Systematic Study of Multifragmentation by using IQMD Model

A Thesis Submitted in Partial Fulfillment of Requirement for
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Master of Science
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Under
the Supervision of

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CERTIFICATE

I hereby declare that the report entitled "**Systematic study of Multifragmentation by using IQMD Model**" is an authentic record of my own work carried out as requirements for the award of degree of M. Sc. (Masters of Science) at Thapar University Patiala (Punjab), under the guidance of Dr. Suneel Kumar (SPMS) during January to June 2010. The matter presented in the thesis has not been submitted in part or full for the award of any other degree.

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Abstract

The present work deals with the theoretical study of multifragmentation and its associated phenomena in heavy ion collisions. This work is done with the framework of Isospin Quantum Molecular Dynamical Model (IQMD) and using Minimum Spanning Tree (MST) algorithm. Firstly we give the brief introduction about multifragmentation and the experimental setup of ALADIN Spectrometer at GSI (Germany), which gave the complete set of multifragmentation data. After that we discussed the Isospin Quantum Molecular Dynamics (IQMD). Finally we gives the various simulated results and we discussed some of them with experimental data obtained experimentally from ALADIN. Finally we will summaries our results with an outlook.

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CHAPTER 1:

HEAVY ION REACTION:

1.1 Introduction:

Nuclear matter shows the four phases at different temperature and densities fig(1.2). At lower densities and lower temperature, it behaves like liquid, at low density and higher temperature, it becomes hadron gas, at higher density and lower temperature the matter is in the state of condensed phase and fourth possibility is at higher density and higher temperature this state of nuclear matter turned in quark-gluon plasma. The above described facts are not only important to nuclear physicists but have great importance for cosmologists to study astrophysical happenings like supernova explosions, which are good candidates for studying the nuclear matter at higher temperature and higher densities. But these happening are far away and rare, such that nothing can be extracted from these happenings. On the other hand the giant resonances generate the densities which are close to the normal nuclear densities. The only remaining candidate is the heavy ion collision at intermediate and relativistic energies. In this domain we can compress the nuclear matter (neutron and proton) within nucleus by 2-3 times more than the normal nuclear matter and temperature of 100 MeV can be reached [1]. At this stage we can extract the information about how it respond and what role the strange particle play in hot and dense nuclear matter? These questions are of fundamental importance for understanding strong interaction and astrophysical research.

The interest to study the low energy nuclear physics or heavy ion collision is to look for the low density phenomena. The reaction cross section at low energy consists of three parts i.e the fusion, quasi elastic and deep inelastic scattering. These processes depend upon the projectile-target combination, the bombarding energy of projectile and on the angular momentum. As shown in fig (1.1) two nuclei collide and make compound nucleus and then fragmented in all possible direction. One can explore this aspect of low energy physics by studying variety of experiments which involves symmetric (e.g^{16}O+^{16}O, ^{40}Ca+^{40}Ca, ^{197}Au+^{197}Au) or very asymmetric nuclei (e.g. ^{16}O+^{118}Sn, ^{16}O+^{114}Nd etc.)[2-3].

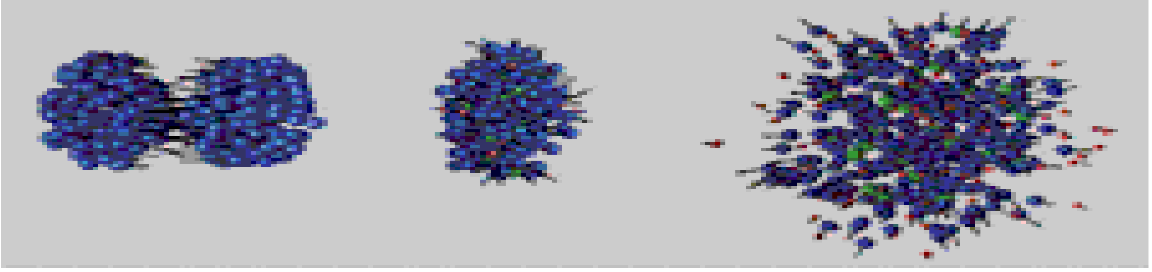

Fig 1.1 Two nuclei collide to form compound nucleus and then fragmented

With the development of accelerator technologies one was able to accelerate heavy ions with bombarding energy comparable to its rest mass. This opened up a new dimension of intermediate and relativistic energy heavy ion physics. The compound nucleus formed at intermediate and relativistic energies gives information to study the nuclear matter under extreme conditions. The properties of this hot and dense nuclear matter depend upon the pressure, density and temperature. This hot and dense nuclear matter is composed of hadronic matter which may have rich structure in this energy domain. As indicated in fig (1.2).

It is well known that when two nuclei collide they break into several pieces and also lots of nucleons are emitted. This branch is termed as multi-fragmentation. Many attempts were made theoretically and experimentally to explore the question why do nuclei break into several fragments? How and when they formed? What is the mechanism behind the multi-fragmentation? Why does nuclei shatter into several fragments if it hit by a projectile? Is this a statistical process? Making new micro-canonical phase space models are the proper tool for its description or are this dynamical process? Can we relate this process to astrophysical happening? etc.

Multifragmentation is one of the active branch of nuclear physics to study the nuclear matter in heavy ion collision for the energy range between 10 MeV/nucleon and 2 GeV/nucleon to explore the properties of nuclear matter like nuclear interactions, fusion –fission, cluster radio activity, formation of super heavy nuclei [4-5] etc. Many attempts have been made to study this domain of nuclear physics theoretically and experimentally by various scientists at various places around the world. In the following we will discuss some outlines of multifragmentation from various aspects. e.g. low. Intermediate & high energies.

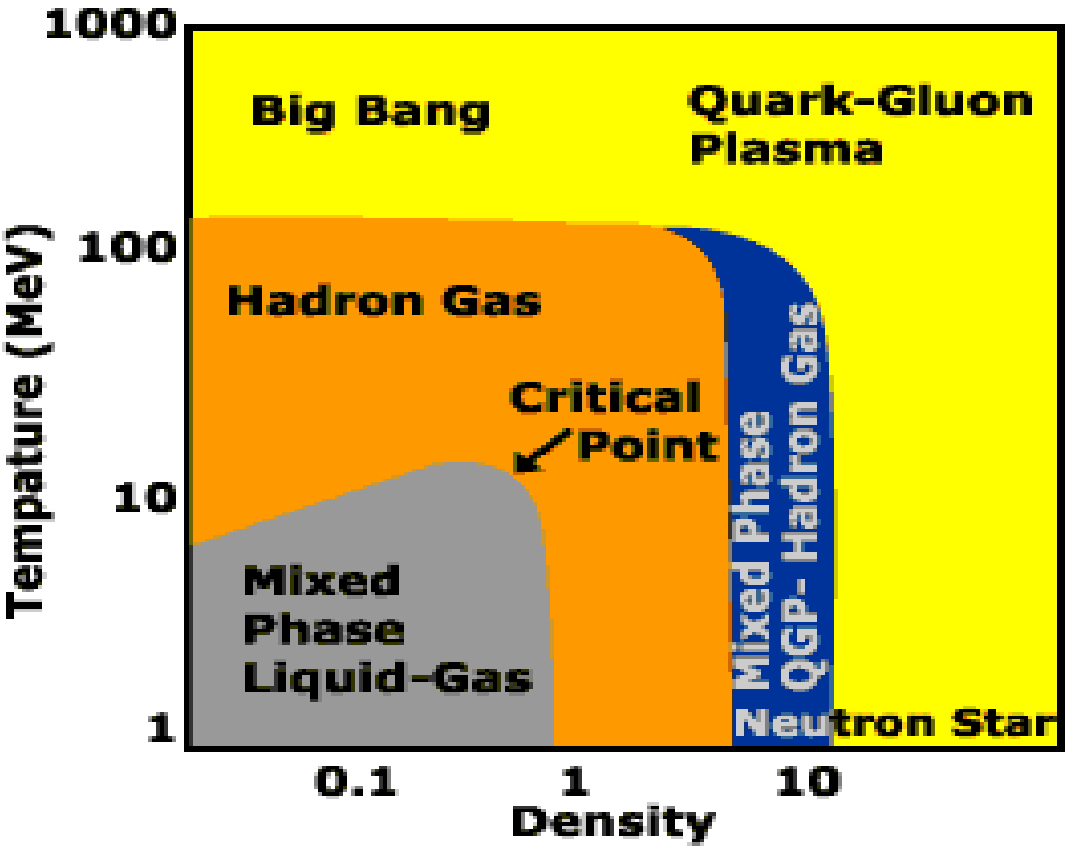

Fig 1.2. Phase diagram of nuclear matter at various temperature and densities.

1.2 Review of Experimental study:

Earlier, one could accelerate the light ions only, therefore, the field was dominated by shooting light particles on heavy targets. As the quest grew, new and larger accelerators were built which could accelerate heavy nuclei up to several hundreds of GeV that led to the new unexplored world of nuclear physics.

Experiments performed at LBL(Lawrance Berkeley Laboratory) in the early 80’s yield first 4π information of the final momentum distributions in heavy-ion reactions. The first experiments at Berkley served mainly to get the experimentalists and theoreticians aware of the problems from medium energy heavy-ion collisions to equation of state. Later on, several accelerators were built at Michigan State University (USA), GANIL (France), and at GSI (Germany) [6]. These experiments enable precise measurements on the emission of primary and secondary particles and therefore provide a stimulating challenge to the theoretical description of heavy ion collisions.

