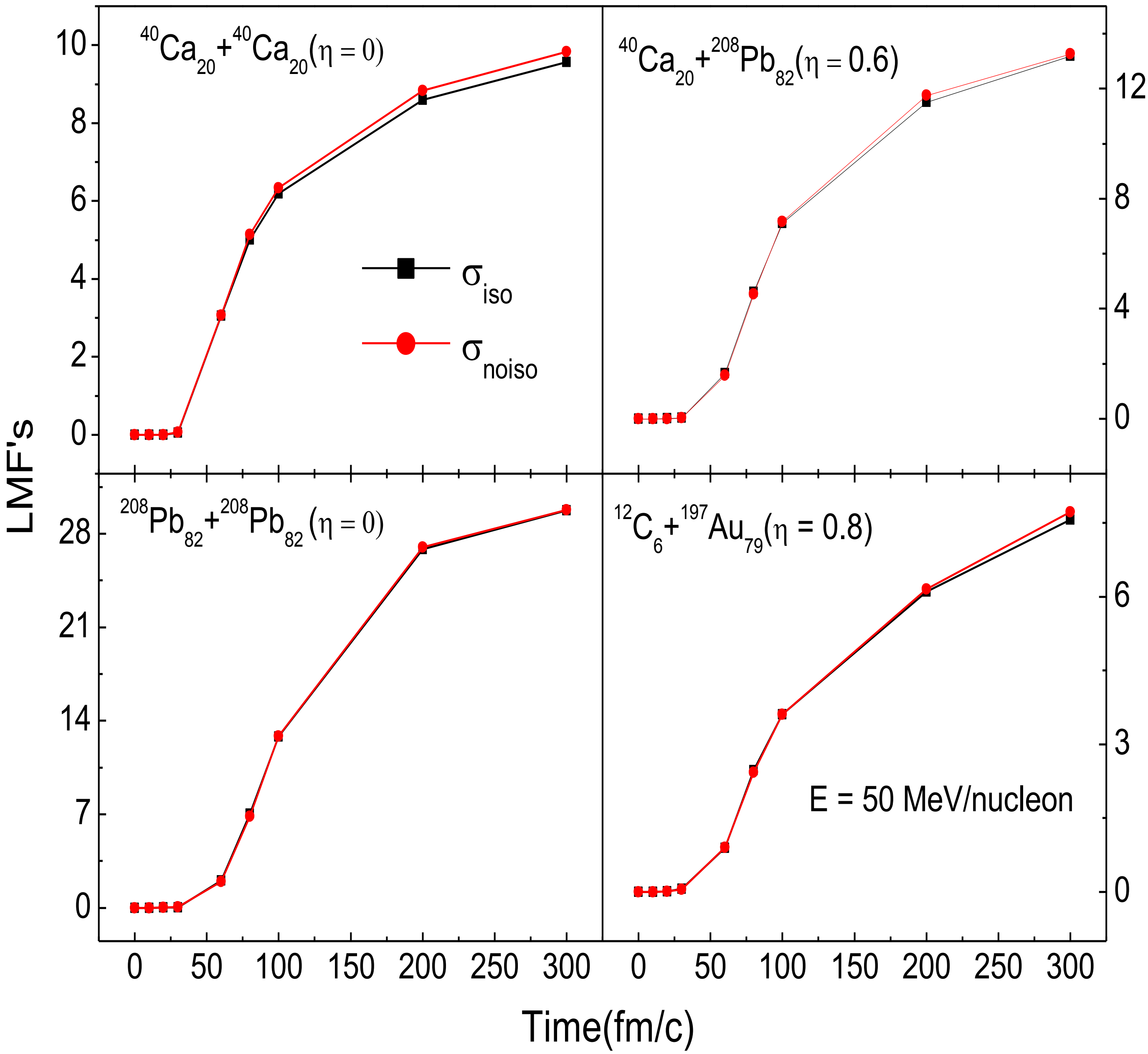

Figure 4.4: Same as figure 4.5 but for light mass fragments (LMF's), 2≤A≤4.

