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Isospin Effects on Pre-Equilibrium Nucleon Emission in Heavy-Ion Collisions

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The isospin-dependent symmetry energy, Coulomb energy, and N-N cross sections are considered in the quantum molecular dynamics model. The influence of isospin effects on the emission of nucleons is discussed in the head-on collisions of the system ^{40}Ar + ^{40}Ar at the incident energy of 25 MeV/u. It is observed that the ratio of neutron to proton of pre-equilibrium emission is higher than that of the reaction system. It is found that the symmetry energy enhances the emission of neutron but reduces the emission of proton and that the isospin-dependent N-N cross sections favor the emission of both proton and neutron, but they seem to be more beneficial to the emission of protons.

Key words: pre-equilibrium emission, isospin effects, nucleon-nucleon cross sections, symmetry energy.

1. INTRODUCTION

In heavy-ion collisions in a low energy region, the pre-equilibrium light particle emission has been found, and the pre-equilibrium emission becomes more and more important with increasing projectile energy. Around the Fermi energy, it was found that the ratio of neutron to proton $(N/Z)_{\text{free}}$ of pre-equilibrium emission was higher than that of the reaction system $(N_p + N_t)/(Z_p + Z_t)$ [1-3]. This phenomenon has been explained qualitatively as due to the isospin-dependent N-N cross sections.

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Experimentally, the n-p cross section at energies less than 100 MeV is 3 times larger than the n-n or p-p cross section and this implies a smaller absorption of neutron in the neutron-rich target nucleus. However, this seems to be only a conjecture and the mechanism resulting in this phenomenon is still an open problem.

In the dynamical process of heavy-ion collisions, it is well known that the variation of N/Z is mainly due to the isospin effects and N/Z is sensitive to the isospin degree of freedom. The dynamics of heavy-ion collisions is governed by the mean field, two-body collision, and the Pauli principle and in order to know the evolution of N/Z in heavy-ion collisions it is essential that the mean field and two-body collision consist of the isospin degree of freedom. In fact, the isospin degree of freedom also affects other reaction mechanisms [4] and the pre-equilibrium nucleon emission is probably a good reaction mechanism to explore the isospin-dependent reaction dynamics.

In this paper, we have modified the quantum molecular dynamics (QMD) model to include the isospin degree of freedom. The symmetry energy is included in the interaction potential and the isospin-dependent form is adopted to the Coulomb potential. Meanwhile, we use two different parametrizations of N-N cross sections: the experimental parametrization which is isospin-dependent and Cugnon's parametrization which is isospin-independent. The calculated results show that $(N/Z)_{\rm free}$ of pre-equilibrium is higher than $(N_p + N_t)/(Z_p + Z_t)$ and the symmetry energy enhances the emission of neutron but reduces the emission of proton; the experimental N-N cross sections enhance the emission of both neutron and proton but they seem to be more beneficial to the emission of protons.

2. DESCRIPTION OF THE MODEL

After considering the isospin-dependent symmetry energy and Coulomb energy in the QMD model, we obtain the interaction of the system as

$$V^{\rm tot} = V^{(2)} + V^{(3)} = V^{\rm loc} + V^{\rm Yuk} + V^{\rm Coul} + V^{\rm sym}, \tag{1}$$

where $V^{\rm tot}$ is the total interaction, $V^{(2)}$ is the two-body interaction, $V^{(3)}$ is the three-body interaction, $V^{\rm loc}$ is the local (Skyrme) interaction, $V^{\rm Yuk}$ is the Yukawa (surface) interaction, $V^{\rm Coul}$ is the Coulomb interaction, and $V^{\rm sym}$ is the symmetry energy term. For the form of $V^{\rm loc}$ and $V^{\rm Yuk}$, see Ref. [5]. The total symmetry energy of system is [4]

$$U^{(2)}_{\rm sym} = \frac{C}{2\rho_0} \sum_{i \neq j} t_{iz} t_{jz} \frac{1}{(4\pi L)^{3/2}} \exp\left[-(\boldsymbol{r}_i - \boldsymbol{r}_j)^2/(4L)\right], \tag{2}$$

the Coulomb energy is

$$U^{(2)}_{\rm Coul} = \frac{e^2}{4} \sum_{i \neq j} \frac{(1 + t_{iz})(1 + t_{jz})\left[1 - {\rm erfc}\,(r_{ij}/\sqrt{4L})\right]}{r_{ij}}. \tag{3}$$