The FOPI and ALADIN group at GSI are studying the variety of reactions giving nearly all kinds of possibilities. It ranges from $_{12}$C to $_{208}$Pb and with incident energy between 100A and 1000A MeV [7]. A lot of physical conclusions are also drawn from these studies. If one goes through above experiments, one will notice that two different varieties (i.e. symmetric and asymmetric reactions merge). The symmetric reaction will generate high compression whereas asymmetric reaction will lead to heat or thermal energies. The aim of heavy target against light projectile is to look for the target multi-fragmentation whereas a heavy projectile on light target gives projectile fragmentation. Naturally, the physics at peripheral collisions is dominated by the spectator physics whereas the central collisions have a fireball dynamics. Different experiments gave indications that the impact parameter can be closely related with the emission of charged particles, thus make it possible to extract the impact parameter experimentally. A large multiplicity of the charged particles is associated with central collisions which decrease with increase in impact parameter [8,9]. If one deals with the intermediate mass fragment production at higher energies, one sees a rise or fall in the multiplicity of the fragments with a change in the impact parameter. Apart from these observations, the associated properties of fragments like collective flow, energy spectra, rapidity distributions are also investigated.

The nucleons are found to be emitted from participant zone whereas the heavy fragments are the remnants of spectators. The collective flow is found to increase with increase in the size of fragments. At very low incident energies, one finds negative sideward flow whereas at high incident energies, the flow is repulsive. This means that while going from low to high energies, the flow will disappear at some incident energy. This energy is termed as balance energy. It was also reported that this balance energy varies as $A^{-1/3}$ [10].

The experiments performed at GSI with ALADIN forward spectrometer were done with Sn, La as projectile at energy of 600 MeV with different fixed targets of and Sn and isotopes of Sn [11,12]. ALADIN gave the data on multifragmentation.

The ALADIN spectrometer consist of many detectors namely Si-CsI(TI) hodoscope, TP-MUSIC, LAND, TOF and central plastic detector collectively covers almost 100% of fragments and particles. A schematic layout of the experimental set up is shown in fig (1.3). For each beam particle, its arrival time and its position in the plane perpendicular to the beam direction were measured upstream of the target with thin plastic scintillator. Their effective thicknesses were 110 and 50 m. The geometric acceptance of the spectrometer of $_{lab}$ ± 9.2^0 horizontally and ± 4.3^0 vertically and its matched with the dimensions of the multiple sampling ionization chamber TP- MUSIC III and by the extended time of flight (TOF) wall. These detector systems permitted the detection close to 100% of all projectile fragments with atomic number $Z \geq 2$. At lower bombarding energies, the angular distribution of some lighter fragments extended beyond the acceptance of the spectrometer but stayed within the acceptance of Si-CsI(TI) hodoscope array that surrounded the entrance to field gap of the ALADIN magnet.

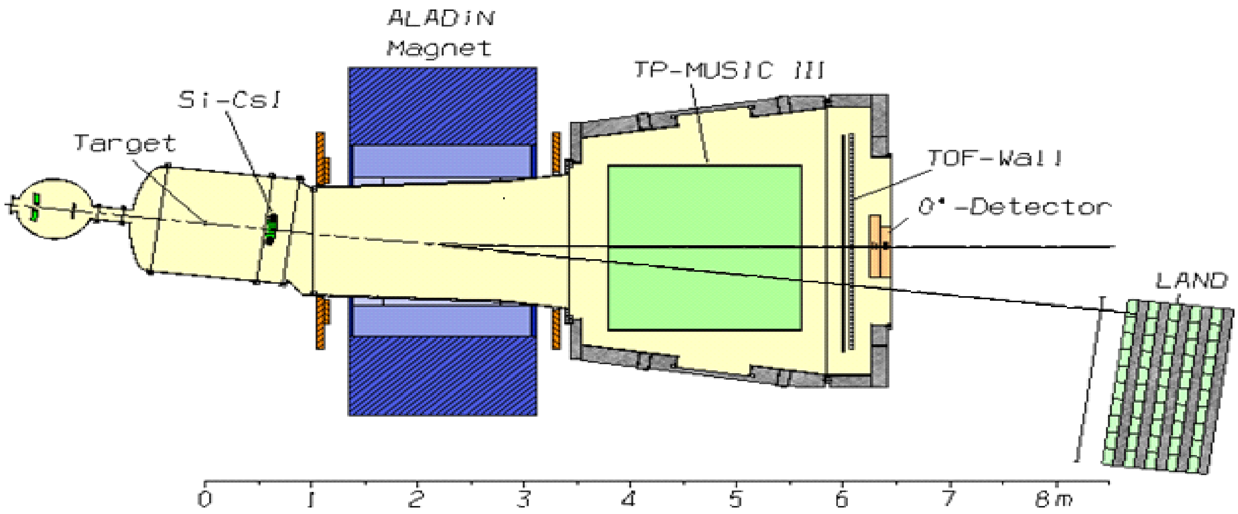

Fig.1.3 cross sectional view of the ALADIN experimental set up. The beam enters from the left and is monitored by two beam detectors before reaching the target. Projectile fragments entering into the acceptance of the magnet are tracked and identification in the TP-MUSIC III detector and in the time-of-flight (TOF) wall. The central plastic detector covers the hole in the TOF wall at the exit for the beam. Fragments and particle emitted in forward direction outside the magnet acceptance and up to $_{lab\ =}$ 16^0 are detected in the Si-CsI array. Neutrons emitted in direction close to 0^0 are detected with the large area neutron detector (LAND). The dashed line indicates the direction of the incident beam. The dash-dotted line represents the trajectory of beam particles after they were deflected by an angle of 7.3^0 .

1.3 Review of Theoretical Methods :

The study of intermediate heavy-ion collision needs correct treatment of nuclear interactions. Naturally if projectile and target are comparably same (symmetric) then reaction leads to high compression of the system whereas, asymmetric reactions lead to the heat or thermal energies. In collision dynamics reaction depends upon many parameters like energies of the projectiles their impact parameter and the mass of projectile and target. In theoretical treatment there are many objective and 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.

Presently many theoretical tools are available. It is relevant to mention that lots of efforts are being made in different parts of the world to compare the theoretical calculations with experimental data.

Note that the experimental setups for the measurements of the multi-fragmentation are quite complex in nature. Therefore all experimental groups (ALADIN,INDRA etc.) have deviced sophisticated and complicated filters[13,16]. The experimental results reported in the literature are subjected to various filters which meet the efficiency cuts of the experiments. The theoretical results should also be subjected to the same filters.

Theoretically, several models have been developed which make the situation more complicated. The key point to remember is that heavy-ion collision involves very complicated non-equilibrium physics, therefore, its numerical modeling is not straight forward. Due to lack of free space at low incident energies about 98% of the attempted collisions are blocked. The whole dynamics at low energies is governed by the mean field or by the two body and three body interactions. In contrary the availability of large free phase space at relativistic energies (>2 GeV) makes Pauli principle’s role quite small (roughly 4% collisions are blocked) and hence the dynamics of reaction is governed by the Cascade picture. On the other hand, both Cascade and mean field emerges at intermediate energies.

The conventional theories like the time dependent Hartree-Fock (TDHF) theory [17,20] or its semi-classical version so called Valsov equation (in phase space) are suitable approaches at low energies, where nucleon-nucleon collisions are negligible. A suitable approach for intermediate energy heavy ion physics should treat the nucleon-nucleon collision and mean field on equal footing. In

TDHF the fundamental assumption is the independent particle behavior for the near-equilibrium nuclear states persists to highly non equilibrium situations if the excitation energies is less than 10 MeV. Some attempts were also made in literature to extend the TDHF to take care of the residual nucleon-nucleon (NN) interactions which are responsible for the two body collision, this was dubbed as Extended Time Dependent Hartree-Fock (ETDHF) [21]. However due to complications, this theory could not be used for large scale investigations.

Increasing the complexity from single-particle description mean field can be used to modulate the overall behavior of nucleons. The semi-classical version ETDHF (i.e. Valsov equation) [22,23] when coupled with nucleon-nucleon collision and thus a new realization named Boltzmann-Uehling-Uhlenbeck equation was developed for large deviation problems of low, intermediate and relativistic ion collisions. The solution of BUU equation provides the time evolution of one body distribution function in six-dimensional phase space. The BUU equation includes the Pauli-blocking and solved by the test particle method. In brief the BUU model is able explain the one body observables like collective flow, stopping and particle spectra nicely. Due to the lack of fluctuations and correlations, the N-body predictions are beyond the scope of this model.

The classical molecular dynamics (MD) [24,26] approach is capable of treating both compression and fragment formation. The molecular dynamics predicts the collective flow in a qualitative agreement with the data. It incorporates the complete classical N-body dynamics which is necessary to describe the formation of fragments. Naturally, the simple classical molecular dynamics needs refinement which should also include quantum features. In nuclear physics, the key problem in MD methods lies in the treatment of the Pauli principle. Nucleons are fermions and it is difficult to speak of nuclei without the Pauli principle. This question is simply overlooked in strictly classical calculations. MD methods with Pauli principle address this question but with disputable success.

The QMD model [27,29]attempts to manipulate a many-body wave function to introduce the correlations needed for cluster formation. Taking the wave function as a product of coherent states and using momentum dependent interactions with Pauli blocking, the model evolves a set of test particles through the temporal evolution of the reaction.

In past decade, several refinements and improvements were made over original QMD. The QMD model takes into account the Pauli principle, but through two-body collisions, which is somewhat contrary to MD picture. In view of the difficulties encountered with taking the Pauli principle in classical MD methods properly into account, a new class of approaches was developed in the beginning of the 1990s, the so called Fermionic Molecular Dynamics (FMD) [30,31] (AMD) [32,33]. The serious numerical problems have restricted the use of FMD and AMD approaches to light nuclei. It is worth to mention that the Intra nuclear Cascade model (INC) developed by Cugnon et al[34], is one of the pioneering models in the field and has acted as a guideline for the development of the field. Isospin dependent Quantum Molecular Dynamics: IQMD 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.