In the fig 4.5 the time evolution of intermediate mass fragments ($5 \leq A \leq A_{tot/6}$) has been displayed at the same conditions as the free nucleons and intermediate mass fragments have been displayed in the fig4.3 and fig 4.4 respectively. It can be seen from the figure 4.5 that the intermediate mass fragments show a rise and fall in multiplicity with time. In the case of IMF's, the role of mass asymmetry can be clearly seen.

As the asymmetry of the reaction increases, the participant zone decreases. Hence the less number of IMF's are produced for more asymmetric reactions. The role of isospin independent cross section is significant here in case of IMF's, as the IMF's are produced from the spectator's zone. The multiplicity of IMF's increases with isospin independent cross section while the asymmetric reactions follow the reverse trend.

We observe a delayed emission of all type of fragments using MST method which is due to the fact that the normal MST method depends on the spatial distance. Due to frequent nucleon-nucleon collisions in central collision geometry, an appreciable part of the nuclear matter is in the form of emitted nucleons and most of initial correlations among nucleons are destroyed which leads to the creation of unstable/unbound fragments. These fragments decay after a while and therefore, one has to follow the reaction dynamics for quite long time to obtain the stable and properly bound fragments. Lot of efforts have been made to avoid the creation of unbound/unstable/weakly bound fragments [12, 13, 14]

4.4 Dependence of total mass of the system on the various fragments formed:

The discussion on the time evolution of various fragments and the effect of mass asymmetry and isospin independent cross section on the fragments formed, motivate us to study the multiplicity vs. total mass of the system. In the present calculations, we are using soft nuclear equation of state. A simple spatial clusterization algorithm dubbed as minimum spanning tree method is used to clusterize the phase space.

In fig.4.6 the multiplicity of various fragments is displayed as a function of total mass of the system at time 200fm/c at energy ranging from 200MeV/nucleon to 1000MeV/nucleon. The total mass of these reactions $^{40}Ca_{20}$ + $^{40}Ca_{20}$ (80) and $^{208}Pb_{82}$ + $^{208}Pb_{82}$ (416) both having η = 0. $^{12}C_{6}$ + $^{197}Au_{79}$ (209) having η = 0.8 and $^{40}Ca_{20}$ + $^{208}Pb_{82}$ (248) having η = 0.6 have been displayed.

