The Isospin Distribution of Fragments in Reactions $^{96}Ru + ^{96}Ru$, $^{96}Ru + ^{96}Zr$, $^{96}Zr + ^{96}Ru$, and $^{96}Zr + ^{96}Zr$ at Beam Energy 400 AMeV

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Abstract

The isospin distribution of particles and fragments in collisions $^{96}Ru + ^{96}Ru$, $^{96}Ru + ^{96}Zr$, $^{96}Zr + ^{96}Ru$, and $^{96}Zr + ^{96}Zr$ at beam energy 400 AMeV is studied with isospin dependent QMD model. We find that the rapidity distribution of differential neutron-proton counting in neutron rich nucleus-nucleus collisions at intermediate energies is sensitive to the isospin dependent part of nuclear potential. The study of the N/Z ratio of nucleons, light charged particles (LCP) and intermediate mass fragments (IMF) shows that the isospin dependent part of nuclear potential drives IMF to be more isospin symmetric and emitted nucleons to be more neutron rich. From the study of the time evolution of the isospin distribution in emitted nucleons, LCP and IMF we find that neutrons diffuse much faster than protons at beginning and the final isospin distribution is a result of dynamical balance of symmetry potential and Coulomb force under the charge conservation.

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Nuclear multifragmentation has been received more and more attention in both theoretical and experimental studies since people believe that it carries abundant information.

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of nuclear dynamics and the properties of nuclear matter, especially, the possible association with liquid-gas phase transition. Following the establishment of radioactive beam facilities at many laboratories, the study of nuclear multifragmentation for isospin asymmetric nuclear system becomes possible. For isospin asymmetric systems, a description of bi-component system should be introduced while a bi-component system will manifest a richer thermodynamical behavior. The new features of phase separation process for asymmetric nuclear system have been discussed earlier by Barranco and Buchler [1] with phenomenological equation of state and later by Müller and Serot [2] with relativistic mean field model. It was pointed out in [1, 2] that the spinodal is defined by the chemical instability rather than by mechanical instability for isospin asymmetric systems, which allows gas and liquid to have different concentration of protons and neutrons.

The dynamical properties of asymmetric nuclear matter were investigated in [3, 4, 5] and it was predicted that the spinodal decomposition is accompanied by a collective diffusion of protons from low- to high-density region. Experimentally, it was found that the N/Z ratio of gas significantly exceeds that of liquid in the multifragmentation process in heavy ion collisions [6, 7, 8]. It was further showed that the properties of liquid-gas phase transition depend on the value of the symmetry energy coefficient [2, 5]. As is well known, the symmetry energy term of EOS (both the density dependence of symmetry potential energy and the value of symmetry energy coefficient) has large uncertainties. For example, the theoretically predicted value of symmetry energy coefficient is about $27 - 38\,\text{MeV}$ by non-relativistic Hartree-Fock approach [9], $35 - 40\,\text{MeV}$ by relativistic mean field approach [10, 11, 12], $31\,\text{MeV}$ by Brueckner-Hartree-Fock theory (BHF) [13] and $28.7\,\text{MeV}$ by extended BHF theory [14]. Furthermore, recent study has showed that the symmetry energy coefficient increases as the isospin asymmetry increases and the increasing slope is rather different for different version of Skyrme force [15]. Therefore it might be interesting to study the sensitivity of various observables of nuclear multifragmentation to symmetry energy coefficient. We will first investigate the dependence of the various observables in multifragmentation on the symmetry energy coefficient and try to find the sensitive observables to the symmetry energy coefficient. Then the effects of the isospin dependent part of nuclear potential on the isospin distribution of emitted nucleons, LCP and IMF in multifragmentation are studied. In order to study the dependence of the isospin distribution on the isospin asymmetry of the system we perform a set of calculations for the mixing reactions of four mass 96+96 systems Ru+Ru, Zr+Zr, Ru+Zr, and Zr+Ru with corresponding N/Z ratios of 1.18, 1.4, 1.28, 1.28. It is noticed that $^{96}\text{Ru}$ is of 6 neutron deficiency and $^{96}\text{Zr}$ is of 6 neutron excess compared with the most stable isotopes $^{102}\text{Ru}$ and $^{90}\text{Zr}$.