In intermediate energy heavy ion collision when two nuclei collide with each other and form compound nucleus which decays in fragments. How can we differentiate a fragment form another. So we need a procedure to define cluster. In a simple picture the nucleons were connected to a cluster using space correlation method. This method identifies two nucleons in a same fragment if their centroids are less than some distance d_{min}. Before one can study the origin of fragments one has to identify the fragments.

$$| r_i - r_j | \leq d_{min}$$

Where r_i and r_j are the spatial positions of both nucleons. This is called the minimum spanning tree (MST) method[29]. Several refinements to this method were proposed later on, but till today this method is one of the most extensively used methods.

1.4 Objective of work:

Objective of our work was to compare our theoretical findings with available experimental data in intermediate heavy ion collisions. Experimental data was available for intermediate mass fragments at different impact parameters of ALADIN collaboration. Following the same work we obtained the theoretical data for reaction ${}_{57}La^{124}+{}_{50}Sn^{124}$, ${}_{50}Sn^{124}+{}_{50}Sn^{124}$ and ${}_{50}Sn^{107}+{}_{50}Sn^{124}$ under the similar condition as were for ALADIN experiment and obtained results are compared with experimental data.

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CHAPTER 2:

METHODOLOGY:

As discussed in Chapter 1. dynamics of heavy-ion collision can be studied in variety of ways. This dynamics of heavy ion includes mean field and N-N collisions. To study this QMD model is suggested in Chapter 1. Recently the isospin dependent effect such as symmetry energy and isospin dependent cross-sections has been taken into account in intermediate energy heavy ion collisions. The best suited method to study isospin effects is the Isospin-dependent Quantum Molecular Dynamics (IQMD). The model is explained in detail in the given section.

2.1 Isospin Quantum Molecular Dynamics Model (IQMD):

The IQMD model[1-3] can explicitly represent the many-body state of the system and contains correlation effects to all orders and all fluctuations. It has basically two advantages:

(1) Many-body process, in particular, the formation of complex fragments is treated.

(2) The model allows an event-by-event analysis of heavy ion reaction.

In order to describe the isospin effects of the dynamical process of HIC, quantum molecular dynamics (QMD) should be modified properly:

(1) The density dependent mean field should contain the correct isospin-dependent terms including symmetry potential and Coulomb potential.

(2) The in-medium N-N cross section should be different for neutron-neutron (proton-proton) and neutron-proton collisions, and finally.

(3) Pauli blocking should be counted by distinguishing neutron and proton.

Initialization:

In IQMD model, centroid of each Gaussian (in a nucleus) is randomly distributed in a phase space sphere ($r \le R$ and $\rho \le \rho_f$) with $R = 1.12\ A^{1/3}$ fermi corresponding to ground state density $\rho_0 = 0.17\ fm^{-3}$. The fermi momentum p_f depends on the ground state density. For $\rho_0 = 0.17\ fm^{-3}$, the value of p_f is 268 MeV/c. Due to this collision, nucleons close to surface (where the local potential energy is low) are unbounded initially.

As a result, binding energy per nucleon is low as compared to Weizsacker mass formula. Therefore, the initialized nuclei are less stable against spurious particle evaporation compared to oriented QMD model.

Pauli Blocking

The consideration of Pauli blocking effect is very important. Whenever a collision has occurred, in the phase space we assume that each nucleon occupies a six dimensional sphere with a volume of $h^3/2$ (considering the spin degree of freedom), 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. We then compare $2V/h^3$ with a random number and decide whether the collision is blocked or not. Therefore, the Pauli blocking is isospin dependent, namely, the Pauli blocking of neutrons and protons is treated separately. In addition, Pauli blocking (of the final state) of nucleons is taken into account by checking the phase space densities in the final states [4].

The final phase space fractions P_1 and P_2, which are already occupied by other nucleons, are determined for each of the scattering nucleons. The collision is then blocked with probability

$$P_{block} = 1 - (1 - P_1)(1 - P_2).$$

Potentials used in IQMD:

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 IQMD model, each nucleon is represented by a Gaussian wave packet of the form:

$$f(\vec{x},\overrightarrow{p},t) = \frac{1}{\pi^3\hbar^3} \times e^{[-(\vec{x}-\vec{x}(t))^2\frac{2}{L}]} \times e^{[-(\vec{p}-\vec{p}(t))^2\frac{2}{2h^2}]} \qquad (2.1)$$

The total one nucleon Weigner density is, therefore, the sum of all nucleons. The expectation value of Hamiltonian is:

<H> = <T> + <V>

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

(2.2)

The baryon-baryon potential V^{ij} consists of real part of Bruckner G-matrix which is supplemented by an effective Coulomb interaction acting between the charged particles. The former part can be parameterized in term of Skyrme type interaction to finite range Yukawa potential as well as momentum dependent contribution. In addition, a symmetry potential between protons and neutrons corresponding to the Bethe-Weizsacker formula has been included. Therefore, V^{ij} consists of:

$$V^{ij} = G^{ij} + V^{ij}_{coul}$$

$$= V^{ij}_{Skyrme} + V^{ij}_{Yukawa} + V^{ij}_{mdi} + V^{ij}_{Coul} + V^{ij}_{sy}$$

$$= t_1\delta(\vec{x}_i - \vec{x}_j) + t_2\delta(\vec{x}_i - \vec{x}_j)\rho^{\gamma-1}(\vec{x}_i) + t_3\frac{\exp\left(\frac{|\overrightarrow{x_i}-\overrightarrow{x_j}|}{\mu}\right)}{\frac{|\overrightarrow{x_i}-\overrightarrow{x_j}|}{\mu}} +$$

$$t_4 \ln^2 (1+t_5 (\vec{\rho}_i - \vec{\rho}_j)^2)\ \delta (\vec{x}_i - \vec{x}_j) + \frac{Z_i\ Z_j\ e^2}{|\vec{x_i} - \vec{x_j}|} + t_6 \frac{1}{\rho_0} T^i_3\ T^j_3 (\vec{r}_i - \vec{r}_j) \tag{2.3}$$

In the description of the Coulomb interaction V^{ij}_{coul}, Z_i, Z_j are the charges of the baryons.

The momentum dependent V^{ij}_{mdi} of the NN interaction, which may optionally be used in the model, is obtained from a fit to the experimental data [5] on the real part of the nucleon optical potential which yields.

$$V^{ij}_{mdi} = \delta . ln^2 (\varepsilon . (\Delta \vec{p})^2 + 1) . \frac{\rho_{int}}{\rho_0} \tag{2.4}$$

The asymmetry energy is taken into account by the term

$$V^{ij}_{sym} = t_6 \frac{1}{\rho_0} T^i_3\ T^j_3 \delta (\vec{r}_i, \vec{r}_j) \tag{2.5}$$

Where $T^i_3$and T^j_3denote the isospin T_3 of particles i and j, i.e. 1/2 for protons and -1/2 for neutrons. The constant t_6 = 100 MeV.

Collision:

Two particles collide if their minimum distance d, i.e. the minimum relative distance of the centroids of the Gaussians during their motion, in their CM frame fulfills the requirement:

$$\left| \vec{r}_i - \vec{r}_j \right| \leq \sqrt{\frac{\sigma_{tot}}{\pi}}, \qquad \sigma_{tot} = \sigma (\sqrt{s}, type) \tag{2.6}$$

Where the cross-section is assumed to be the free cross section of the regarded collision type (N − N, N − Δ, . . .). The total cross-section is the sum of the elastic cross -section and all inelastic cross-sections.

$$\text{Elastic: } \begin{cases} N + N \rightarrow N + N \\ \Delta + \Delta \rightarrow \Delta + \Delta \\ N + \Delta \rightarrow N + \Delta \end{cases} \tag{2.7}$$

$$\text{Inelastic: } \begin{cases} \mathrm{N} + \Delta \rightarrow \mathrm{N} + \mathrm{N} \\ \mathrm{N} + \mathrm{N} \rightarrow \mathrm{N} + \Delta \end{cases} \tag{2.8}$$

The total cross-section is the sum of the elastic cross-section and all inelastic cross-sections

$$\sigma_{\mathrm{tot}} = \sigma_{\mathrm{el}} + \sigma_{\mathrm{inel}} \tag{2.9}$$

For instance for a pp collision we may have

$$\sigma_{\mathrm{tot}} = \sigma_{\mathrm{el}} + \sigma(\mathrm{pp} \rightarrow \mathrm{p}\,\Delta^{+}) + \sigma(\mathrm{pp} \rightarrow \mathrm{n}\,\Delta^{++}) \tag{2.10}$$

The cross-sections for the different channels are given by experiment or by spin/isospin coefficients. For the pp case for example we have

$$\sigma(\mathrm{pp} \rightarrow \mathrm{n}\,\Delta^{++}) = 3\sigma(\mathrm{pp} \rightarrow \mathrm{p}\,\Delta^{+}) = \frac{3}{4}\sigma_{\mathrm{inelastic}} \tag{2.11}$$

Inaccessible reactions like ΔN → NN are calculated from their reverse reactions (here NN → ΔN) using detailed balance method. The possibility of reaching a channel in a collision is given by its contribution to the total cross-section

$$\mathrm{P}_{\mathrm{channel}} = \frac{\sigma_{\mathrm{channel}}}{\sigma_{\mathrm{tot}}} \qquad e.g.\ \ \mathrm{P}_{\mathrm{pp}\rightarrow \mathrm{p}\Delta^{+}} = \frac{1}{4}\frac{\sigma_{\mathrm{tot}} - \sigma_{\mathrm{el}}}{\sigma_{\mathrm{tot}}}$$

(2.12)

2.2 Cluster Analysis:

The minimum spanning tree method (MST) [6,7] is used in cluster analysis and track finding, if we consider tracks to be clusters of points. In MST, two nucleons share the same fragment if their centroids are closer than a distance $\mathrm{d}_{\mathrm{min}}$,

$$|\mathrm{r}_{\mathrm{i}} - \mathrm{r}_{\mathrm{j}}| \leq \mathrm{d}_{\mathrm{min}} \tag{2.13}$$

Where r_i and r_j are the spatial positions of both nucleons. The minimum distance d_{min} has been used as a free – parameter which varies between 2-4 fm. Its influence on multifragmentation (at 200 – 300 fm/c) is reported to be small[14]. This approach (being a spacial approach cannot detect different fragments which are (almost) overlapping and therefore, will give a single big fragment during early stage of the reaction where density is quite high and the interactions among nucleons are still active. One simulates the reaction using IQMD. Then spacial distance of all nucleons is checked. A nucleon is part of a fragment if there is another one within a distance of min r_{min} = 4 fm.