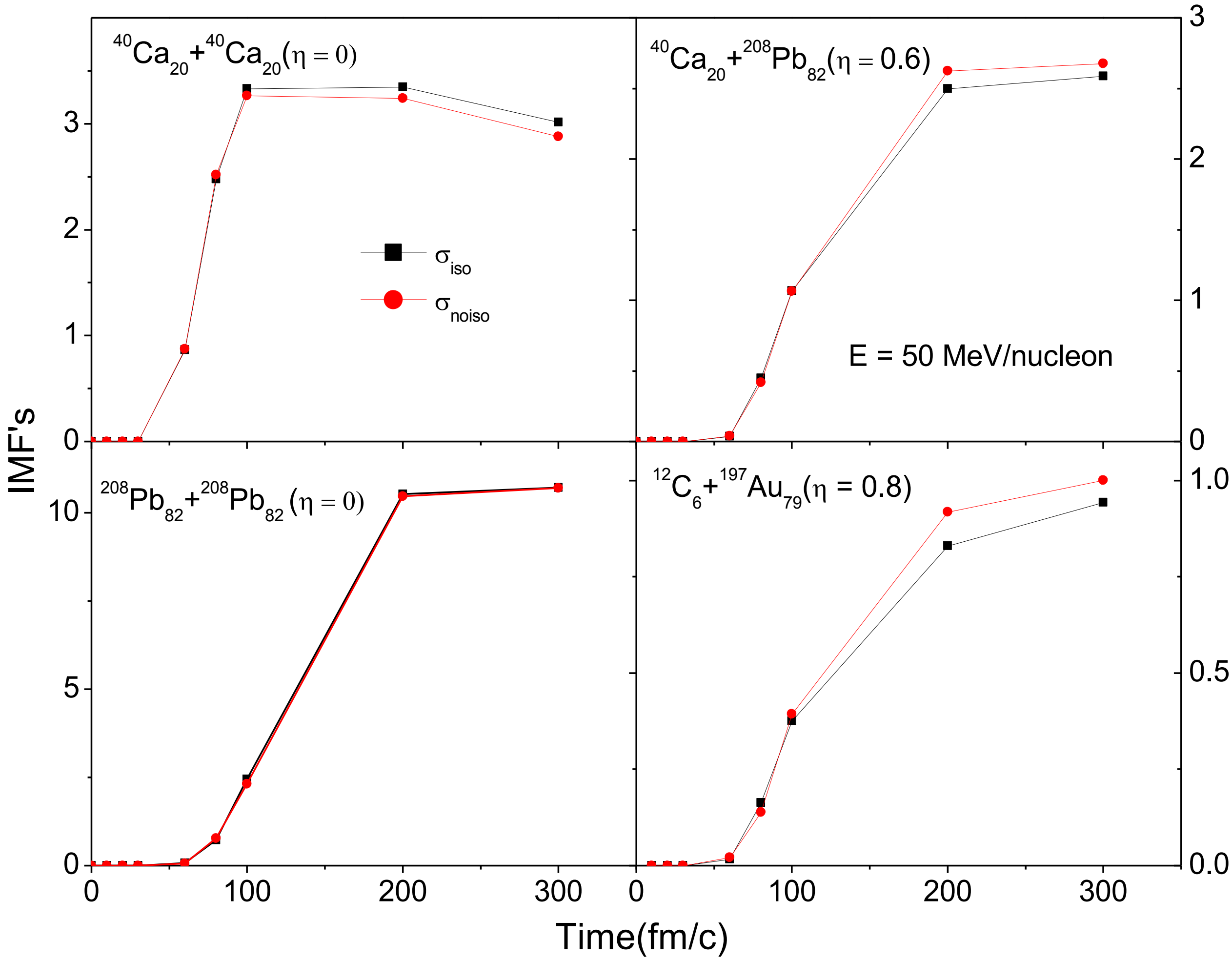

Figure 4.5 Same as figure 4.5 but for intermediate mass fragments (IMF's), $5 \leq A \leq A_{tot/6}$

It has been seen from the figure 4.6 that the universal behavior of increase in multiplicity of fragments with the size of the system is observed in the presence of mass asymmetry as well as with isospin independent cross section. One can see from the figure that the trend for the isospin dependent cross section and for the isospin independent cross section is same.

Both free nucleons and LMF's show increasing trends. With the increase in the size of system, number of the participant nucleons increases. This will lead to more thermalization of the system. Due to this reason, increase in multiplicity of fragments will always be observed, which will originate from the participant zone.

The intermediate mass fragments do not follow the trend as followed by free nucleons and LMF's. IMF's shows the rise and fall behaviour with the increase in the mass of the system. This is due the reason that the IMF's are produced from the spectator zone and the middle two masses i.e 209 and 248 belong to asymmetric systems. Also the less number of IMF's are produced as compared to free nucleons and LMF's.

Also with the increase in the value of incident energy, the multiplicity of various fragments also increases. This will be clearer in the next section.

