Isospin fractionation in the nucleon emissions and fragment emissions in the intermediate energy heavy ion collisions

Jian-Ye Liu 1,2,3,5, Wen-Jun Guo 2, Yong Zhong Xing 1,3,5, Hang Liu 4

1Institute for the theory of modern physics, Tianshui Normal University, Gansu, Tianshui 741000, P. R. China
2Institute of Modern Physics, Chinese Academy of Sciences, P.O.Box 31, Lanzhou 730000, P.R. China
3Center of Theoretical Nuclear Physics, National Laboratory of Heavy Ion Accelerator Lanzhou 730000, P.R. China
4Department of Physics and Astronomy, Ohio University, Athens, OH 45701, U.S.A
5CCAST(Word Lab.), P.O.Box 8730, Beijing 100080 Lanzhou 730000, P.R. China

Abstract

The degree of isospin fractionation is measured by \( \frac{N/Z}_n / \frac{N/Z}_{N_{imf}} \), where \( \frac{N/Z}_n \) and \( \frac{N/Z}_{N_{imf}} \) are the saturated neutron-proton ratio of nucleon emissions (gas phase) and that of fragment emissions (liquid phase) in heavy ion collision at intermediate energy. The calculated results by using the isospin-dependent quantum molecular dynamics model show that the degree of isospin fractionation is sensitive to the neutron-proton ratio of colliding system but insensitive to the difference between the neutron-proton ratio of target and that of projectile. In particular, the degree of isospin fractionation sensitively depends on the symmetry potential. However its dependences on the isospin dependent in-medium nucleon-nucleon cross section and momentum dependent interaction are rather weak. The nucleon emission (gas phase) mainly determines the dynamical behavior of the degree of isospin fractionation in the isospin fractionation process, compared to the effect of fragment emission. In this case, we propose that \( \frac{N/Z}_n / \frac{N/Z}_{N_{imf}} \) or \( \frac{N/Z}_n \) can be directly compared with the experimental data so that the information about symmetry potential can be obtained.
1 Introduction

The studies of the isospin effects at intermediate energy heavy ion collision can be used to get the information about isospin dependent in-medium nucleon-nucleon cross section and isospin dependent mean field (symmetry potential). In order to obtain this information several interesting isospin effects in heavy ion collisions have been explored both experimentally and theoretically over the last few years[1 – 16, 26 – 28]. Bao-An Li et al investigated the isospin effect of the mean field and showed that the neutron-proton ratio of preequilibrium nucleon emissions, the neutron-proton differential flow and proton ellipse flow are probes for extracting the information of the symmetry potential [1, 2, 14, 15, 16]. R.Pak et al have found that the isospin dependences of collective flow and balance energy are mainly originated from the isospin-dependent in-medium nucleon-nucleon cross section [17, 18]. In order to extract above information Bao-An Li , M.Di Toro , M. Colonna and V.Baran et al studied the isospin fractionation in the intermediate energy heavy ion collisions in recent years [15, 16, 19, 30]. The isospin fractionation is an unequal partitioning of the neutron to proton ratio N/Z of unstable isospin asymmetry nuclear matter in the low and high density regions. Bao An Li ’s work proposed a very useful point of review about isospin fractionation [14]. V.Baran et al studied the isospin fractionation dynamics in details and gave more interesting results to explain the isospin fractionation dynamics[30]. An indication of this phenomenon has been found recently in the intermediate energy heavy-ion experiments by H. Xu et al [9]. However the two essential ingredients in heavy ion collision dynamics, the isospin dependent in-medium nucleon-nucleon cross section and the symmetry potential have not been well determined so far. In order to compare with experimental data directly it is important to quantify the gas phase and the liquid phase as well as their dependences on the dynamical ingredients in isospin fractionation process. Based on the isospin dependent quantum molecular dynamics model (IQMD)[2, 20, 21, 22, 26] we
investigated the degree of isospin fractionation \((N/Z)_n/(N/Z)_{Nimf}\), where \((N/Z)_n\) and \((N/Z)_{Nimf}\) are the saturated neutron to proton ratio of nucleon emissions and that of the fragment emissions respectively. We investigated the dependences of \((N/Z)_n/(N/Z)_{Nimf}\) on the symmetry potential, isospin dependent in-medium nucleon nucleon cross section and momentum dependent interaction in some reaction processes. The calculated results show that \((N/Z)_n/(N/Z)_{Nimf}\) only sensitively depends on symmetry potential for neutron-rich colliding system. We simulated and discussed the dependences of isospin fractionation degree on the neutron proton ratio of colliding system and the difference between neutron proton ratio of projectile and that of target. The roles of gas phase and liquid phase in the isospin fractionation process are also investigated in detail.