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Chapter 3:

Multifragmentation:

3.1 Introduction:

The curiosity of scientists about the nucleus opens many doors to study the nucleus. To study the nucleus at intermediate energy is our present interest. At intermediate energies when two nuclei collide then first they form compound nucleus then this compound nucleus breaks into several medium, light mass fragments along with the emission of free nucleons in all possible directions. This phenomena is termed as 'Multifragmentation'. Extensive experimental and theoretical efforts have been made during last 20 years to understand this mechanism. The factors effecting Multifragmentation, nuclear equation of state (EOS) and associated phenomena will be the main emphasis of present work.

The most recent ALADIN experiment has been devoted to investigating isotopic effects in the decay of projectile spectators at relativistic energies. Three different projectile with an incident energy 600 MeV/nucleon allow us to study various combinations of masses and N/Z ratios in the entrance channel: ${}_{57}La^{124}+{}_{50}Sn^{124}$, ${}_{50}Sn^{124}+{}_{50}Sn^{124}$, ${}_{50}Sn^{107}+{}_{50}Sn^{124}$ [1].

3.2 RESULTS AND DISCUSSION:

For the present study we have simulated ${}_{57}La^{124}+{}_{50}Sn^{124}$, ${}_{50}Sn^{124}+{}_{50}Sn^{124}$ and ${}_{50}Sn^{107}+{}_{50}Sn^{124}$ reactions by using isospin quantum molecular dynamics (IQMD) model [2-3] at incident energies 600 MeV/nucleon at scaled impact parameters (0.0, 0.2, 0.4, 0.6, 0.8, 0.9). The collision geometry used is from central to peripheral one. The Phase space obtained from IQMD model is analyzed by using Minimum spanning tree (MST) [4] algorithm. The results obtained are discussed in the following section:

3.3 Time Evolution of Nucleon-Nucleon Collision:

It is evident from the figure, that density and no. of allowed collisions have one to one relation. To understand this in fig (3.1), the time evolution of allowed as well as total collisions is displayed. The time evolution of allowed and total collision is found to obey the similar trend.

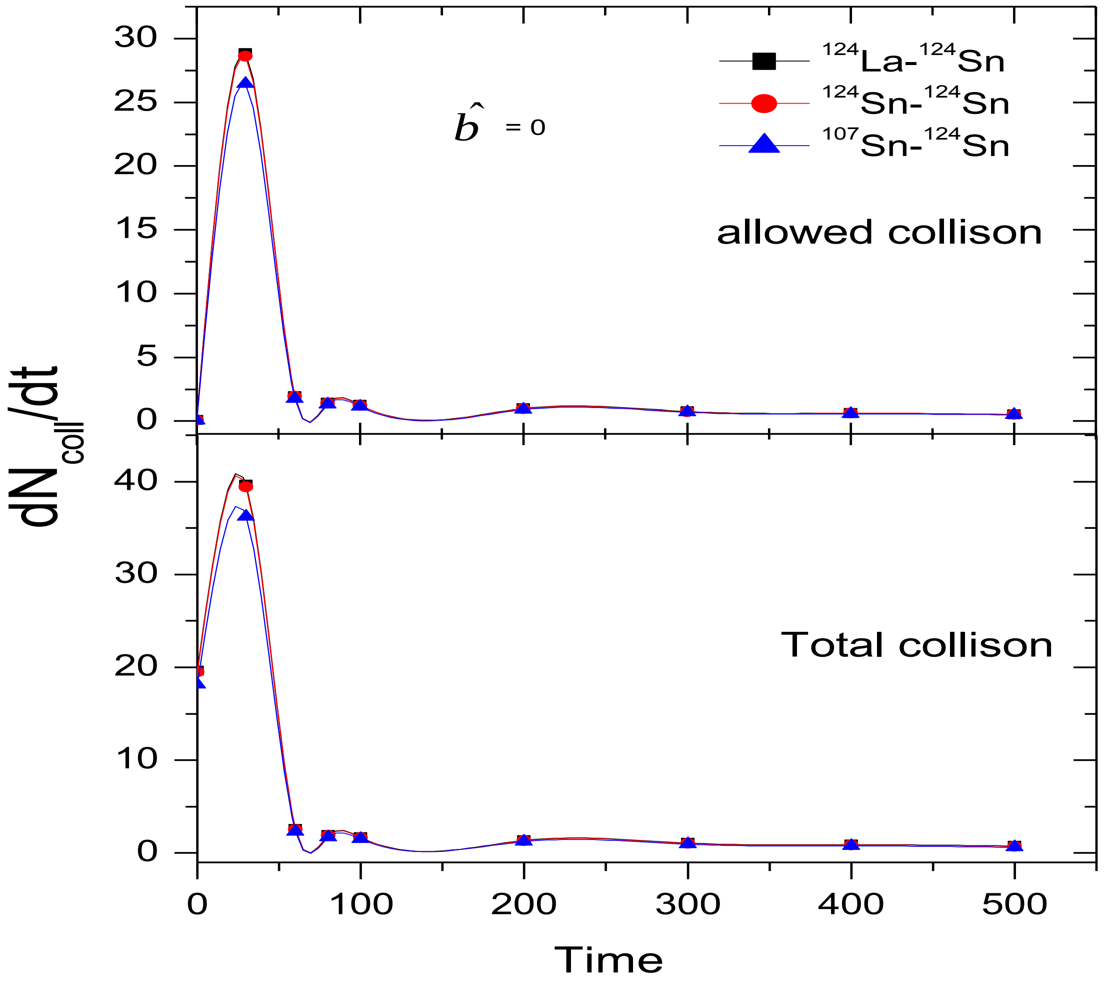


Fig. (3.1) Time evolution of rate of collision.

It means that first increase with increase in time upto the region of maximum compression. Maximum compression is around 30fm/c. After the compression stage, system starts expanding and hence decrease in the no. of collisions with time is observed. Then system is supposed to be saturated and hence no. of collisions becomes constant. The saturation time in this case is around & after 200fm/c. The no. of collisions are found to be sensitive towards the different combinations under study. The allowed collisions are less than that of total collisions. It is evident that some of the collisions are blocked. For example at the time of max. compression, out of 40 only 10 collisions are blocked.

3.4 Time Evolution of Multiplicity:

The formation of fragment and their multiplicities are shown in fig (3.2). & fig. (3.3). We have shown here that the emitted free nucleons ($1 \leq A \leq 1$), the light mass fragments (LMF's) ($2 \leq A \leq 4$) and intermediate mass fragments (*IMF*'s) ($5 \leq A \leq 42$) as a function of time at various scaled impact parameter ($\hat{b}=b/b_{max}$) of reaction ${}_{57}La^{124}+{}_{50}Sn^{124}$ at energy 600 MeV/nucleon for Hard and Soft equation of state (EOS). In case of free particle and LMF's, smother trend is observed for time evolution. In other words the production of the particles decreasing with increase in impact parameter. This is indicating that origin for production of particle is the participant zone. In case of IMF's drastic changes are observed with the increase in impact parameter. The peak is obtained upto $\hat{b}=0.4$, after $\hat{b}=0.4$ no peak is observed in the production of IMF's. This is due to the decay of IMF's, in the lighter particles which comes from the participant zone. On the other hand, the contribution in IMF's is from the spectator zone after $\hat{b}=0.4$, which remains undisturbed and no decay further into lighter particles. Similar behavior is observed from the fig (3.2) & (3.3). The fragments are found to be sensitive toward hard and soft equation of state. The production is more with soft as compared to hard equation of state.

