Influence of medium correction of nucleon nucleon cross section on the fragmentation and nucleon emission

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Abstract

The influence of medium correction from an isospin dependent nucleon nucleon cross section on the fragmentation and nucleon emission in the intermediate energy heavy ion collisions was studied by using an isospin dependent quantum molecular dynamical model (IQMD). We found that the medium correction enhances the dependence of multiplicity of intermediate mass fragment $N_{imf}$ and the number of nucleon emission $N_n$ on the isospin effect of the nucleon nucleon cross section, while the momentum dependent interaction (MDI) produces also an important role for enhancing the influence of the medium correction on the isospin dependence of two-body collision in the fragmentation and nucleon emission processes. After considering the medium correction and the role of momentum...
dependent interaction the increase for the dependence of $N_{imf}$ and $N_n$ on the isospin effect of two-body collision is favorable to learn the information about the isospin dependent nucleon nucleon cross section.

**Keywords**: Medium correction; Isospin effect; Nucleon-nucleon cross section; Fragmentation; nucleon emission.

**PACCS**: 25.70.Pq, 02.70.Ns, 24.10.Lx.

1 Introduction

The isospin physics in heavy-ion collision (HIC) at intermediate energies has been an important topic in recent years[1,3,18]. These studies is not only important for understanding the collision mechanism and nuclear structure but also for getting the knowledge about the isospin asymmetric nuclear matter equation of state (EOS) and isospin dependent nucleon nucleon cross section. Recently, some observables were found to be the good probes for extracting the information of an isospin asymmetric nuclear matter EOS and the in-medium nucleon nucleon cross section at intermediate energies [4-29] because they are sensitive only to one of the isospin dependent mean field and the isospin dependent in-medium nucleon nucleon cross section. Bao-an Li[22] has pointed out, for instance, that the proton neutron differential collective flow and proton ellipse flow can be used to probe the isospin asymmetric nuclear matter equation of state. He also found recently that the isospin asymmetry of the high density nuclear matter formed in high energy heavy-ion collision is uniquely determined by the high density behavior of the nuclear symmetry energy[23]. Our studies in last few years indicated that the nuclear stopping, the number of nucleon emission and the multiplicity of intermediate mass fragments in HIC at intermediate energies can be used to probe the isospin-dependent in-medium nucleon nucleon cross section[24,25]. In this work we investigate further the influence of the medium correction of the isospin dependent nucleon nucleon cross section on the fragmentation and the nucleon emission in the heavy ion collisions at intermediate energies by using an isospin dependent quantum molecular dynamical model. We found that the multiplicity of intermediate mass fragments $N_{imf}$ and the number of nucleon emission $N_n$ for
the medium effect $\alpha = -0.2$ (see in Eq.(7)) are always less than those for $\alpha = 0.0$ (free nucleon nucleon collision) in the intermediate energy heavy ion collisions. In particular, the differences between $N_{\text{imf}}$’s or $N_n$’s from an isospin dependent nucleon nucleon cross section and an isospin independent one with $\alpha = -0.2$ are always larger than those with $\alpha = 0.0$, i.e., the medium correction of two-body collision increases the dependence of $N_{\text{imf}}$ and $N_n$ on the isospin effect of nucleon nucleon cross section, while MDI enhances also the influence of the medium correction on the isospin effect of two-body collision in the fragmentation and nucleon emission processes.

2 IQMD model

The quantum molecular dynamics(QMD)[30] contains two ingredients: density dependent mean field and in-medium nucleon nucleon cross section. To describe isospin effects appropriately, QMD should be modified properly: the density dependent mean field should contain correct isospin terms including symmetry potential and coulomb potential, the in-medium nucleon nucleon cross sections should be different for neutron neutron (proton proton) and neutron proton collisions, in which the Pauli blocking should be counted by distinguishing neutrons and protons. In addition, the initial condition of the ground state of two colliding nuclei should also contain isospin information.

Considering the above ingredients, we have made important modifications in QMD to obtain an isospin dependent quantum molecular dynamics(IQMD)[1, 3]. The initial density distributions of the colliding nuclei in IQMD are obtained from the calculations of the Skyrme-Hatree-Fock with parameter set SKM∗[30]. The initial code of IQMD was used to determine the ground state properties of the colliding nuclei, such as the binding energies and RMS radii, which agree with the experimental data for obtaining the parameters of interaction potential as an input data for the collision dynamics calculations by using the code of IQMD.
The interaction potential is

\[ U(\rho) = U^{Sky} + U^c + U^{sym} + U^{Yuk} + U^{MDI} + U^{Pauli} \]  

(1)

where \( U^c \) is Coulomb potential.