2 IQMD Model

As we have known that quantum molecular dynamics (QMD)[21, 22] contains two dynamical ingredients: density dependent mean field and in-medium nucleon nucleon cross section. To describe isospin effects appropriately, QMD should be modified accordingly. The density dependent mean field should contain correct isospin terms, including the symmetry potential and the Coulomb potential. The in-medium \(N-N\) cross section should identify neutron-neutron, proton-proton and neutron-proton collisions, in which Pauli blocking should be counted by distinguishing neutrons and protons.

Considering the above ingredients, we made important modifications in QMD to obtain the isospin dependent quantum molecular dynamics (IQMD). In IQMD model the initial density distributions of the colliding nuclei are from the calculations by applying the Skyrme-Hatree-Fock model with the parameter set \(SKM^*[23]\). The code of IQMD without the collision term is used to obtain the ground state properties of the colliding nuclei. The ground state properties, such as binding energies and RMS radii etc, are consistent with the experimental data. Thus the parameters of interaction potentials are fixed and used as input data in the dynamical calculations by IQMD. In our calculations the interaction potentials are taken as:

\[
U(\rho) = U^{Sky} + U^{Coul} + U^{sym} + U^{Yuk} + U^{MDI} + U^{Pauli},
\]
where $U^{\text{Sky}}, U^{\text{Coul}}, U^{\text{Yuk}}$ and $U^{\text{Pauli}}$ are Skyrme potential, Coulomb potential, Yukawa potential and Pauli potential. $U^{\text{MDI}}$ is momentum dependent interaction with the form of

$$U^{\text{MDI}} = t_4 \ln^2 \left[ t_5 \left( \frac{\mathbf{p}_1}{\mathbf{p}_2} \right)^2 + 1 \right] \frac{\rho}{\rho_0}. \quad (2)$$

The more detailed physics ingredients and their numerical realization in the IQMD model can be found in Refs [Chapter 10 in Ref.2,20,21,22,26]. $U^{\text{sym}}$ is the symmetry potential. In this paper, three different forms of $U^{\text{sym}}$ are used [1,15],

$$U^{\text{sym}}_1 = c F_1(u) \delta \tau_z \quad (3)$$
$$U^{\text{sym}}_2 = c F_2(u) \left[ \delta \tau_z - \frac{1}{4} \delta^2 \right] \quad (4)$$
$$U^{\text{sym}}_3 = \frac{2c F_3(u) \delta \tau_z}{1 + u} + \frac{c F_3(u) \delta^2}{(1 + u)^2} \quad (5)$$

with

$$\tau_z = \begin{cases} 1 & \text{for neutron} \\ -1 & \text{for proton} \end{cases}$$

Here $c$ is the strength of symmetry potential, with the value of 32MeV, $F_1(u) = u$, $F_2(u) = u^{1/2}$ and $F_3(u) = u^2$, $u = \frac{\rho}{\rho_0}$. $\delta$ is the relative neutron excess $\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$. $\rho, \rho_0, \rho_n$ and $\rho_p$ are the total, normal, neutron and proton densities respectively.

The curvatures $K^{\text{sym}}$ of $U^{\text{sym}}_1$, $U^{\text{sym}}_2$ and $U^{\text{sym}}_3$ are -27 MeV, -69 MeV and 61 MeV respectively.

An empirical density dependent expression of the in-medium N-N cross section is [24]:

$$\sigma_{NN} = (1 + \alpha \frac{\rho}{\rho_0}) \sigma_{NN}^{\text{free}} \quad (6)$$

with the parameter $\alpha \approx -0.2$ which can well reproduce the flow data. Here $\sigma_{NN}^{\text{free}}$ is the experimental nucleon nucleon cross section[25]. The free neutron-proton cross section is about 3 times larger than the free proton-proton or the free neutron-neutron cross section below about 400 MeV. It should be pointed out that the ratio $\sigma_{np}/\sigma_{pp}$ in the nuclear medium sensitively depends on the evolutions of the nuclear density distribution and beam energy. Here we made use of equation (6) to take the medium effect of two-body collision into account, in which the neutron-proton cross section is always larger than the neutron-neutron or proton-proton cross section in
the medium at the beam energies studied in this paper.