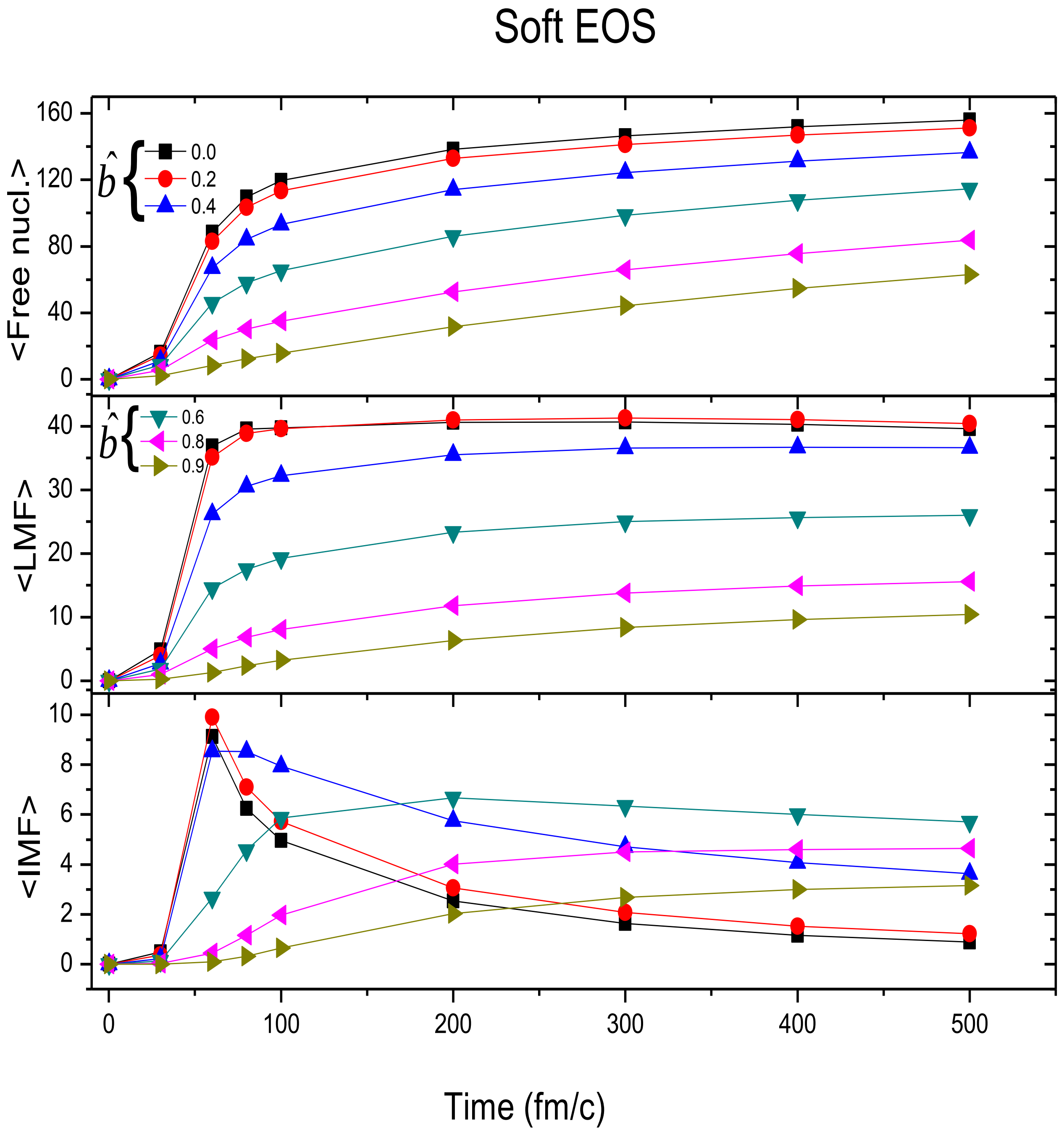


Fig (3.2) Multiplicity of IMF's, LMF's and Free nucleons for soft EOS.

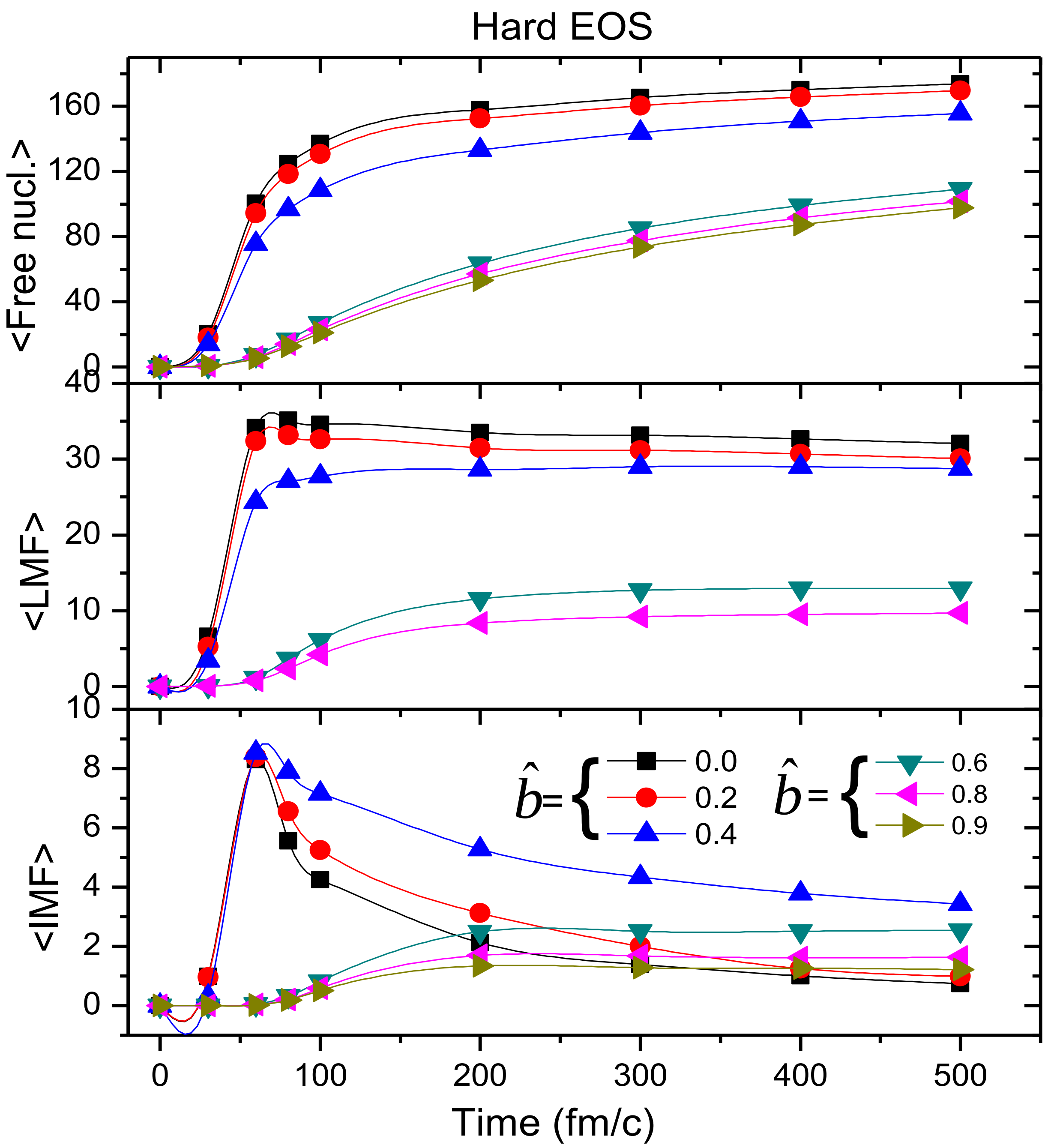


Fig (3.3) Multiplicity of Free nucleons LMF's and IMF's for hard equation of state (EOS).

In fig(3.4) we have shown the change of multiplicities of IMF's using range of impact parameter. At central collisions (b= 0 – 3 fm) the overlapping of participation zone is large and more number of IMF's observed. As we go from central to semi central (b= 0 – 6 fm) and peripheral (b= 0 - 9 fm) the overlapping of participation zone decrease which leads to the lower number of IMF's. As clear from the fig.(3.4) with increasing impact parameter the lines becomes lower and lower.