The density dependent Skyrme potential \( U^{Sky} \), the Yukawa potential \( U^{Yuk} \), the momentum dependent interaction \( U^{MDI} \) and the Pauli potential \( U^{Pauli} \) [30, 37] are given by the following equations, respectively

\[ U^{Sky} = \alpha \left( \frac{\rho}{\rho_0} \right) + \beta \left( \frac{\rho}{\rho_0} \right)^\gamma, \]

(2)

\[ U^{Yuk} = t_3 e^{\exp\left( \frac{|\vec{r}_1 - \vec{r}_2|}{m} \right) / 2}, \]

(3)

\[ U^{MDI} = t_4 \ln^2\left[ t_5 \left( \frac{\vec{p}_1 - \vec{p}_2}{2\rho_0} \right)^2 + 1 \right] \frac{\rho}{\rho_0}, \]

(4)

\[ U^{Pauli} = V_p \left( \frac{\hbar}{\rho_0 q_0} \right)^3 \exp\left\{ -\frac{(\vec{r}_1 - \vec{r}_j)^2}{2q_0^2} - \frac{(\vec{p}_1 - \vec{p}_j)^2}{2p_0^2} \right\} \delta_{p_1,p_2}, \]

(5)

with

\[ \delta_{p_1,p_2} = \begin{cases} 
1 & \text{for neutron-neutron or proton-proton} \\
0 & \text{for neutron-proton}. 
\end{cases} \]

In this work we used following different symmetry potentials[1,3]:

\[ U_1^{sym} = \pm 2e_a u \delta \]

\[ U_2^{sym} = \pm 2e_a u^2 \delta + e_a u^2 \delta^2 \]

\[ U_0^{sym} = 0.0 \]

(6)

Here \( e_a \) is the strength of symmetry potential taking the value of 16MeV and \( U_0^{sym} = 0.0 \) indicates the case without any symmetry potential. \( u = \frac{\rho}{\rho_0}, \delta \) is the relative neutron excess \( \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p} = \frac{\rho_n - \rho_p}{\rho} \). Here \( \rho, \rho_0, \rho_n \) and \( \rho_p \) are total, normal, neutron and proton densities, respectively. In the first terms on the right side of Eq.(6) the upper + means repulsive for neutrons and the lower - is attractive for protons. The parameters of interaction potentials are in table 1.0

Table 1. The parameters of the interaction potential

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The parameters are:

- \( U_1^{sym} = \pm 2e_a u \delta \)
- \( U_2^{sym} = \pm 2e_a u^2 \delta + e_a u^2 \delta^2 \)
- \( U_0^{sym} = 0.0 \)
The NOMDI in table 1 means without MDI. The influence of medium correction on the nucleon nucleon cross section is an important topic in HIC at intermediate energies\cite{31,32}. D. Klakow et al proposed that the in-medium nucleon nucleon cross section should be a function of the nucleon distribution density as follows \cite{33}

$$\sigma_{NN} = (1 + \alpha \frac{\rho}{\rho_0}) \sigma_{NN}^{free}.$$ \hspace{1cm} (7)

The parameter $\alpha = -0.2$ has been found to reproduce the flow data\cite{34,35}. The free neutron proton cross section is about a factor of 3 times larger than the free proton proton or the free neutron neutron one below 400 MeV, which contributes the main isospin effect from nucleon-nucleon collisions at intermediate heavy ion collisions. In fact, the ratio of the neutron proton cross section to proton proton(or neutron neutron) cross section in the medium, $\sigma_{np}/\sigma_{pp}$, depends sensitively on the evolution of the nuclear density distribution and beam energy. We used equation (7) to take into account the medium effects, 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 in this paper. Here $\sigma_{NN}^{free}$ is the experimental nucleon nucleon cross section\cite{36}.