3 Results and Discussions

The isospin effect of the in-medium nucleon nucleon cross section on the observables is defined by the difference between the observables from an isospin dependent nucleon nucleon cross section $\sigma^{iso}$ and those from an isospin independent nucleon nucleon cross section $\sigma^{noiso}$. The $\sigma^{iso}$ is illustrated by $\sigma_{np} \geq \sigma_{nn} = \sigma_{pp}$ where $\sigma_{np}, \sigma_{nn}, \sigma_{pp}$ are neutron proton, neutron neutron and proton proton cross sections in medium respectively. In $(N/Z)_{n}/(N/Z)_{imf}$, the multiplicity of intermediate mass fragments $N_{imf}$ includes all fragments with the charge number from 2 to $(Z_p + Z_t)/2$, where $Z_p$ and $Z_t$ are the charge numbers of the projectile and target respectively.

3.1 The dependences of the degree of isospin fractionation on the symmetry potential and isospin dependent in-medium nucleon nucleon cross section

Fig.1 shows the impact parameter averaged values of $\langle (N/Z)_{n} \rangle_{b} / \langle (N/Z)_{imf} \rangle_{b}$ as a function of the beam energy $E$ in the reaction system $^{124}Sn + ^{124}Sn$. There are four different cases: $U_{1}^{sym} + \sigma^{iso}$ (solid line), $U_{2}^{sym} + \sigma^{iso}$ (dashed line), $U_{2}^{sym} + \sigma^{noiso}$ (dot-dashed line) and $U_{1}^{sym} + \sigma^{noiso}$ (dot line).

It is found that for the different nucleon nucleon cross sections, $\sigma^{iso}$ and $\sigma^{noiso}$, the variations among the $(N/Z)_{n}/(N/Z)_{imf}$ are smaller when the symmetry potential is fixed as either $U_{2}^{sym}$ or $U_{1}^{sym}$. However for different symmetry potentials $U_{2}^{sym}$ and $U_{1}^{sym}$ the gaps between the $(N/Z)_{n}/(N/Z)_{imf}$ are larger when the nucleon nucleon cross section is fixed as either $\sigma^{iso}$ or $\sigma^{noiso}$. So it might be concluded that $(N/Z)_{n}/(N/Z)_{imf}$ sensitively depends on the symmetry potential and weakly on the isospin effect of in-medium nucleon nucleon cross section. More complete understanding of the isospin fractionation processes can be obtained from the analysis of the density dependent chemical potentials for neutrons and protons [30]. As one
part of chemical potential, the symmetry potential is repulsive for neutrons and attractive for protons in the expanding process of the colliding system. This leads to the different chemical potential degradations with nuclear density $\rho_q$ for the neutron and proton in the low density region below normal nuclear density. However the mass flow in the nonequilibrium expanding process is determined by the difference in the local values of the chemical potential and such difference directs the system from higher chemical potential region into lower values until equilibrium. This transport effect induces the unstable isospin asymmetric nuclear matter to be separated into a neutron-rich low density phase and a neutron-poor high density phase for the neutron-rich system. Namely it is the different chemical potential degradations with nuclear density for neutrons and protons below normal nuclear density that induces the isospin fractionation.

According to above analysis the symmetry potential in the chemical potential is a main dynamical ingredient for producing the isospin fractionation but the influence of two-body collision on it is rather weak in the beam energy region in this paper.