The isospin dependent quantum molecular dynamics (IQMD) model [16, 17] is used in the calculations. In this model, each nucleon is represented by a Gaussian wave packet centered at $\mathbf{r}_i$ and $\mathbf{p}_i$. The time evolution of $\mathbf{r}_i$ and $\mathbf{p}_i$ is governed by Hamiltonian equation of motion:

$$
\dot{\mathbf{r}}_i = \frac{\partial H}{\partial \mathbf{p}_i}, \quad \dot{\mathbf{p}}_i = -\frac{\partial H}{\partial \mathbf{r}_i}.
$$  (1)
The Hamiltonian $H$ consists of the kinetic energy and effective interaction potential energy,

$$ H = T + U. \quad (2) $$

The effective interaction potential energy includes the nuclear local interaction potential energy and Coulomb interaction potential energy,

$$ U = U_{\text{loc}} + U_{\text{Coul}}. \quad (3) $$

The local interaction potential energy can be obtained by

$$ U_{\text{loc}} = \int V_{\text{loc}} d^3r, \quad (4) $$

where $V_{\text{loc}}$ is the potential energy density which can be obtained from Skyrme type interaction and reads as:

$$ V_{\text{loc}} = \frac{\alpha}{2} \frac{\rho(r)^2}{\rho_0} + \frac{\beta}{3} \frac{\rho(r)^3}{\rho_0^2} + \frac{C_s}{2} \frac{(\rho_p(r) - \rho_n(r))^2}{\rho_0}. \quad (5) $$

The third term in the right side of equation (5) is the symmetry potential energy density, in which a linear density dependence of the symmetry potential energy is adopted. In general, $V_{\text{sym}}$ can be expressed as:

$$ V_{\text{sym}} = \frac{C_s}{2} \frac{(\rho_n - \rho_p)^2}{\rho^2} \rho F(u). \quad (6) $$

Here $F(u)$ gives the density dependence of symmetry potential energy and $u = \rho/\rho_0$. Phenomenologically, Prakash, Ainsworth, and Lattimer proposed the forms of $F(u)$ as $u$, $u^{1/2}$, and $2u^2/(1 + u)$, respectively. For the form of $u^{1/2}$ or $2u^2/(1 + u)$, we can hardly get the analytical expression of $U_{\text{sym}}$ from expression (4). However, it has been shown in many microscopic studies that the linear density dependence of symmetry energy was almost valid at not very far from normal densities. (see, for example, [13, 14]). Thus in this work a linear density dependence of symmetry potential energy, $F(u) = u$, is still adopted for the convenience of performing IQMD calculations. Of course the knowledge of the density dependence of the symmetry potential energy is very much concerned, which will be studied in the future. The symmetry potential energy term in equation (5) can be re-written as

$$ V_{\text{sym}}(\rho, \delta) = \frac{C_s}{2} \frac{\rho}{\rho_0} \delta^2 \rho, \quad (7) $$

where

$$ \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}. \quad (8) $$

The corresponding symmetry energy coefficient is

$$ a_{\text{sym}} = \frac{3}{5} (2^{2/3} - 1) \epsilon_F^0 + \frac{C_s}{2} \epsilon_F^0 \approx \frac{\epsilon_F^0}{3} + \frac{C_s}{2}. \quad (9) $$
Here $\epsilon^0_0$ is the Fermi energy of the symmetric system at $\rho = \rho_0$ and taken to be 38 MeV. The effect of the isospin dependent part of nuclear potential on the isospin distribution in multifragmentation is tested by taking different values of $C_S$ in the calculations. In this work we take $C_S$ equals 0 MeV, 27 MeV, 35 MeV and 50 MeV, corresponding to the values of symmetry energy coefficient $a_{sym}$: 0 MeV, 27 MeV, 31 MeV and 38 MeV, respectively.