In the above equations, C is the symmetry energy strength and is determined by the ground state properties of finite nucleus. In this study C is used as a free parameter and we can investigate its influence on nucleon emission. The refc (x) is the remnant error function. L is the Gaussian wave packet width, the relative distance $r_{ij} = |\boldsymbol{r}_i - \boldsymbol{r}_j|$, and

$$t_{iz} = \begin{cases} 1 \ (\text{proton}), \\ -1 \ (\text{neutron}), \end{cases} \tag{4}$$

is the z component of the isospin degree of freedom of the i-th nucleon.

Concerning the N-N cross sections, we adopt two parametrizations: one is the Cugnon's parametrization which is isospin-independent; the other is experimental parametrization which is isospin-dependent and the total cross sections are as follows [6]:

for p − n collisions

$$\sigma = \begin{cases} -\dfrac{5067.4}{E^2} + \dfrac{9069.2}{E} + 6.9466\ (\text{mb}),\ E \le 40\ (\text{MeV}) \\ \dfrac{239380}{E^2} + \dfrac{1802.0}{E} + 27.147\ (\text{mb}),\ 40 < E \le 400\ (\text{MeV}) \\ 34.5\ (\text{mb}), \qquad 400 < E \le 800\ (\text{MeV}) \end{cases} \tag{5}$$

for p − p or n − n collisions

$$\sigma = \begin{cases} -\dfrac{1174.8}{E^2} + \dfrac{3088.5}{E} + 5.3107\ (\text{mb}),\ E \le 40\ (\text{MeV}) \\ \dfrac{93074}{E^2} - \dfrac{11.148}{E} + 22.429\ (\text{mb}),\ 40 < E \le 310\ (\text{MeV}) \\ \dfrac{887.37}{E} + 0.05331E + 3.5475\ (\text{mb}),\ 310 < E \le 800\ (\text{MeV}) \end{cases} \tag{6}$$

The quantity E in the above equations is the incident kinetic energy per nucleon in the laboratory system.

For the incident energy $E = 25$ MeV/u, it is easy to find that for experimental parametrization the n − p cross section is about 3 times larger than n − n or p − p cross sections which are about 3 times larger than that of Cugnon's parametrization. By using the two different parametrizations above, one can study the influence of N-N cross sections on nucleon emission.

The method of considering the Pauli blocking effect is as follows: for each collision we assume that in the phase space each nucleon occupies a sphere of volume $h^3 / 4$ (considering spin and isospin degree of freedom, h is the Planck constant), then check the probability of this sphere being occupied by other spheres and decide if the collision is blocked or partly blocked.

The stability of the propagation of the initialized nuclei has been checked in detail. According to the evolution of root mean squared radius and mean binding energy of initialized nuclei it can last for at least 300 fm/c.

3. RESULTS OF CALCULATION AND ANALYSES

We have calculated systematically the head-on collisions of the system ^{40}Ar (25 MeV/u) + ^{40}Ar (30 events) in the present study. At first, by using the Cugnon's parametrization and setting $C = 0$, 20, and 32 MeV, respectively, we obtain the time evolution of $(N/Z)_{\text{free}}$ and the numbers of neutrons and protons as shown in Figs. 1(a) and 1(c), respectively. The similar calculated results are shown in Figs. 1(b) and 1(d) by using the experimental parametrization.

Here, the free nucleon is defined as the nucleon with local density less than $\rho_0 / 7$ and its distances from the other nucleons are all larger than 3.5 fm. As we know, there have been various criteria for thermalization of the collision system [7]. Here, we have only calculated the z component of the quadrupole moment of momentum distribution per nucleon in the heavy residue Q_{zz} / A_{res}, which