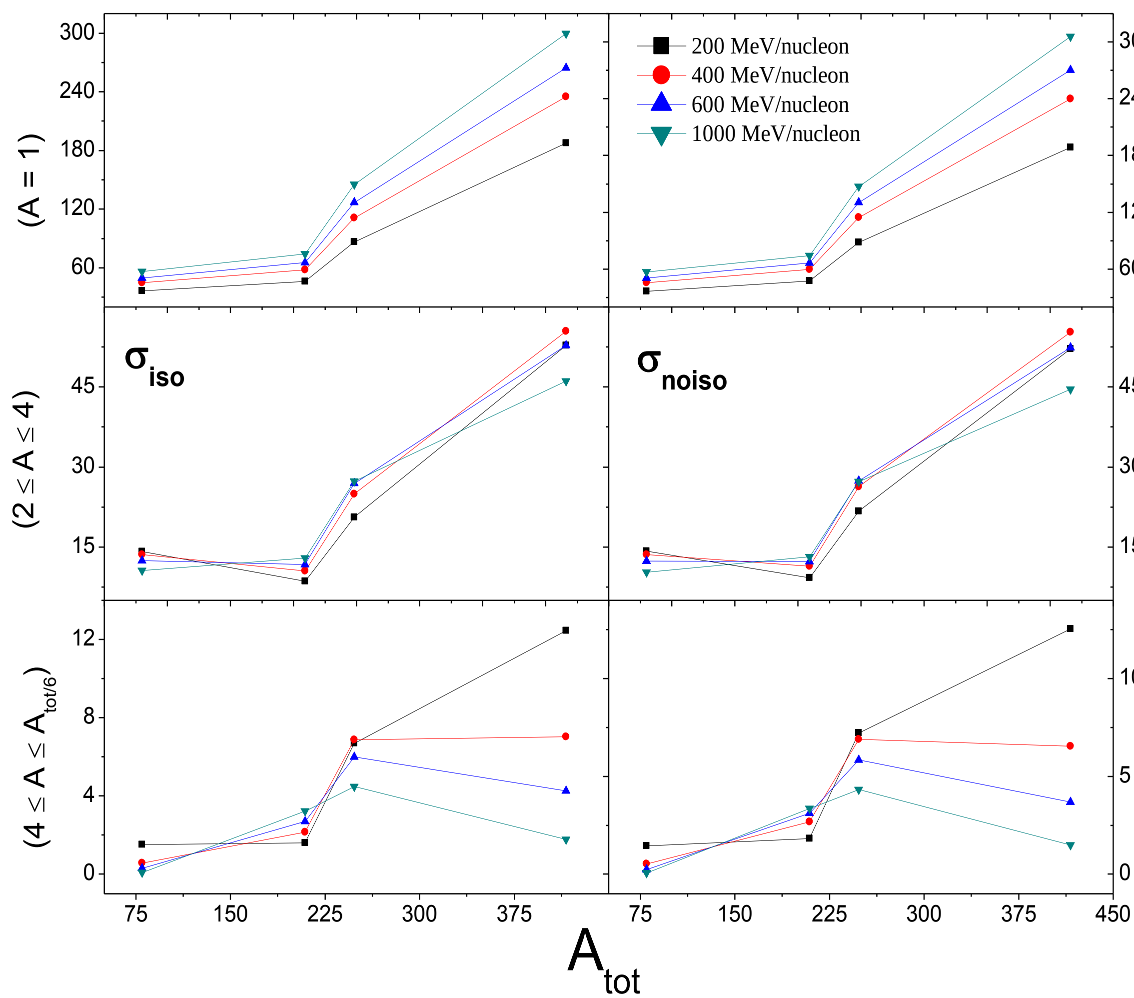

Figure 4.6: Multiplicity of various fragments as a function of total mass of the system for different energies. The left panel represents the plots with isospin dependent nucleon nucleon cross section and the right panel represents the plots isospin independent nucleon nucleon cross section. The values are taken at 200fm/c.

4.5 Energy dependence of various fragments formed:

In this section, we shall discuss the multiplicity of various fragments as a function of energy at characteristic time i.e. 200fm/c.

In fig 4.7 we have displayed the free nucleons with isospin dependent as well as isospin independent cross section as a function of energy for symmetric systems and asymmetric systems for scaled impact parameters. As it is clear from the figure that the number of free nucleons is increasing with the increase in energy. This is due to the reason that at central collision all the nucleons are taking part in the collision. The collisions becomes more violent as the energy is increases. The maximum number of free nucleons will be produced at high energy due to more compression zone at high energy. Also with increase in energy Pauli blocking effect decreases. The correlations among the nucleons are destroyed at high energies and hence more number of free nucleons are produced. With the increases in the value of scaled impact parameter the multiplicity of free nucleons is decreasing as compared to central collision. Interesting to see the effect of isospin independent cross section (σ_{noiso}). σ_{noiso} lead to enhanced production of free nucleons at all the energies and for all asymmetries. For symmetric reactions the difference in the production of free nucleons is more for the energy range 400 MeV/nucleon to 1000 MeV/nucleon. But the asymmetric reactions, the influence is more from 200MeV/nucleon to 600MeV/nucleon.