The experimental isospin dependent binary elastic scattering cross section is used in calculations. In [19] it was shown that up to hundreds MeV the elastic proton-neutron cross section is about $2 - 3$ times larger than that of proton-proton (neutron-neutron)’s.

Concerning the treatment of the Pauli blocking, we firstly distinguish protons and neutrons, and then we use the following two criteria:

$$\frac{4\pi}{3} p_{ij}^3 \cdot \frac{4\pi}{3} p_{ij}^3 \geq \frac{\hbar^3}{4},$$  \hspace{1cm} (10)

and

$$P_{block} = 1 - (1 - f_i)(1 - f_j),$$  \hspace{1cm} (11)

where $f_i$ is the distribution function in phase space for particle $i$ and reads as

$$f_i(\vec{r}, \vec{p}, t) = \frac{1}{\pi \hbar^3} \exp\left(-\frac{(\vec{r} - \vec{r}_i(t))^2}{2L^2}\right) \exp\left(-\frac{(\vec{p} - \vec{p}_i(t))^2}{2L^2/\bar{\hbar}^2}\right),$$  \hspace{1cm} (12)

where $L$ is a parameter which represents the spatial spread of wave packet, and $\vec{r}_i(t)$ and $\vec{p}_i(t)$ denote the center of the wave packet of particle $i$ in coordinate and momentum space respectively. The first condition (expression (10)) gives the criterion for the uncertainty relation of the centroids of Gaussian wave packets of two particles. The second one is the probability of the Pauli blocking effect for the scattering of two particles, which is especially useful for collisions of heavy nuclei. In this paper, we construct clusters in terms of the conventional coalescence model [20], in which particles with relative momenta smaller than $P_0$ and relative distances smaller than $R_0$ are considered to belong to one cluster. In this work $R_0$ and $P_0$ are taken to be 3.5 fm and 300 MeV/c, respectively, following Ref. [21]. In addition, only the cluster with reasonable proton number $Z$ and neutron number $N$ are selected in order to get rid of nonphysical clusters.

The soft EOS ($K = 200 MeV$) is used in the calculations, and the corresponding main parameters are listed in Table 1.

First of all, in order to check our IQMD model, we calculate the rapidity distribution of protons to make comparison with experimental data of [23]. Fig. 1 shows the calculated rapidity distribution of protons (including deuterons for comparing with experiments) for four colliding systems: Zr+Zr (solid line), Ru+Ru (dashed line), Zr+Ru (dotted line) and Ru+Zr (dash-dotted line) at $E = 400 AMeV$ and $b = 0 fm$, in which $C_S = 35 MeV$ is used and the angle selection (10° < $\theta_{lab}$ < 28° and 34° < $\theta_{lab}$ < 145°) is taken which is the same with that of the experimental data [23]. The experimental data are
also given in the figure (solid circles and open circles reflected from experimental data assuming a backward/forward symmetry). This figure shows that our calculation results can reproduce the experimental data quite well, only at the projectile and target region, the calculated results deviate from experimental data, which is because the calculated results are for head on collisions while the experimental data are for central collisions. It is also shown in the figure that the rapidity distribution of protons for Ru+Ru is higher than that for Zr+Zr at whole rapidity region because of the difference of their initial proton number. The rapidity distribution for asymmetric reactions Zr+Ru and Ru+Zr is between that of Zr+Zr and Ru+Ru. It is checked that the results do not change much when $C_S$ is taken to be from 27 MeV to 50 MeV.