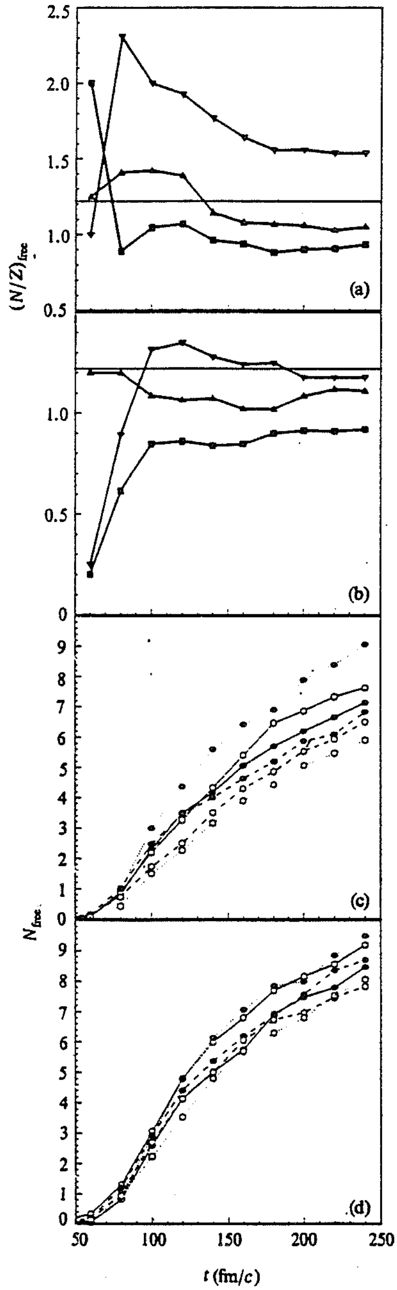

Fig. 1

The times evolution of $(N/Z)_{free}$ and the number of emitted nucleons.

-▪- C = 0MeV; -•-n, C = 0MeV;
-o-p, C = 0MeV; -▴- C = 20MeV;
-•-n, C = 20MeV; -o-p, C = 20MeV;
-▾- C = 32MeV; ··•··n, C = 32MeV;
··o··p, C = 32MeV.

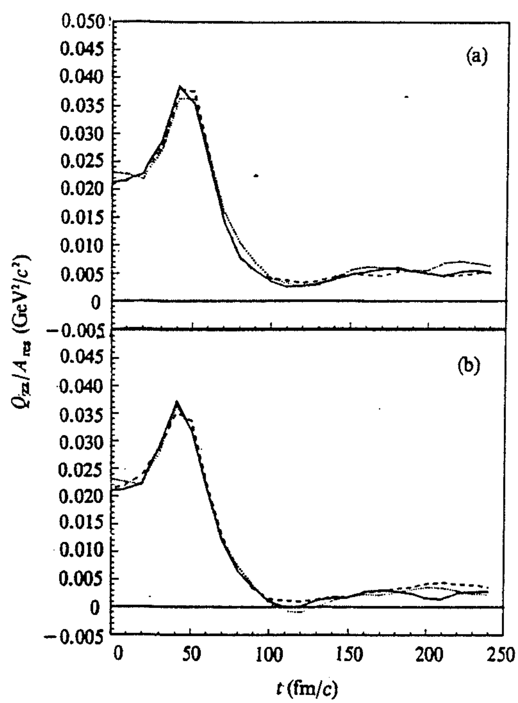

Fig. 2

The times evolution of quadrupole moment of momentum distribution per nucleon in the heavy residue.

(a) Isospin-independent N-N cross section
(b) Isospin-dependent N-N cross section.
– C=0MeV; -- C=20MeV; ··· C=32MeV.

is defined as

$$\langle Q_{zz} \rangle = \langle 2p_z^2 - p_z^2 - p_y^2 \rangle \tag{7}$$

Here, the heavy residue is defined as the composition of nucleons with local densities larger than $\rho_0 / 7$. In Fig. 2, we display the evolution of Q_{zz} / A_{res}, where A_{res} is the mass number of the residue.

From Fig. 2, it can be seen that Q_{zz} / A_{res} is very close to zero after about t = 110 fm/c, indicating the thermalization of the collision system. It is also found that the experimental N-N cross sections seem to be more beneficial to thermalization than Cugnon's N-N cross sections.