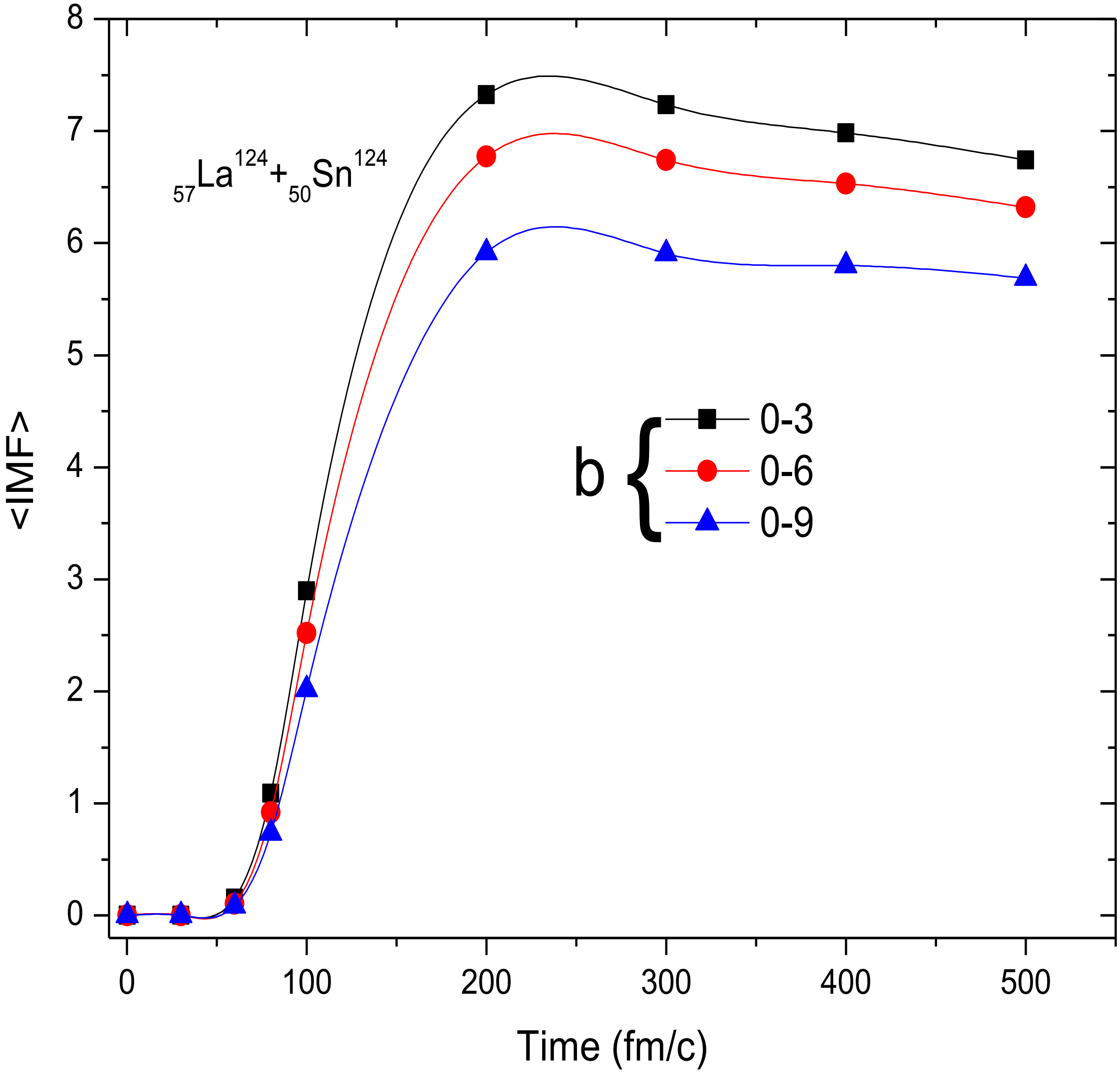


Fig (3.4) Multiplicity of IMF's of $_{57}La^{124}+_{50}Sn^{124}$ by using range of impact parameters.

3.5 Rapidity distribution:

The degree of stopping of nuclear matter can be studied from rapidity distribution which is defined as:

$$\mathrm{Y(i)} = \frac{1}{2}\ \mathrm{ln}\frac{E(i)+P_z(i)}{E(i)-P_z(i)} \qquad (3.2)$$

Where $E(i)$and $P_z(i)$are representing the total energy and longitudinal momentum of ith particle. For complete stopping one should expect a single Gaussion shape of rapidity. In fig(3.5) we have shown a rapidity of $_{57}La^{124}+_{50}Sn^{124}$, $_{50}Sn^{124}+_{50}Sn^{124}$ and $_{50}Sn^{107}+_{50}Sn^{124}$ of intermediate mass fragments (IMF's) at energy 600 MeV/nucleon at time 200 fm/c for soft EOS. We see that IMF's in central collisions are originated from a completely stopped source. The central collisions are better randomized comparable to the collisions of peripheral ones. With increase in impact parameter, single Gaussian become broader and further at higher impact parameter into two peaks. These two peaks specify either projectile like or target like remnants. This is indicating that nuclear stopping is maximum at central collisions, which goes on decreasing with increase in the impact parameter.

3.6 Mass distribution:

In fig.3.6, we have shown the mass distribution at three impact parameters ($\hat{b}$= 0.0, 0.4, 0.9) at 200 fm/c. As clear from the figure there is direct dependence of mass distribution on impact parameter. At central collision no heavy fragment observed because of the violent nature of central collision. In central collision no fragment observed of mass (A) greater than (>20-25). In semi peripheral collisions the participant zone decreases approximately half the value so there is no complete destruction of target and projectile and fragments of A ≈ 55 observed.

At peripheral collision the participant further decrease and heavy fragments A ≈ 120 observed. The conclusion is that by increasing impact parameter the overlapping of target and projectile decreases by virtue of which heavy fragments observed. The output of heavier cluster provides a tool to determine the impact parameter [5,6].

3.7 Charge Distribution:

In fig(3.7) we have shown the charge distribution of reactions ${}_{57}La^{124}+{}_{50}Sn^{124}$, ${}_{50}Sn^{124}+{}_{50}Sn^{124}$ and ${}_{50}Sn^{107}+{}_{50}Sn^{124}$ for scaled impact parameter (0.0, 0.4, 0.9) at energy 600 MeV/nucleon. The behavior is different at different impact parameters. For central collisions no heavy fragment survive because the excitation energy deposited in the system is very large. But in case of peripheral collision the reaction cross section decrease and excitation energies does not go upto proper extent to produce heavy fragments. The bumps in the reaction mainly in peripheral reaction indicates that less amount of momentum is transferred for participant to spectator matter which leads to the emission of less number of IMF’s. These bumps indicates the heavier cluster formation. Similar results are also published in literature [7,8]

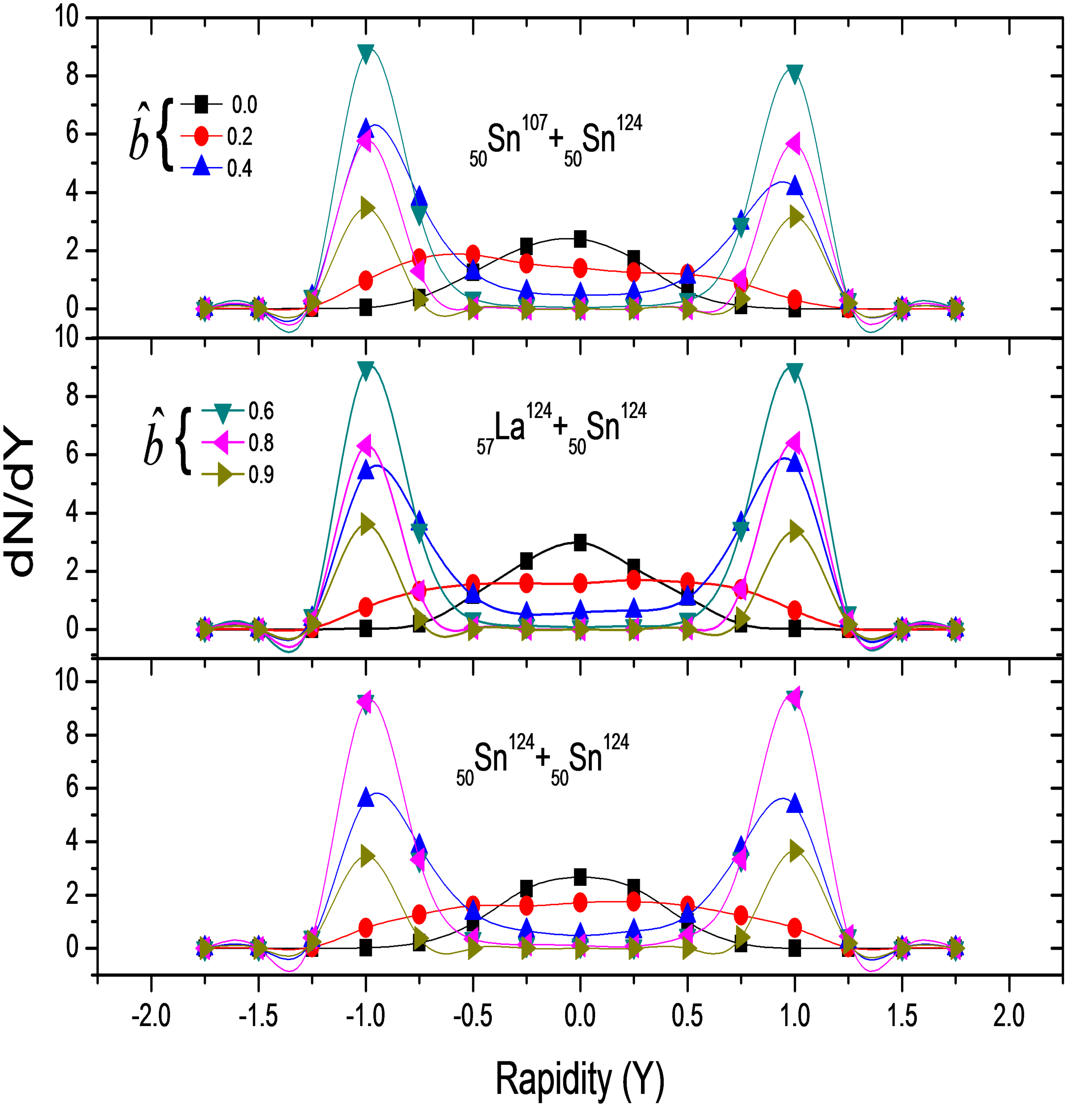


Fig (3.5) Rapidity distribution IMF' of reactions.