Now let us investigate the sensitivity of the proton number counting to the value of $C_S$ because the proton number counting for the mixing reactions of four mass 96+96 systems Ru+Ru, Zr+Zr, Ru+Zr, Zr+Ru was experimentally measured by FOPI/GSI recently [22, 23]. In [23] a normalized proton number counting $R_Z$ is introduced:

$$R_Z = \frac{2 * Z - Z_{Zr} - Z_{Ru}}{Z_{Zr} - Z_{Ru}}. \quad (13)$$

By definition $R_Z = 1$ for Zr+Zr, $R_Z = -1$ for Ru+Ru. Fig. 2 shows the rapidity distribution of $R_Z$ calculated with $C_S = 0 \text{MeV}, 27 \text{MeV}, 35 \text{MeV}$ and $50 \text{MeV}$. And we can see that $R_Z$ can explore the non-equilibrium effect in nucleus-nucleus colliding process successfully. However the results with $C_S=0 \text{MeV}, 27 \text{MeV}, 35 \text{MeV}$ and $50 \text{MeV}$, respectively, are indistinguishable. It means that the normalized proton number counting $R_Z$ is not sensitive to the value of symmetry energy coefficient, which may be understood from the definition of $R_Z$ where the effect of changing $C_S$ on $R_Z$ is significantly reduced. So we have to seek the other observables which are sensitive to $C_S$.

Here we introduce the normalized differential neutron-proton counting which is defined as:

$$N_{np} = \frac{< n > - < p >}{< n > + < p >}. \quad (14)$$

Where $< n >$ and $< p >$ is the average number of emitted neutrons and protons, respectively. The relation between $N_{np}$ and average $N/Z$ ratio of emitted nucleons is

$$N/Z = \frac{1 + N_{np}}{1 - N_{np}}. \quad (15)$$

The rapidity distribution of normalized differential neutron-proton counting has been shown in Figs. 3 with different $C_S$ of $0 \text{MeV}, 27 \text{MeV}, 35 \text{MeV}$, and $50 \text{MeV}$, in which a),
b), c), d) corresponds to reactions Zr+Zr, Ru+Ru, Zr+Ru, and Ru+Zr, respectively. The dependence of \( N_{np} \) on \( C_S \) is very pronounced at the projectile and target rapidity region. The general tendency is that \( N_{np} \) increases with \( C_S \). When the isospin dependent part of nuclear potential is switched off (\( C_S = 0 \)), the rapidity distribution of \( N_{np} \) becomes flat for symmetric reactions Zr+Zr and Ru+Ru while for asymmetric reactions Zr+Ru and Ru+Zr, it becomes an inclined line from Zr side to Ru side, which indicates the non-equilibrium effect in reactions. And the N/Z ratio of emitted nucleons (by using Eq. 13) at central rapidity (\( Y = 0 \)) is almost equal to the initial N/Z ratio. As soon as the isospin dependent part of nuclear potential is switched on \( N_{np} \) increases with \( C_S \) for off central rapidity cases. And one can find from Fig. 3 a) and Fig. 3 b) that at projectile and target rapidity region the difference in \( N_{np} \) calculated with different \( C_S \) is more pronounced for Zr+Zr than that for Ru+Ru. It indicates that the sensitivity to \( C_S \) increases as the system becomes more neutron rich, which can be understood from the expression of the symmetry potential energy term(see Eq.(7)). Therefore the rapidity distribution of normalized differential neutron-proton counting in neutron rich nuclear collisions at intermediate energies can be considered to be a good candidate of sensitive observables to the symmetry energy coefficient.