It can be seen from Figs. 1(a) and 1(b), that in the case of C = 20 and 32 MeV, $(N / Z)_{free}$ of pre-equilibrium is obviously larger than that of equilibrium and $(N / Z)_{free}$ finally reaches a stable value for all C values after equilibrium. Moveover, in the case of C = 32 MeV and with experimental parametrization, the stable value is very close to $(N_p + N_t) / (Z_p + Z_t)$ (the dotted line in Fig. 1). It is also found that both symmetry energy and N-N cross sections have great influence on $(N / Z)_{free}$ and the former enhances $(N / Z)_{free}$ while the latter reduces it. This phenomenon can also be seen from Figs. 1(c) and 1(d). Apparently, the symmetry energy (C = 20 and 32 MeV) enhances neutron emission but reduces proton emission; the stronger the symmetry energy, the greater the neutron emission and the smaller the proton emission, which leads to the increase of $(N / Z)_{free}$. At the same time, it is found that the isospin-dependent N-N cross sections enhance both neutron and proton emission but seem to be more favorable to proton emission, which leads to the decrease of $(N / Z)_{free}$.

That symmetry energy enhances neutron emission but reduces proton emission is due to its systematical effect to repulse neutron outwards and compress proton inwards. Coulomb energy has the opposite effect to symmetry energy. These features are in agreement with the results from the symmetry effect of isotope shift in the nuclear structure [8]. In the case of C = 0, $(N / Z)_{free}$ of pre-equilibrium is not larger than that of equilibrium, which may due to the repulsion of Coulomb force to protons. This is also in agreement with the results found in Ref. [9].

From our calculations, it is indicated that the maximum $(N / Z)_{free}$ of pre-equilibrium is determined jointly by symmetry energy, Coulomb energy, and N-N cross sections. In fact, during pre-equilibrium the energies of nucleons are very different from each other and a few high energy nucleons may obtain higher energies and emit outwardly during the process of collisions, which is a general explanation of pre-equilibrium nucleon emission. Moreover, the emission of nucleons decreases drastically after equilibrium, which can be seen from the slope of curves in Figs. 1(c) and 1(d). In the case of $C = 0$, $(N / Z)_{free}$ of pre-equilibrium nucleons has no clear maximum, because only Coulomb energy, but no symmetry energy is included. Compared with the Cugnon's parametrization, the experimental parametrization increases the collision probabilities of both neutron and proton. However, it is easy to imagine that for normal neutron-rich target nuclei, protons will get a larger collision probability and the experimental N-N cross sections are more favorable to proton emission.

That the $(N / Z)_{free}$ of pre-equilibrium is larger than $(N_p + N_t) / (Z_p + Z_t)$ may due to the isospin-dependent N-N cross sections [1] or the isospin-dependent mean field, but is almost independent from N-N cross sections [9]. From preceding analyses, however, it is shown that the isospin-dependent mean field and N-N cross sections are both important. It should be stressed that in this study we cannot adjust the factor of Pauli blocking; however, we believe that the Pauli blocking effect is also an interesting element to influence nucleon emission. Qualitatively, the Pauli blocking effect in the area with larger local density should be stronger than that in the area with a smaller local density. Hence, during pre-equilibrium the Pauli blocking around the center of collision system should be stronger than that around the surface. Besides, the nucleons around the surface of the collision system are bound very loosely and may emit easily. In addition, the isospin-dependence of Pauli blocking effect is also an interesting problem which should be studied further. Through preceding analyses, it is shown that studying nucleon emission in heavy-ion collisions is very useful to understand symmetry energy strength C and to explore isospin-dependent reaction dynamics.

4. CONCLUSIONS

The isospin-dependent symmetry energy, Coulomb energy, and N-N cross sections are included in heavy-ion collision dynamics. By studying nucleon emission in the head-on collision of system ^{40}Ar (25 MeV/u) + ^{40}Ar, one can have a deep understanding about the experimental phenomenon that neutron/proton ratio $(N / Z)_{free}$ of pre-equilibrium is higher than that of the whole reaction system $(N_p + N_t) / (Z_p + Z_t)$. It is shown that the mechanism resulting in this phenomenon is due to the isospin-dependent reaction dynamics. The isospin-dependent symmetry energy in mean field enhances both $(N / Z)_{free}$ and neutron emission but reduces proton emission, while isospin-dependent N-N cross sections enhance the emission of both neutron and proton but seem to be more beneficial to proton emission and therefore for reducing $(N / Z)_{free}$. The Coulomb energy has the opposite effect to symmetry energy. It seems to be one-sided to simply affirm or deny a certain aspect.

It can be foreseen that to explore the N / Z of nuclear fragments in heavy-ion collisions is an important probe for studying isospin-dependent reaction dynamics. The analysis of whether or not the isospin degree of freedom reaches equilibrium in heavy-ion collisions is still in progress.

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