On the IMF Multiplicity in $Au + Au$ Reactions

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Abstract

Intermediate mass fragment (IMF) multiplicity has been investigated for $Au + Au$ reactions at incident energies of 100, 250 and 400 MeV/A. From the analysis of the impact-parameter-dependence of the IMF multiplicity using our QMD plus statistical evaporation model, we found that 1) statistical decay process modifies the results greatly, and 2) the Fermi motion plays a role to increase the IMF multiplicity for whole impact-parameter range.

25.70.Mn, 25.70.Pq

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Intermediate mass fragment (IMF) emission is one of the central interest in heavy-ion reaction study because the observation of IMF is a good tool to study the dynamics and statistics of the violent heavy-ion collisions. There are many experimental data indicating a "multi-fragmentation" nature of the phenomenon but the total understanding of it is not yet achieved. What is clear is that we need a mechanism which is not described by the standard two-body reaction plus statistical evaporation mechanism. Not only the reaction mechanism but also the equation of state of the nuclear matter might be closely related to the IMF emission phenomenon.

Among various theoretical models, the molecular dynamics approach [1] occupies a special position with respect to its many-body dynamical nature. The property and performance of the model is not so clear, however, when both target and projectile are very heavy. There are not many models published so far for these very heavy systems because the calculation is so time-consuming and in addition, the stability of the ground state is hard to be achieved. In this report, we will attach the IMF multiplicity for very heavy system using QMD plus statistical decay model [2,3] which has several differences from the forgoing models.

Our concern is to check the ability of the molecular dynamics model to understand the multifragmentation reaction at relatively low incident energies. For that purpose, we adopted the Au+Au collisions for the incident energies per nucleon of 100, 250 and 400 MeV. For these reactions, there are published data of intermediate-mass-fragment (IMF, defined as fragment of $3 \leq Z \leq 30$) multiplicities as a function of the impact parameter [4]. These data are suitable for the check of the reaction model because the impact parameter dependence with three different incident energies gives detailed information to the reaction mechanism. In [4], these data were analyzed with QMD [5] and QPD [6] models, both of them based on the molecular dynamics approach. It was found that these two models underestimated the data much, especially at large impact parameters. To get rid of this failure, they tried [4] to connect two statistical cluster emission models. One is the combination of QMD [5] and statistical multifragmentation model [7] and the other is QPD [6] and expanding evaporating source model [8]. These combined models are able to yield increased multiplicity at
large impact parameters. However, the impact parameter dependence for 100MeV incident energy was totally broken with the addition of these cluster emission models. From these observations, the conclusion [4] was that the ability of the molecular dynamics approach to understand the multifragmentation was questionable.

We think, however, that we should try more extended survey of the performance of the molecular dynamics model before coming to the final conclusion. For that purpose, we will present calculations based on our model of molecular dynamics. We use exactly the same model as was discussed in [2,3]. This model proved to reproduce the experimental data well for nucleon-induced reactions from about 100MeV up to 3GeV incident energies. By combining the QMD model and the standard statistical model, they were able to reproduce the emission of particles from 1MeV to several GeV. There are essentially two points in this model which differ from the foregoing models used in [4]. One is that this model produced the ground state of the heavy nuclei without introducing the Pauli potential. Therefore, all the nucleons are moving around which is in contrast with the models of [5,6] where the internal velocities of the nucleons are very small due to the way of constructing the ground state. The second point is that we combine the statistical model [2], which is based on the simple evaporation model, to our molecular dynamics calculations. We don’t assume any fragmentation mechanism in this part of the model because our concern is to check the ability of the dynamical model to describe the multifragmentation. Another reason not to introduce the statistical fragmentation model is because it’s hard to avoid the double counting between dynamical part and statistical part. It will turn out that the influence of the standard statistical model we used in this paper is very large and it changes the results greatly, which will be one of our main conclusions of this paper.