In fig 4.8, the multiplicity of light mass fragments (LMF's), $2 \leq A \leq 4$ with isospin dependent as well as without isospin dependent cross section as a function of energy for scaled impact parameter($\hat{b}$ = 0 and $\hat{b}$ = 0.3) have been displayed. From the figure, it is clear that the number of LMF's first increases as energy increases, reaches a peak value at 200MeV/nucleon and then decreases as the energy increases. This trend is for symmetric systems i.e for $^{40}Ca_{20}$+$^{40}Ca_{20}$ and for $^{208}Pb_{82}$+$^{208}Pb_{82}$. But this trend is not followed by mass asymmetric systems. i.e $^{12}C_{6}$+$^{197}Au_{79}$ and $^{40}Ca_{20}$+$^{208}Pb_{82}$. In mass asymmetric systems the number of LMF's increases with the increase in energy. The opposite effect that we have observed in case of free nucleons. For asymmetric systems the difference is more because mass asymmetry play significant role on reaction dynamics as studied in the ref [1].

Now if effect of isospin independent cross section is observed then it is seen that there is considerable effect of cross section on the mass asymmetric systems than on symmetric systems.

It can be seen from the figure 4.8 that the number of light mass fragments formed without isospin dependent nucleon nucleon cross section is more as compared to symmetric systems. In case of symmetric systems the number of LMF's is decreasing with increasing energy by taking the isospin independent cross section.