$$\sigma_{np}^{free} = \begin{cases} 381.0(\text{mb}) & \text{E} \leq 25(\text{MeV}) \\ \frac{5067}{E^4} + \frac{909.2}{E} + 6.9466(\text{mb}) & 25 < \text{E} \leq 40 (\text{MeV}) \\ \frac{239380.0}{E^2} + \frac{1802.0}{E} + 27.14(\text{mb}) & 40 < \text{E} \leq 310 (\text{MeV}) \\ 34.5(\text{mb}) & 310 < \text{E} \leq 800(\text{MeV}) \end{cases}$$ \hspace{1cm} (8)

$$\sigma_{nn}^{free} = \sigma_{pp}^{free} = \begin{cases} 80.6(\text{mb}) & \text{E} \leq 25(\text{MeV}) \\ -\frac{1174.8}{E^2} + \frac{3088.5}{E} + 5.3107(\text{mb}) & 25 < \text{E} \leq 40 (\text{MeV}) \\ \frac{93074.0}{E^2} + \frac{11148}{E} + 22.429(\text{mb}) & 40 < \text{E} \leq 310 (\text{MeV}) \\ \frac{887.37}{E^2} + 0.05331E + 3.5475(\text{mb}) & 310 < \text{E} \leq 800(\text{MeV}) \end{cases}$$ \hspace{1cm} (9)

We constructed the clusters by means of a modified coalescence model \cite{37}, in which particle relative momentum is smaller than $p_0=300\text{MeV}/c$ and relative distance is smaller than $R_0= 3.5 \text{ fm}$. The restructured aggregation model\cite{38} has been applied to avoid the
nonphysical clusters after constructing the clusters, until there were not any nonphysical clusters to be produced.

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 for an isospin dependent nucleon nucleon cross section $\sigma^{iso}$ and for an isospin independent one $\sigma^{noiso}$ in the medium. Here $\sigma^{iso}$ is defined as $\sigma_{np} \geq \sigma_{nn} = \sigma_{pp}$ and $\sigma^{noiso}$ means $\sigma_{np} = \sigma_{nn} = \sigma_{pp}$, where $\sigma_{np}$, $\sigma_{nn}$ and $\sigma_{pp}$ are the neutron proton, neutron neutron and proton proton cross sections in medium, respectively.

3.1 Influence of medium correction of two-body (collision) on the $N_n$ and $N_{imf}$

In order to study the influence from the medium correction of the isospin dependent nucleon nucleon cross section on the isospin effects of the fragmentation and the nucleon emission, we investigated the number of nucleon emission $N_n$ as a function of the beam energy at impact parameter $b= 4.0$ fm for the mass symmetry system $^{76}$Kr + $^{76}$Kr (top panels) and mass asymmetry system $^{112}$Sn + $^{40}$Ca (bottom panels). Two colliding systems are the same system mass $A_t + A_p = 152$, where $A_t$ and $A_p$ are projectile mass and target mass respectively. The different symmetry potentials $U_{sym}^1$, $U_{sym}^2$ and $U_{sym}^0$ as well as different kinds of nucleon nucleon cross sections, i.e., the isospin dependent in-medium nucleon nucleon cross section $\sigma^{iso}$ and the isospin independent one $\sigma^{noiso}$ are used here. Namely, there are six cases: $U_{sym}^0 + \sigma^{iso}$, $U_{sym}^1 + \sigma^{iso}$, $U_{sym}^2 + \sigma^{iso}$, $U_{sym}^1 + \sigma^{noiso}$, $U_{sym}^2 + \sigma^{noiso}$ with $\alpha = -0.2$ (left panels) and $\alpha = 0.0$ (right panels) in Fig.1. The detail explanations about line symbols in the Fig.1 are in figure. It is clear to see that all of lines with filled symbols are larger than those with open symbols, i.e., all of $N_n's$ with $\sigma^{iso}$ are larger than those with $\sigma^{noiso}$ because the collision number is larger for $\sigma^{iso}$ than that for $\sigma^{noiso}$. We also found that the gaps between lines with the filled symbols and with the open symbols are larger but the variations among lines in each group are smaller. Because
the large gaps come from the isospin effect of two-body collision and small variations are produced from the symmetry potential, i.e., $N_n$ depends sensitively on the isospin effect of in-medium nucleon nucleon cross section and weakly on the symmetry potential. In particular, the gaps between two group lines with $\alpha = -0.2$ are larger than those with $\alpha = 0.0$, i.e., the medium correction of two-body collision enhances the dependence of $N_n$ on isospin effect of two-body collision.