The details of our model are given in [2,3] and we will not repeat them here but point out some essences: A nucleon is represented by a Gaussian wave packet of the width fixed as $L = 2.0 \text{fm}^2$ (cf.Eq.(1) of [2] ) and the total wave function is assumed as a direct product of these single-particle wave functions. The basic equations of motion are determined from the time-dependent variational principle where the basic Hamiltonian is composed of the
Skyrme and Coulomb interactions and symmetry potential. The soft EOM which gives compressibility of $237.3\,MeV$ is adopted but the effect caused by switching to hard EOM will also be discussed in this paper. The coefficient of the symmetry potential is fixed as $Cs = 25\,MeV$ (cf. Eq.(5) of [2]). No momentum-dependent interaction is included and the ground state is prepared with the condition that the experimental binding energy is reproduced. We should mention here that if we include the momentum dependent term, it’s almost impossible to prepare the ground state of very heavy nuclei without introducing the Pauli potential or other stabilizing mechanisms. For the collision term, included are the elastic scattering of nucleons and pions, and inelastic channels of $\Delta$ and $N^*$ resonances are treated explicitly (cf.Eq.(9) of [2]). For the other details of the inelastic collisions, see [2]. The relativistic kinematics are adopted and in addition, the argument of the interaction is defined as Lorentz scalar quantity which has a merit of compensating the unreasonably large Lorentz contraction effect(cf. Eqs.(29-42) of [2]).

Calculations are done by counting the number of IMF ($3 \leq Z \leq 30$). For the classification of fragments, we used a minimum distance chain procedure, i.e., two nucleons are considered to be bound in a fragment if the distance between their centers of Gaussian wave packets is smaller than $4.0\,fm$. We checked the dependence of the final results on this minimum distance and found that it causes little change if the switching time from the QMD calculation to statistical model calculation is not too short. The standard switching time used in [2] for nucleon induced reactions was $100\,fm/c$. In the present case of $Au + Au$ system, this choice is a little too short and we fixed the time as $200\,fm/c$, which value was also used in [5]. In $100\,fm/c$, the fragment separation for low impact parameters is not finished yet, especially for low incident energies. The choice of switching time $100\,fm/c$ therefore causes the change of the final results depending on the minimum distance. For the choice of the switching time between $200\,fm/c$ to $400\,fm/c$, we found that the physical quantities calculated in this paper is rather stable, the deviation is within a few percent. The same statistical model as [2] was used after this switching time in which the emissions of $n, p, d, t, ^3He$ and $^4He$ are explicitly included. The inclusion of heavier fragments is expected
to modify the result somewhat but not much.

In fig.1, we plot the mean IMF multiplicity as a function of the impact parameter b for three different incident energies. Experimentally, the impact parameter b is determined with the total charge multiplicity. IMF multiplicity data are plotted with solid circles with error bars [4]. Our calculation at $t = 200\, fm/c$ using the QMD output is shown by solid lines. For comparison, two other theoretical calculations performed in [4] are given: one is the QMD model calculation [5] which is shown by the dashed lines and the other is the QPD model calculation [6] which is shown by the dash-dotted lines, both are taken from Fig.2 of [4]. The filtering of the experimental acceptance is not included in all calculations given in this paper, since the filter was not available for us. The change caused by the filter is seen in figs.2 and 3 of [4] for four kinds of calculations given there. One has to keep in mind of this fact in the following discussion on the comparison between calculations and data.

For $E/A = 100\, MeV$, we achieved a good reproduction of the data, which is much better than other two theoretical calculations. For two higher energies, our calculations deviate from the data in two ways: one is the shift of the peak to lower energy and another is the overestimation of IMF at low impact parameters. The shift of peak to lower energies seems to be common to other two theoretical calculations. It looks that the shift of our calculation is not so large as compared to other two calculations. On the other hand, the overestimation of the multiplicity at low impact parameters are not seen in these two calculations. They underestimate the data for whole impact parameter values. As a whole, our calculations gives a larger IMF multiplicity than other two model calculations.