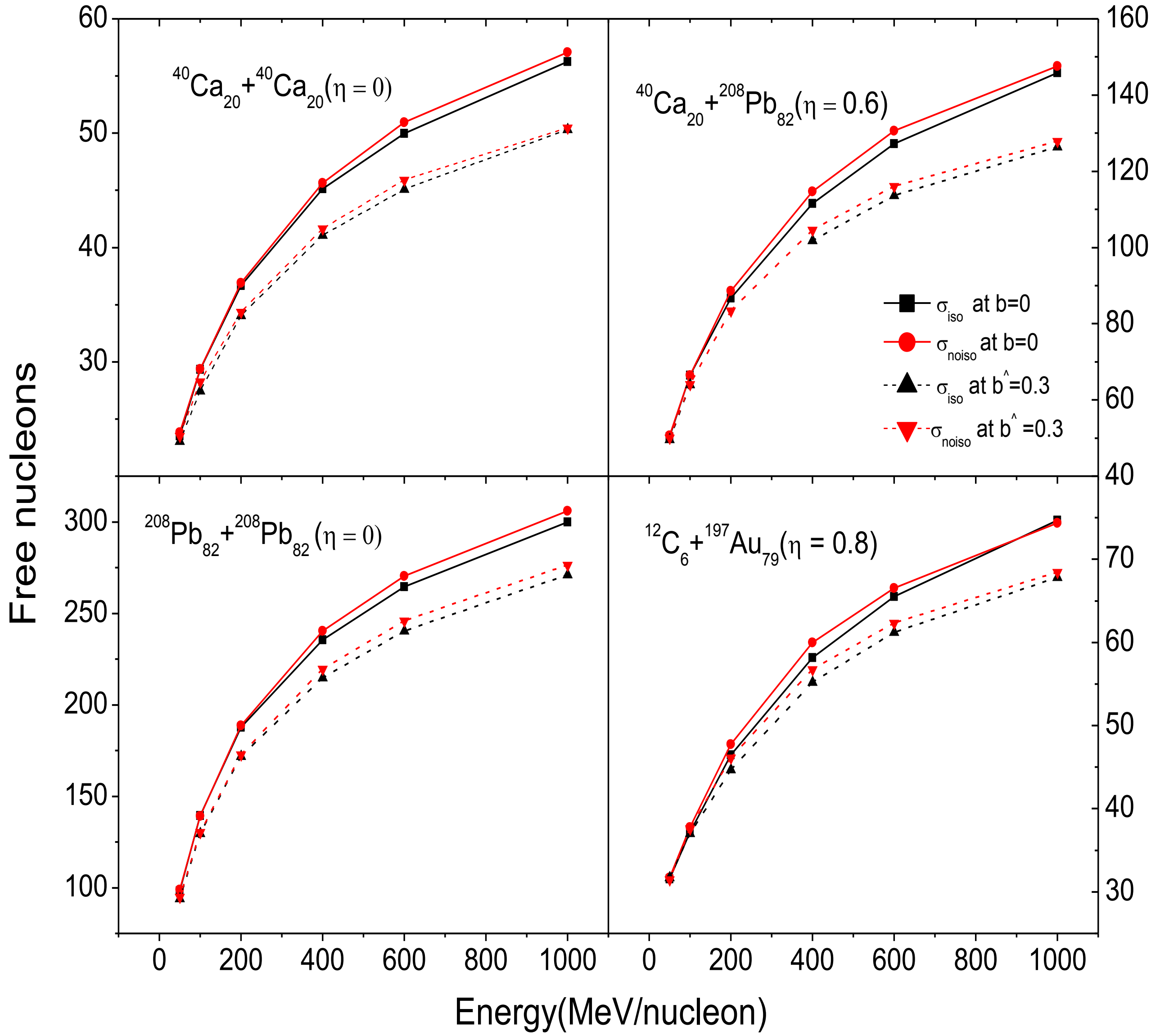

Figure 4.7: Multiplicity of free nucleons as a function of energy at scaled impact parameters with isospin dependent cross section and isospin independent cross section.