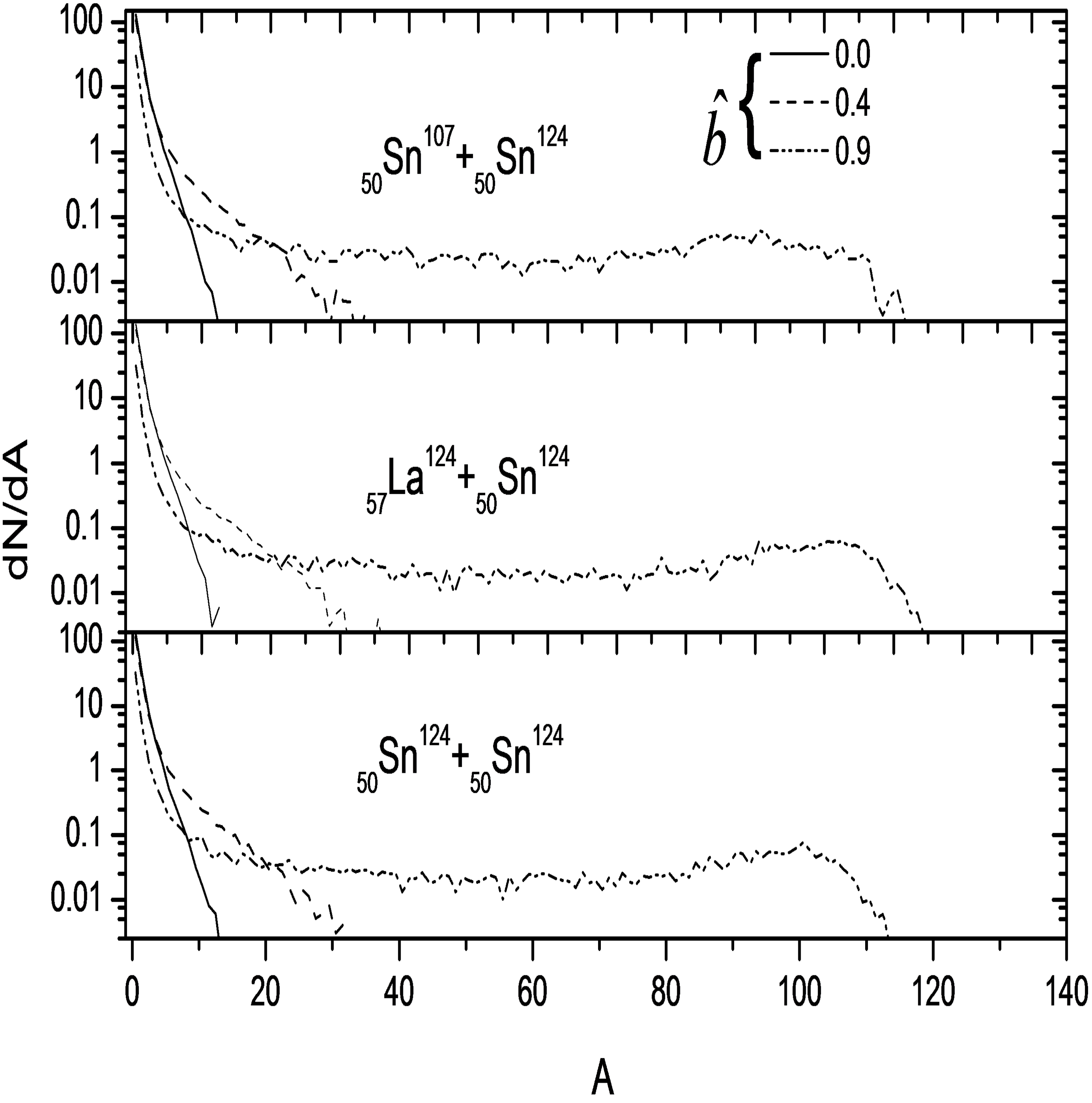


Fig.(3.6) The Mass distribution of $_{57}La^{124}+_{50}Sn^{124}$, $_{50}Sn^{124}+_{50}Sn^{124}$ and $_{50}Sn^{107}+_{50}Sn^{124}$.

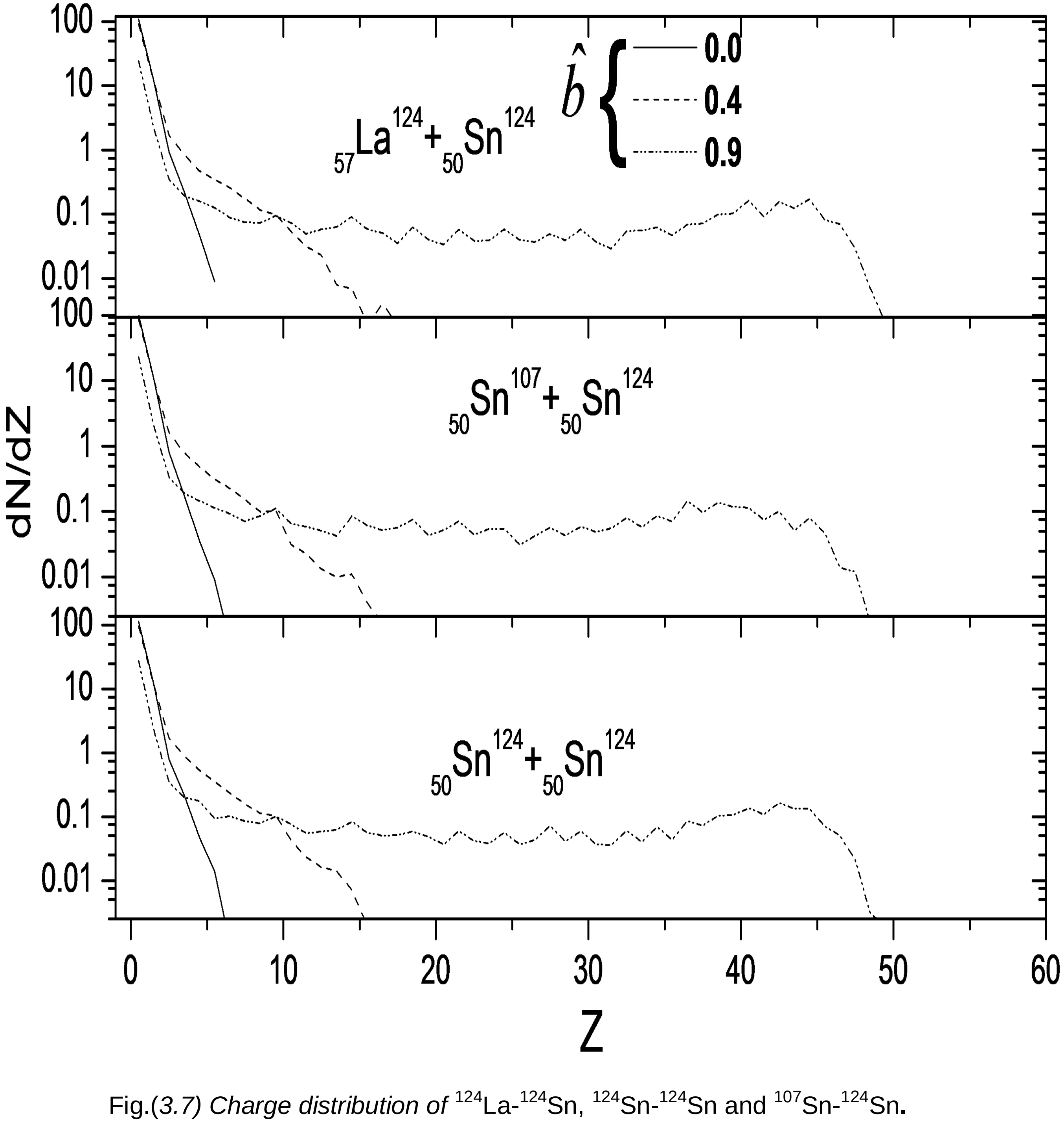


Fig.(*3.7) Charge distribution of* ^{124}La-^{124}Sn, ^{124}Sn-^{124}Sn and ^{107}Sn-^{124}Sn**.**

3.8 Impact Parameter Dependence:

In fig(3.8) we displayed the multiplicities as a function of scaled impact parameter($\hat{b}$=b/b$_{max}$). The displayed quantities are Free nucleons (1≤A≤1), LMF's (2≤A≤4) and IMF's (5≤A≤42) for the reactions $_{57}La^{124}+_{50}Sn^{124}$, $_{50}Sn^{124}+_{50}Sn^{124}$ and $_{50}Sn^{107}+_{50}Sn^{124}$ at energy 600 MeV/nucleon at time 200 fm/c. One can see that there is a similar behavior of LMF's and free nucleons but different for IMF's. IMF's shows the transition from multifragmentation to complete disassembly of nuclear matter so called 'rise and fall' of fragmentation product. At lower and higher impact parameters there are very few IMF's, due to the violent nature of central collision maximum energy deposition on the system therefore none or very few IMF's survive. At peripherals due to very small overlap, the system does not receive enough energy and hence cool down emitting few nucleons/LMF's. There is no rise and fall in the light mass fragments (LMF's) and free nucleon production with a change in the impact parameter. At lower impact parameter, energy depositions are more so that destruction of system into free nucleons and LMF's is more prominent. With decreasing overlapping (increasing impact parameter) multiplicity of free nucleons and LMF's decrease. This is indicating the source of origin for free, LMF's and IMF's. The clear indication of origin for free & LMF's is from the participant zone, while for IMF's is from spectator zone.

If one compares the figures for the symmetric systems, the production of all kind of fragments is more for the neutron rich systems as compared to neutron poor systems. This is indicating the importance of neutron rich system in intermediate energy heavy ion collisions.