The N/Z ratio of particles and fragments is relevant to the mechanism of multifragmentation for isospin asymmetric nuclear systems. So we further study the N/Z ratio of emitted nucleons, LCP (the cluster of Z=1 or 2) and IMF (the cluster of Z=3-16) as well as the average N/Z ratio in regardless of fragments or particles at projectile (\( |Y - 1| < 0.5 \)), central (\( |Y| < 0.5 \)) and target (\( |Y + 1| < 0.5 \)) rapidity regions, respectively. Fig. 4 shows the calculated results with different \( C_S \) for reaction Zr+Zr. The general feature of the N/Z ratio of particles and fragments is: the largest one is the N/Z ratio of nucleons, then that of LCP, and smallest is that of IMF among them. One can further find from the figure that the symmetry potential drives the N/Z ratio of LCP and IMF to approach to unit from sides of N/Z > 1 and N/Z < 1, and simultaneously the N/Z ratio of nucleons is driven to the higher value than initial one, i.e., to be more neutron rich. The larger the \( C_S \) is the stronger the effect is. It implies that the diffusion of neutrons increases faster than that of protons as \( C_S \) increases. However, the total number of neutrons and protons has to be conserved and there is a balance of the numbers of neutrons and protons in nucleons, LCP and IMF at central, projectile and target rapidity region. Therefore the N/Z ratios of all products in multifragmentation is interdependent. If one looks at Fig. 4 more carefully one can find that at the central rapidity region, the N/Z ratio of LCP at central rapidity region decreases while the N/Z ratio of nucleons increases as \( C_S \) increases but the former one is more sensitive to \( C_S \) than the later one. On the other hand, the N/Z ratio of IMF increases towards unit when the isospin dependent term of nuclear potential is switched on. But generally, the dependence of N/Z ratio of IMF on \( C_S \) at projectile and target rapidity region is a little weaker than that of nucleons at projectile and target region and LCP at central rapidity region. Therefore we may also consider the N/Z ratio of LCP at central rapidity region to be a relatively sensitive observable to \( C_S \). The similar
tendency of the sensitivity of N/Z ratio of emitted nucleons, LCP and IMF to $C_S$ is found for reaction Ru+Ru.

It is convenient for a transport model to study the time evolution of isospin distribution, from which we can also understand more deeply the dynamical balance of isospin distribution in emitted nucleons, LCP and fragments. In Fig. 5, we show the time evolution of the average N/Z ratio of all particles and fragments a), nucleons b), LCP c), and IMF d). The time ranges from $30\, fm/c$ to $100\, fm/c$. Here $30\, fm/c$ is the time when the density in a sphere of $1\, fm^3$ at center drops to $\rho_0$. In Fig. 5, the corresponding N/Z ratios at different time are given by different line types. From this figure, we firstly see that at $30\, fm/c$ the N/Z ratio for nucleons and LCP is larger than unit, especially the former one. But for IMF it is much smaller than unit (it should be noticed that the number of IMF at time is small). It means that neutrons diffuse much faster than protons, which simultaneously results in emitted IMF being neutron deficient. As time goes on, the N/Z ratio of nucleons goes down which means that more protons are emitted during this period. After $50\, fm/c$, the N/Z ratio of emitted nucleons decreases very slowly. The final N/Z ratio of emitted nucleons at central rapidity zone closes to the initial N/Z ratio of colliding systems but still higher than initial one. While at projectile and target rapidity region it is still much higher than initial N/Z ratio. And at the same time span, the N/Z ratio of LCP and IMF firstly goes up far away from unit before $50\, fm/c$ because of emitting of more protons during $30\, fm/c - 50\, fm/c$, and then goes downward to approach to unit. So from the above discussion about the time evolution of the isospin distribution in multifragmentation for heavy ion collisions at the energy studied we can draw two conclusions: 1) neutrons diffuse much faster than protons so the number of neutrons emitted much larger than that of protons at the beginning, and 2) the final isospin distribution is a result of dynamical balance of symmetry potential and Coulomb force under the total charge number conservation which leads to the N/Z ratio of IMF more close unit and emitted nucleons more neutron rich.