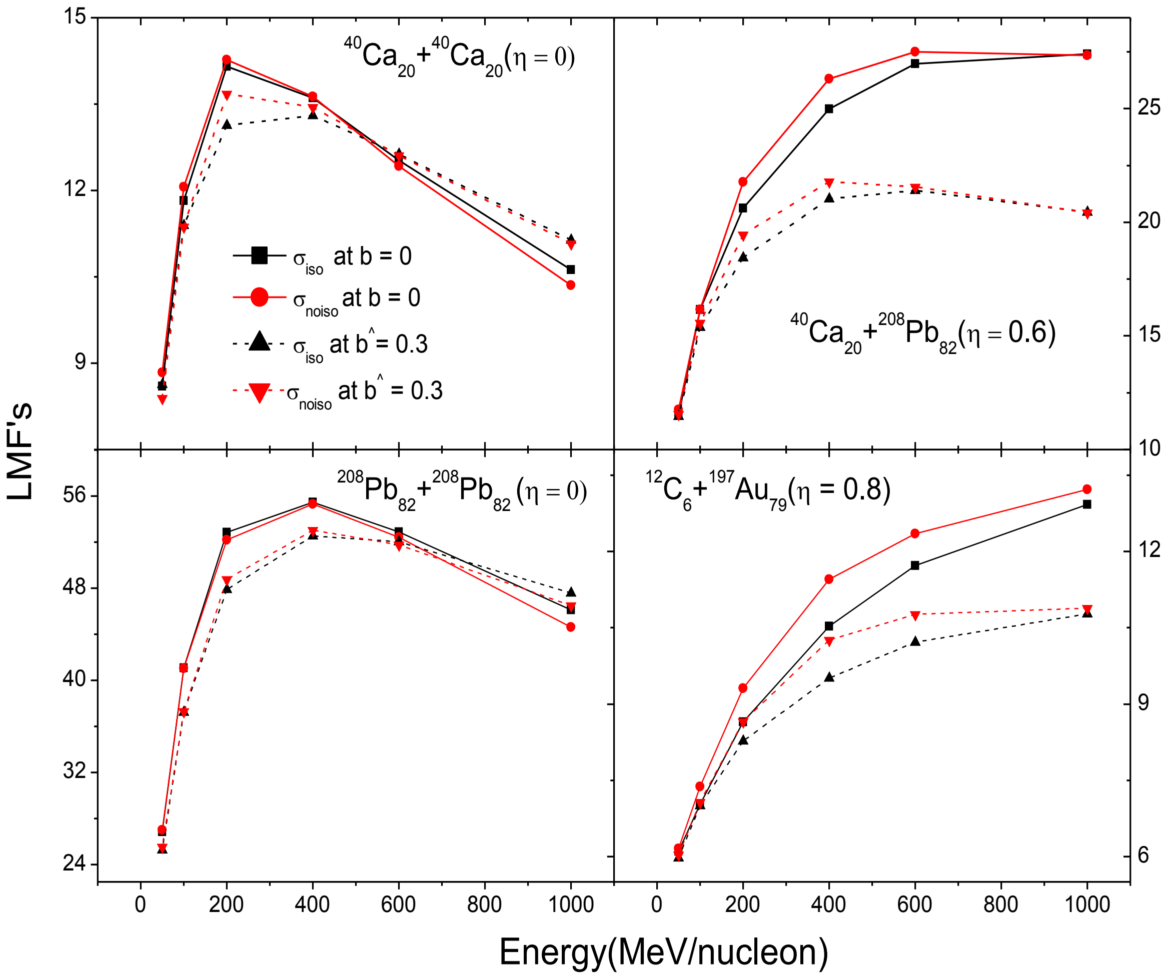

Figure 4.8 same as fig 4.9 but for light mass fragments (LMF's), $2 \leq A \leq 4$

When a nucleus is excited to and beyond its total binding energy, it is predicted to decay into several IMF's. In Fig 4.9, the multiplicity of intermediate mass fragments with isospin dependent cross section and without isospin dependent cross section have been displayed at scaled impact parameters.

The mass asymmetry plays a dramatic role in observing the heavy ion reactions. The system having least asymmetry gives rise to more IMF's as compared to system having large asymmetry [1]. The calculations with soft equation of state and reduced isospin dependent cross section results in the maximum IMF multiplicity at central geometry. At central collisions the NN collisions occurring at these energies do not allow any IMF's production whereas at peripheral collisions, not enough energy is transferred from participant to spectator matter, therefore very few IMF's are obtained.

The effect of cross section is more for free nucleons and LMF's as compared to IMF's because IMF's are produced from spectator zone. It is seen that multiplicity of intermediate and light mass fragments decrease with the increase in energy but in contrary it goes on increasing with energy for free nucleons. The emission of free nucleons will show disassembly (vaporization) of the matter [15, 16]. The production of LMF's is highest at low energy which decreases with the increase in energy. Due to very small overlap at large impact parameter, the system does not receive enough energy and hence cools down after emitting few nucleons/LMF. The production of IMF's is maximum at low energy and largest impact parameter.