### 3.2 The dependence of $(N/Z)_n/(N/Z)_{Nimf}$ on neutron to proton ratio of the colliding system

In order to investigate the evolution of $(N/Z)_n/(N/Z)_{Nimf}$ with the neutron to proton ratio of the colliding system, Fig.2 shows the $(N/Z)_n/(N/Z)_{Nimf}$ as a function of the neutron-proton ratio of the colliding system for the reactions $^{104}Sn +^{104}Sn, ^{112}Sn +^{112}Sn$ and $^{124}Sn +^{124}Sn$ at the beam energy $E=50$ MeV/nucleon, impact parameter $b=0.0$ fm (right window) and $4.0$ fm (left window). The neutron to proton ratios of the above three colliding systems are 1.01,1.34 and 1.48. In Fig.2 there are three different symmetry potentials $U_{1}^{sym}$, $U_{2}^{sym}$ and $U_{3}^{sym}$. The calculation results of the three reactions show that the $(N/Z)_n/(N/Z)_{Nimf}$ and its dependence on the symmetry potential are enhanced with increasing the neutron to proton ratio of the colliding systems. In particular, the $(N/Z)_n/(N/Z)_{Nimf}$ is larger than 1.0 for the neutron-rich system $^{124}Sn +^{124}Sn$, which means the neutron-rich gas phase and the neutron-poor liquid phase, compared to the neutron to proton ratio of colliding system. It is also found that the $(N/Z)_n/(N/Z)_{Nimf}$ is enhanced.
with increasing symmetry potential strength. The amplitudes of \((N/Z)_n/(N/Z)_{N_{imf}}\) from large to small correspond to the order of symmetry potential strength. The order of symmetry potential strengths in the lower density region below the normal nuclear density are from \(U_2^{sym}\) (dot line), \(U_1^{sym}\) (solid line) to \(U_3^{sym}\) (dot-dashed line) for the neutron-rich system. The order of symmetry potential strength below the normal density is contrary to those at the normal nuclear density (see Fig.4.1 in [1]). However for the neutron-poor systems, such as, \(^{104}\text{Sn}+^{104}\text{Sn}\) and \(^{112}\text{Sn}+^{112}\text{Sn}\) the values of \((N/Z)_n/(N/Z)_{N_{imf}}\) are decreased gradually below 1.0 with decreasing the neutron-proton ratio of colliding system. This means the neutron-poor gas phase and neutron-rich liquid phase, compared to the neutron proton ratio of colliding system. In the isospin fractionation process for the neutron-poor system, \((N/Z)_n\) is deceased due to neutron-poor colliding system. On the other hand, \((N/Z)_{N_{imf}}\) is increased, compared to the initial neutron proton ratio of neutron-poor colliding system. This can be explained by the fact that the excited primary neutron-poor fragments decays to a stable neutron-rich one which is closer to the beta stable line.

### 3.3 The dependences of \(< (N/Z)_n >_b / (N/Z)_{N_{imf}} >_b\) on the gas phase and liquid phase

In order to study the dependences of \(< (N/Z)_n >_b / (N/Z)_{N_{imf}} >_b\) on the gas phase and liquid phase, Fig.3 shows the impact parameter averaged values of \(< (N/Z)_n >_b\) (in the left panel) and \(< (N/Z)_{N_{imf}} >_b\) (in the right panel) as a function of the beam energy \(E\) for the different symmetry potentials \(U_1^{sym}\) and \(U_2^{sym}\). The incident channel conditions and the line symbols in Fig.3 are the same as those in Fig.1. It is clear to see that the dynamical behavior of \(< (N/Z)_n >_b\) (gas phase) is very similar to that of \(< (N/Z)_n >_b / (N/Z)_{N_{imf}} >_b\) in Fig.1. However all lines for \(< (N/Z)_{N_{imf}} >_b\) (liquid phase) corresponding the different symmetry potentials \(U_1^{sym}\) and \(U_3^{sym}\) as well as different nucleon nucleon cross sections \(\sigma^{iso}\) and \(\sigma^{noiso}\) are very close to each other. Namely \(< (N/Z)_{N_{imf}} >_b\) is insensitive to both the symmetry potential and the isospin effect of in-medium nucleon nucleon cross section. So the nucleon emissions (gas phase) mainly determine the dynamical behavior of the degree of isospin fractionation for the neutron-rich colliding system in the beam energy region studied here.
It should be pointed out that the calculated results in above three figures are taken by accounting the time up to 300 fm/c. This time roughly corresponds to the freeze-out time because during fragmentation stage the colliding system breaks up and the fragment formation process occurs up to the time around 240-300 fm/c in the beam energy region studied here. From the time evolution of impact parameter averaged value of nucleon emission number $<N_n>_b$ and that of fragment emission number $<N_{imf}>_b$ in the reaction $^{124}Sn + ^{124}Sn$ at E= 50 MeV/nucleon shown in Fig.4.b, we can see that $<N_{imf}>_b$ almost stabilizes after 250 fm/c, even though $<N_n>_b$ continues to be enhanced very slowly after 250 fm/c. However the impact parameter averaged value of the neutron proton ratio of nucleon emission and that of fragment emission $<(N/Z)_n>_b$ and $<(N/Z)_{N_{imf}}>_b$ shown in Fig.4.a are almost constant after 200 fm/c.