In summary, in this work we have introduced a normalized differential neutron-proton counting for rich nuclei heavy ion in collisions at intermediate energies as a sensitive observable to probe the symmetry energy coefficient. We have also studied the dependence of the average N/Z ratio of nucleons, LCP and IMF at central, projectile and target rapidity region on $C_S$ and we find that at the energy studied in this work the general effect of isospin dependent part of nuclear potential is to drive emitted nucleons to be more neutron rich and IMF to be more isospin symmetry. The stronger the isospin dependent part of nuclear potential is the stronger the effect is. It is also shown that the N/Z ratio of LCP at central rapidity region is relatively more sensitive to $C_S$ than the others. The time evolution of the isospin distribution in multifragmentation process shows that neutrons diffuse faster than protons and the final isospin distribution is a result
of dynamical balance of symmetry potential and Coulomb force under the total charge number conservation.

Table. 1 Parameters used in calculations

| $\alpha\ (MeV)$ | $\beta\ (MeV)$ | $\gamma$ | $\rho_0\ (fm^{-3})$ | $K\ (MeV)$ | $L\ (fm)$ | $C_{Yuk}\ (MeV)$ |
|-----------------|--------------|--------|----------------|------------|----------|---------------|
| $3.56$          | $303$        | $7./6.$| $0.168$        | $200$      | $2.1$    | $-5.5$        |

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CAPTIONS

Fig. 1 The rapidity distribution of protons and deuterons for $^{96}\text{Ru} + ^{96}\text{Ru}$, $^{96}\text{Ru} + ^{96}\text{Zr}$, $^{96}\text{Zr} + ^{96}\text{Ru}$, $^{96}\text{Zr} + ^{96}\text{Zr}$ at $E = 400\text{AMeV}$, $b = 0\text{fm}$. The experimental data of [23] are also given in the figure.

Fig. 2 The rapidity distribution of proton counting number $R_z$ with different $C_S$ for the same reactions given in Fig. 1.

Fig. 3 The rapidity distribution of differential neutron-proton counting with different $C_S$ for a) $^{96}\text{Zr} + ^{96}\text{Zr}$, b) $^{96}\text{Ru} + ^{96}\text{Ru}$, c) $^{96}\text{Zr} + ^{96}\text{Ru}$, and d) $^{96}\text{Ru} + ^{96}\text{Zr}$ at 400 $\text{AMeV}$, $b = 0\text{fm}$.

Fig. 4 The average $N/Z$ ratio of emitted nucleons, LCP and IMF at projectile rapidity region, central rapidity region, and target rapidity region with different $C_S$ for $^{96}\text{Zr} + ^{96}\text{Zr}$ at 400 $\text{AMeV}$, $b = 0\text{fm}$.

Fig. 5 The time evolution of average $N/Z$ ratio of emitted nucleons, LCP and IMF at projectile rapidity region, center rapidity region, and target rapidity region for the same reactions as Fig. 4.
E = 400 AMeV
b = 0 fm

\( \frac{dN}{dY} \)

- **Zr+Zr**
- **Ru+Ru**
- **Zr+Ru**
- **Ru+Zr**

Ru+Ru Expt.
Reflected
E=400 AMeV
b=0 fm

Ru + Zr

Zr + Ru

C_s

- - - 0 MeV
- - - 27 MeV
- - - 35 MeV
- - - 50 MeV

R_Z

Y
\[ b = 0 \text{ fm} \]
\[ E = 400 \text{ AMeV} \]

- **Zr+Zr**
  - \( C_s = 0 \text{ MeV} \)
  - \( C_s = 27 \text{ MeV} \)
  - \( C_s = 35 \text{ MeV} \)
  - \( C_s = 50 \text{ MeV} \)

- **Ru+Ru**

- **Zr+Ru**

- **Ru+Zr**
Zr+Zr

E=400 AMeV
b=0 fm

Nucleons

\[ C_S = 0 \text{ MeV} \]
\[ C_S = 27 \text{ MeV} \]
\[ C_S = 35 \text{ MeV} \]
\[ C_S = 50 \text{ MeV} \]

LCP

IMF

Y

N/Z
Zr+Zr

- E=400 AMeV
- b=0 fm
- C_s=35 MeV

Nucleons

LCP

IMF