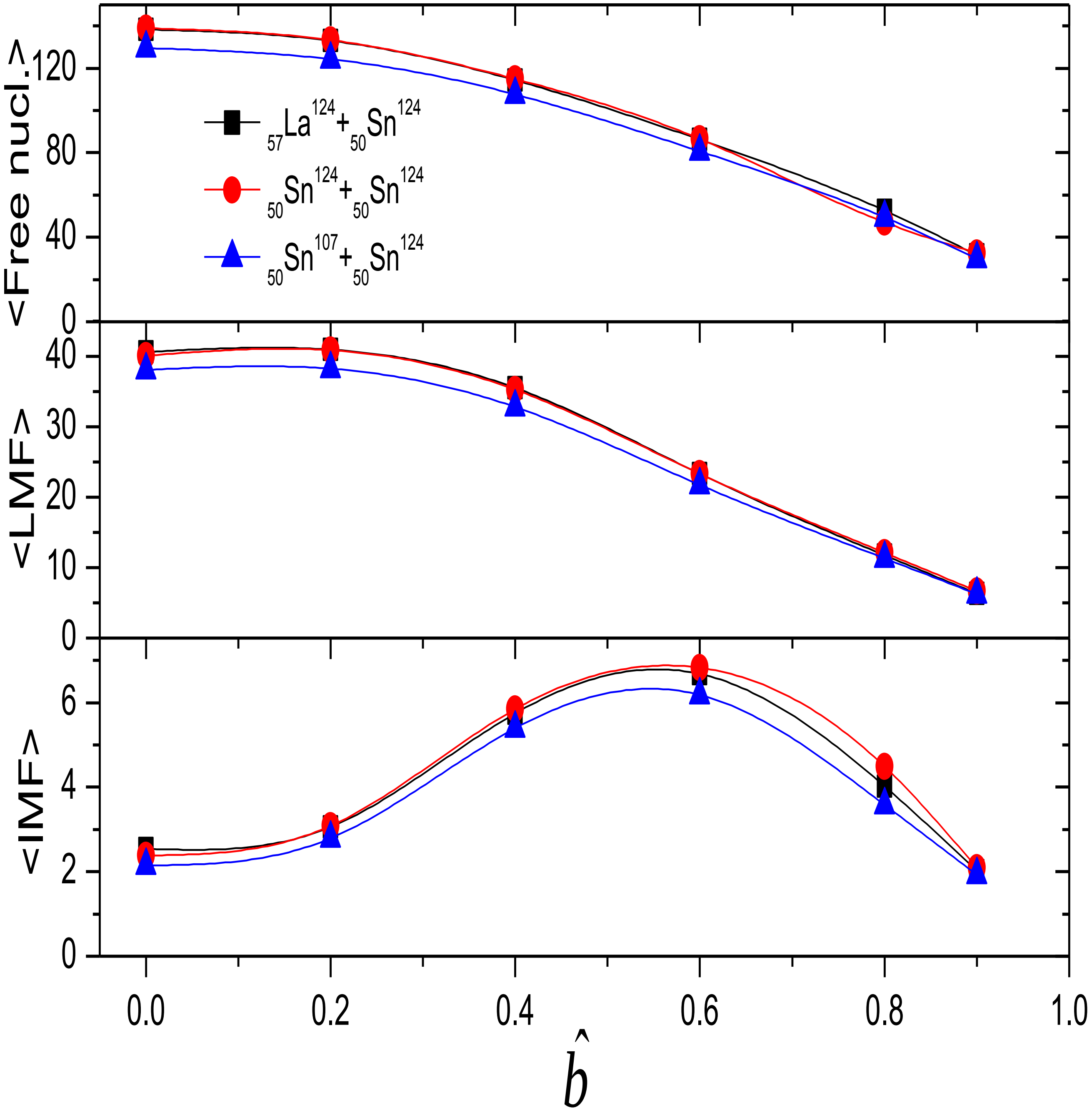
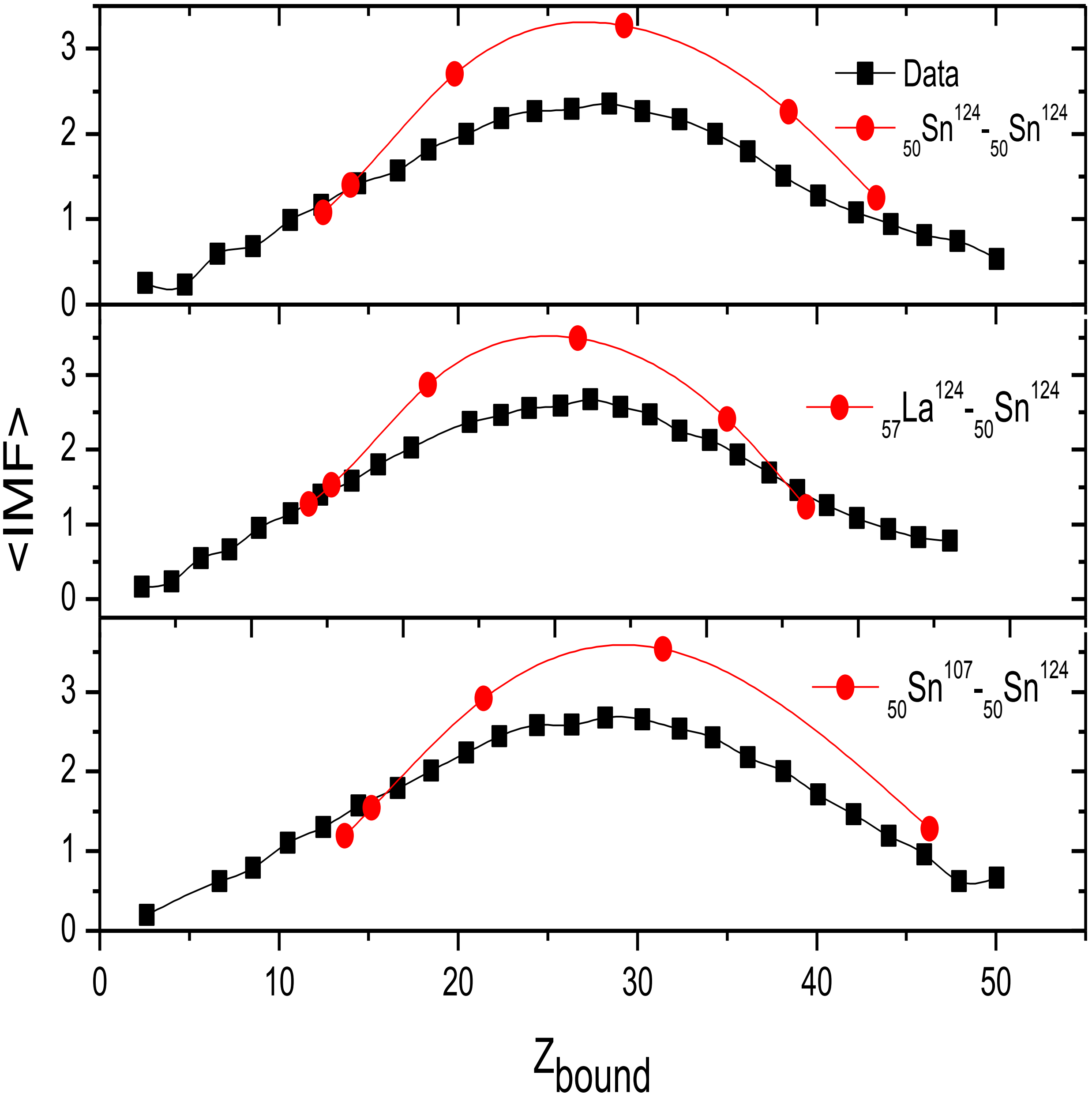


Fig.(3.8) Multiplicity as a function of impact parameter.

3.9 IMF production dependence on Projectile and Target mass:

The ALADIN results are the most complete piece of data available for multifragmentation. In heavy ion collisions energy depositions are reached which covers the range of particle evaporation to multifragmentation emission and the total disassembly of the nuclear matter so called the '*rise and fall'* of multifragmentation [9]. The most prominent feature of the multifragment decay is the universality of the fragment and fragment charge correlation. The loss of memory of the entrance channel is an indication that the equilibrium is attained prerior to the fragmentation stage of the reaction. Here we are comparing our results with experimental data of reactions ${}_{57}La^{124}+{}_{50}Sn^{124}$, ${}_{50}Sn^{124}+{}_{50}Sn^{124}$ and ${}_{50}Sn^{107}+{}_{50}Sn^{124}$ at energy 600 MeV/nucleon. In fig(3.9) we have shown IMF's as a function of Z_{bound} . The quantity Z_{bound} is defined as sum of all atomic number Z_i of all projectile fragment with $Z_i > 2$. Here we observe that at semi peripheral collisions multiplicity <IMF> shows a peak because most of the spectator source does not take part in collision and large number of IMF's are observed. In case of central collision the collisions are violent so there few number of IMF's observed at last for peripheral collisions very small portion of target and projectile overlap so again few number of IMF's observed most of the fragments goes out in heavy mass fragments (HMF's). In this way we get a clear '*rise and fall'* in multifragmentation emission. It is observed that IMF's shows the agreement with data at low impact parameters but fails at intermediate impact parameters. This failure is due to the drawbacks in the method of analysis MST which we had used in our analysis. MST method gives the heavy cluster at the time of high densities. To overcome this failure many attempts were made in literature to successfuly explain the experimental results [10].



Fig(3.9) Multiplicity of IMF.

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Chapter 4:

Summary and outlook:

This thesis contains a theoretical study of multifragmentation of three reactions ${}_{57}La^{124}+{}_{50}Sn^{124}$, ${}_{50}Sn^{124}+{}_{50}Sn^{124}$ and ${}_{50}Sn^{107}+{}_{50}Sn^{124}$. Isospin Quantum Molecular Dynamics (IQMD) is used to study these reactions at 600 MeV/nucleon energy and at different scaled impact parameters (0.0, 0.2, 0.4, 0.6, 0.8, 0.9). A brief introduction of multifragmentation and ALADIN spectrometer is discussed in **chapter 1.**

In **chapter 2.** We discussed the IQMD model for our present study.

In **chapter 3**. We have studied the detailed analysis of multifragmentation. Different parameters like time evolution, impact parameter dependence is studied for IMF's. it is concluded that free & LMF's have a different trend as compare to IMF's. This is due to different origin of formation. The rise and fall in the multiplicity of IMF's is observed. The rise & fall is further compared with the experimental data of ALADIN and are found to be in close agreement. The better agreement can be obtained by taking into account different methodology analysis.