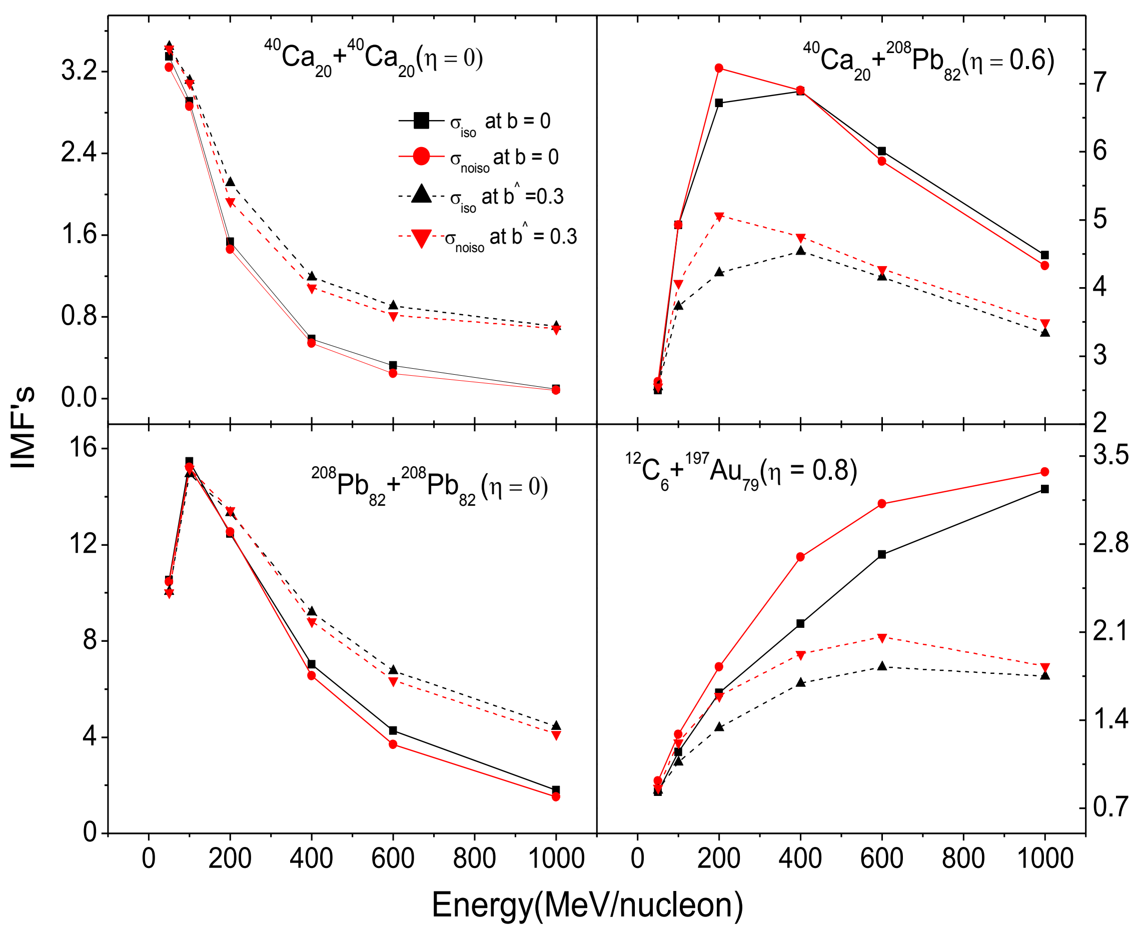

Figure 4.9: same as fig 4.9 but for intermediate mass fragments (IMF's), $5 \leq A \leq A_{tot/6}$

4.6 References:

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Chapter 5

Summary

In the recent times, the experimental study of multifragmentation motivated us to do the theoretical study of heavy ion physics at intermediate energy.

In the **chapter 1**, the discussion of the topics related to the influence of mass asymmetry on the nuclear reaction dynamics has been given. Also the experimental and theoretical scenario related to multifragmentation has been discussed there.

In the **chapter 2**, the details about the model which has been used for the study related to the nuclear reaction dynamics at intermediate energy has been given. The model used is isospin dependent quantum molecular dynamics (IQMD).

In the **chapter 3**, we have compared the coordinate and momentum phase space of symmetric and asymmetric systems with isospin dependent cross section and isospin independent cross section. The significant difference between the phase space of symmetric and asymmetric systems as well as for isospin dependent cross section and isospin independent cross section has been found.

In the **chapter 4**, the simulations of symmetric and asymmetric reactions with isospin dependent cross section and with isospin independent cross section have been carried out which then have been clusterized using minimum spanning tree (MST) method. First of all the time evolution of the density profile and the number of allowed collisions have been discussed. It has been seen that the maximum value of allowed collisions increases with the change from isospin dependent cross section to isospin independent cross section. Then the multiplicity of various fragments (free nucleons, LMF's, IMF's) with time and then with energy have been discussed for isospin dependent and isospin independent cross section. It has been seen that there is significant effect of isospin independent cross section on mass asymmetric systems.