From above analysis and discussion in Fig.4 we might conclude that even though the simulation by IQMD could not include all secondary decaies, it does not matter too much on the values of $<(N/Z)_n>_b$ and $<(N/Z)_{N_{imf}}>_b$ at 300 fm/c and the conclusions. Furthermore the observable for comparing with the experimental data in this paper is $<(N/Z)_n>_b/<(N/Z)_{N_{imf}}>_b$.

3.4 The dependence of $(N/Z)_n/(N/Z)_{N_{imf}}$ on the difference between neutron to proton ratios for projectile and target

Fig.5 shows the time evolution of $(N/Z)_n/(N/Z)_{N_{imf}}$ in the reaction systems which have different neutron-proton ratios for target and projectile but with the same mass and the same neutron-proton ratio of colliding system, the same $U_i^{sym}$ and the same $\sigma^{iso}$ at beam energy E=50 MeV/nucleon and impact parameter of 2.0 fm. In Fig.5 there are two couples of reactions $^{74}Zn + ^{74}Se$ and $^{74}Ge + ^{74}Ge$ (left window) as well as $^{132}Sn + ^{112}Sn$ and $^{124}Sn + ^{124}Sn$ (right window). The neutron-proton ratios of projectile, target and colliding system are listed in table 1.

| Nucleus       | $^{74}Zn$ | $^{74}Se$ | $^{74}Ge$ | $^{112}Sn$ | $^{132}Sn$ | $^{124}Sn$ |
|---------------|-----------|-----------|-----------|-------------|-------------|-------------|
| N/Z           | 1.47      | 1.18      | 1.31      | 1.32        | 1.64        | 1.48        |

| system       | $^{74}Zn + ^{74}Se$ | $^{74}Ge + ^{74}Ge$ | $^{132}Sn + ^{112}Sn$ | $^{134}Sn + ^{116}Sn$ | $^{125}Sn + ^{125}Sn$ |
|--------------|---------------------|---------------------|----------------------|----------------------|----------------------|
| N/Z          | 1.31                | 1.31                | 1.48                 | 1.48                 | 1.48                 |
From Fig.5 it is clear to see that all solid lines and all dashed lines are very close to each other for the same mass and the same neutron proton ratio of each couple of colliding systems. It shows that the difference between the neutron-proton ratios for target and projectile doesn’t influence isospin fractionation process, instead it sensitively depends on the neutron-proton ratio of colliding system as observed in Fig.2.

It is worth mentioning that because the scaling time of the isospin fractionation process is faster than that of fragmentation process, \((N/Z)_n\) is much larger than \((N/Z)_{N_{imf}}\) before 125 fm/c. This indicates that the large fluctuation before 100 fm/c, then \((N/Z)_n\) and \((N/Z)_{N_{imf}}\) gradually approach their equilibrium values with the increasing colliding time. This is why the beginning time of the time evolutions for figures is started at 100 fm/c.

### 3.5 The role of MDI on the dynamical process of isospin fractionation

The nonlocal property of the nuclear interaction leads to a repulsive momentum dependent interaction \((U^{MDI})\) in the intermediate energy heavy ion collisions. In order to study the influence of the \(U^{MDI}\) on the dynamical process of isospin fractionation Fig.6 shows the time evolution of impact parameter averaged values of \(<(N/Z)_n>_b / <(N/Z)_{N_{imf}}>_b\) with the same \(\sigma^{iso}\) but different symmetry potentials \(U_1^{sym}\) and \(U_2^{sym}\). In calculations we consider momentum dependent interaction \(U^{MDI}\) and momentum independent interaction \(U^{noMDI}\) for the reaction \(^{124}Sn + ^{124}Sn\) at E= 50 MeV/nucleon. There are four cases: \(U_1^{sym} + U^{MDI} ; U_1^{sym} + U^{noMDI} ; U_2^{sym} + U^{MDI}\) and \(U_2^{sym} + U^{noMDI}\). The gap between the values of \(<(N/Z)_n>_b / <(N/Z)_{N_{imf}}>_b\) is smaller for the \(U^{MDI}\) and \(U^{noMDI}\) with the same \(U_1^{sym}\) or \(U_2^{sym}\). However, the gap between the values of \(<(N/Z)_n>_b / <(N/Z)_{N_{imf}}>_b\) is larger for the same the \(U^{MDI}\) or \(U^{noMDI}\) but different symmetry potentials. It turns out that the influence of \(U^{MDI}\) on the isospin fractionation process is not obvious because the emission probabilities induced by \(U^{MDI}\) are about the same for the neutrons and protons.
4 Summary and conclusions