A rather large deviation of our results compared with other two model calculations is the point of interest. Out results are nearer to the QMD of [5] but the IMF multiplicity is larger in our case, especially at low and high impact parameter values. To our regret, the calculation of $E/A = 250\, MeV$ is lacking for the model of [5] in [4] and the systematic comparison is not perfect. When we compare our results with those of QPD [6], we observe still larger difference. The reason of these differences is not very clear but we think the following consideration is important. As we mentioned earlier, the main difference of our
model to other two models is that they included Pauli potential. As a result, the velocity of each nucleon has zero or almost zero value at the ground state although it has finite momentum value. The Fermi motion is much suppressed in their treatment compared with ours and thus no wonder that fragmentation dynamics also changes. We cannot say which model is better at this stage but it looks that Fermi motion has tendency to increase the IMF yield in these reactions. The effect of Fermi motion was clearly observed in the nucleon-induced reaction [3].

In fig.2, we show our results of the b-dependence of IMF multiplicity after we transferred the results of our QMD output at 200\(fm/c\) to statistical evaporation code and calculated the decay chains, which is shown by the solid lines. We gave the same data as in fig.1 and also two other model calculations taken from fig.3 of [4]: one is QMD [5] plus statistical multifragmentation model (SMM) [7] which is shown by the dashed lines and the other is QPD [6] plus expanding evaporating source (EES) model [8] which is shown by the dash-dotted lines.

First of all, we observe a very big change caused by our statistical evaporation model by comparing with fig.1. Our statistical model is a standard evaporation model which assumes no special fragmentation mechanism. Therefore the change of our calculations from fig.1 to fig.2 means that the decay of excited fragment by evaporating light charged particles and neutron is quite important to count the IMF multiplicity. The raw QMD results should not be compared with experimental data. As a result of this evaporation, our calculated values are reduced quite much, especially for the low impact parameters. The overestimation at low impact parameters and a resultant skewed b-dependence shape observed in fig.1 no more exist. The shape of the b-dependence becomes very good for all three incident energies. The problem is the overall underestimation of the data and a shift of the b-dependence shape to lower b values. In contrast, other model calculations show a very different behavior. For \(E/A = 400MeV\), many IMF are produced in the statistical calculation stage and they overestimate the data, especially in QMD plus SMM model calculations. One should notice, however, that this model reproduces the data well after the filter is applied as is seen in
Fig. 3 of [4]. The QPD plus ESS model underestimates the data at low and high b values. At $E/A = 100\text{MeV}$, QMD plus SMM model gives larger deviation from data than QMD alone which is shown in fig.1. It is hard to draw conclusion for these other calculations but we think our results give quite a reasonable b-dependence behavior and therefore, our OMD plus statistical decay model hits some basic mechanism of IMF production. We should find a reasonable explanation, however, why the IMF value is about the half of the experimental data. In this respect, we tried the calculations with different Skyrme interaction parameters which give a hard equation of state with the compressibility of 380MeV. The IMF multiplicity obtained with this interaction, however, changed only a little from the one obtained with the soft equation of state. The typical change was a few percent and thus the equation of state is not the origin of the underestimation of IMF multiplicity.

In concluding, from the analysis of the impact parameter dependence of IMF multiplicity for $Au + Au$ collisions at $E/A = 100, 250$ and $400\text{MeV}$ with QMD plus statistical evaporation model, two important findings are obtained. First is the necessity of calculating the statistical decay of the excited fragments produced in the molecular dynamics calculations before comparing with the experimental data. Inclusion of this greatly changes the results, both for the b-dependence and for the absolute values of IMF. Final b-dependent shape resembles the data but absolute values are about the half of the data. Second is the importance of the Fermi motion for whole region of impact parameters. Suppression of Fermi motion caused by introducing Pauli potential has tendency to result in a further shortage of calculated IMF multiplicities.


Figure Captions

Fig.1 IMF multiplicities for three incident energies of $Au + Au$ reactions plotted as functions of the impact parameter $b$. Data [4] are shown by the solid points and our QMD calculations are shown by the solid lines. Dashed lines and dash-dotted lines depict the QMD [5] and QPD [6] calculations, respectively, both taken from [4].

Fig.2 Same as fig.1 for data points. Solid lines represent our IMF multiplicities after statistical decay. Dashed lines and dash-dotted lines depict the QMD+SMM and QPD+EES calculations, respectively, taken from [4].