In summary, from the calculation results we can get following conclusions: (1) The $< (N/Z)_n >_b / < (N/Z)_{N_{imf}} >_b$ is enhanced with increasing the neutron to proton ratio of colliding system and symmetry potential strength for neutron-rich system. However, the isospin fractionation process is insensitive to all these ingredients for the neutron-poor system in beam energy region studied here.

(2) In particular, $< (N/Z)_n >_b / < (N/Z)_{N_{imf}} >_b$ and $< (N/Z)_n >_b$ sensitively depend on the symmetry potential but weakly on the isospin effect of in-medium nucleon-nucleon cross section and momentum dependent interaction for the neutron-rich system.

(3) The dynamical behavior of $< (N/Z)_n >_b / < (N/Z)_{N_{imf}} >_b$ is mainly determined by the nucleon emissions (gas phase).

(4) The $(N/Z)_n/(N/Z)_{N_{imf}}$ sensitively depends on the neutron to proton ratio of colliding system but weakly on the difference between the neutron proton ratios for target and projectile.

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**Figure captions**

**Fig.1** The impact parameter averaged value of \(< (N/Z)_n >_b / < (N/Z)_{N_{imf}} >_b\) as a function of the beam energy E for the reaction system \(^{124}Sn + ^{124}Sn\) and the different symmetry potentials \(U_1^{sym}\) and \(U_2^{sym}\) with \(\sigma^{iso}\) or \(\sigma^{noiso}\).

**Fig.2** The \((N/Z)_n/(N/Z)_{N_{imf}}\) as a function of the neutron-proton ratio of colliding systems \(^{104}Sn + ^{104}Sn\), \(^{112}Sn + ^{112}Sn\) and \(^{124}Sn + ^{124}Sn\) for three different symmetry potentials \(U_1^{sym}\), \(U_2^{sym}\) and \(U_3^{sym}\) at the beam energy of 50 MeV/nucleon and impact parameter of 4.0 fm (left panel) and 0.0 fm (right panel).

**Fig.3** The impact parameter averaged values of \(< (N/Z)_n >_b\) (left panel) and \(< (N/Z)_{N_{imf}} >_b\) (right panel) as a function of beam energy E for the different symmetry potentials \(U_1^{sym}\) and \(U_2^{sym}\) as well as the reaction \(^{124}Sn + ^{124}Sn\).
**Fig. 4** The time evolutions of impact parameter averaged values of nucleon emission number \(< N_n >_b\) and fragment emission number \(< N_{imf} >_b\) (Fig. 4.b)) as well as that of neutron proton ratio of nucleon emission \(< (N/Z)_n >_b\) and that of fragment emission \(< (N/Z)_{imf} >_b\) (Fig. 4.a) for the reaction \(^{124}Sn + ^{124}Sn\) at \(E= 50\) MeV/nucleon.

**Fig. 5** Time evolution of \( (N/Z)_n/(N/Z)_{imf}\) for different neutron-proton ratios for target and projectile but the same mass and the same neutron proton ratio of each couple of colliding systems for the reactions \(^{74}Zn + ^{74}Se\) and \(^{74}Ge + ^{74}Ge\) (left window) as well as \(^{132}Sn + ^{112}Sn\) and \(^{124}Sn + ^{124}Sn\) (right window).

**Fig. 6** the time evolutions of the impact parameter averaged values of \(< (N/Z)_n >_b\) / \(< (N/Z)_{imf} >_b\) with the same \(\sigma^{iso}\), the same \(U^{MDI}\) or \(U^{noMDI}\) but different symmetry potentials \(U^{sym}_{1}\) and \(U^{sym}_{2}\) for the reaction \(^{124}Sn + ^{124}Sn\) at the beam energy of 50 MeV/nucleon.