In order to investigate quantitatively the influence of the medium correction of two-body collision on the nucleon emission, it is to define

$$\Delta N_n(\Delta \sigma, \alpha) = N_n(\sigma^{iso}, \alpha) - N_n(\sigma^{noiso}, \alpha).$$

(10)

Fig. 2 shows the time evolution of $\Delta N_n(\Delta \sigma, \alpha = -0.2)$ (solid line) and $\Delta N_n(\Delta \sigma, \alpha = 0.0)$ (dashed line) at impact parameter $b = 4.0 fm$ for $^{76}\text{Kr} + ^{76}\text{Kr}$ at $E=100$ MeV/nucleon (top panels) and $^{112}\text{Sn} + ^{40}\text{Ca}$ at $E=200$ MeV/nucleon (bottom panels). In this case, there are about the same center of mass energy per nucleon for two colliding systems. The symmetry potentials are $U_1^{sym}$ (left panels) and $U_2^{sym}$ (right panels). It is clear to see that all of solid lines are higher than dashed lines, i.e., the medium correction of nucleon nucleon cross section increases sensitively the dependence of $N_n$ on the isospin effect of two-body collision as above mentioned.

To investigate the evolution of above dependence with increasing beam energy for two different colliding systems, the variation $\Delta N_n(\Delta \sigma, \Delta \alpha)$ as a function of beam energy at impact parameter of 4.0 fm for symmetry potential $U_1^{sym}$ is given in Fig.3. Where $\Delta N_n(\Delta \sigma, \Delta \alpha)$ is defined as

$$\Delta N_n(\Delta \sigma, \Delta \alpha) = \Delta N_n(\Delta \sigma, \alpha = -0.2) - \Delta N_n(\Delta \sigma, \alpha = 0.0)$$

(11).

In which $\Delta N_n(\Delta \sigma, \alpha)$ is taken from Eg.(10). From Fig.3 we can see that all of $\Delta N_n(\Delta \sigma, \Delta \alpha)$ are larger than zero, i.e., the medium correction of the nucleon nucleon cross section increases the dependence of $N_n$ on the isospin effect of two-body collision in the beam energy region from 50 MeV/nucleon to 300 MeV/nucleon. we also find that $\Delta N_n(\Delta \sigma, \Delta \alpha)'s$ for mass symmetry system are always larger than those for mass asymmetry system due to more collision number for the mass symmetry system with the same system mass.
In order to investigate the contributions from all of impact parameters to $N_n$, Fig.4 shows the impact parameter average values of $<N_n>_b$ (from at equilibrium time $200 fm/c$) as a function of the beam energy for above two colliding systems with the same incident channel conditions and line symbols as in Fig.1. The same conclusion as mentioned in Fig.1 is also obtained here, i.e., the medium correction of nucleon nucleon cross section enhances the dependence of $<N_n>_b$ on the isospin effect of two-body collision.

Fig.5 shows the impact parameter average values of the multiplicity of intermediate mass fragment, $<N_{imf}>_b$ (at equilibrium time $200 fm/c$), as a function of the beam energy for the same incident channel conditions and line symbols as in Fig.4. Where the charge number of intermediate mass fragment is taken from 3 to 13. From Fig.5 we got the same conclusions as $<N_n>_b$, namely, $<N_{imf}>_b$ depends sensitively on the isospin effect of in-medium nucleon nucleon cross section and weakly on the symmetry potential. In particular, the gaps between two group lines with $\alpha = -0.2$ are larger than those with $\alpha = 0.0$, which indicates that the medium correction enhances also the dependence of $<N_{imf}>_b$ on the isospin effect of the two-body collision.

### 3.2 Important role of MDI on $N_{imf}$ and $N_n$ in the medium corrections of two-body collision

We also found an important role of the MDI on $N_{imf}$ and $N_n$ in the medium correction of two-body collision. Fig.6 shows the time evolution of $N_{imf}$ for the reaction $^{76}Kr + ^{76}Kr$ with symmetry potentials $U_{1}^{sym}$ at beam energy of 100 MeV/nucleon and impact parameter of 4.0 fm. They are four cases: (1) $\alpha = -0.2 + \sigma^{iso}$ ( solid line),(2) $\alpha = 0.0 + \sigma^{iso}$ ( dashed line),(3) $\alpha = -0.2 + \sigma^{noiso}$ ( dot line ) and (4) $\alpha = 0.0 + \sigma^{noiso}$ ( dot-dashed line) with MDI in the left window and NOMDI in the right window. It is clear to see that the gap between the lines with MDI is larger than corresponding gap between lines with NOMDI in the medium($\alpha = -0.2$), i.e., MDI increases the isospin effect of two-body collision on the $N_{imf}$ in the medium because above gaps are produced from the isospin effect of nucleon-nucleon cross section in the medium.

For the $<N_n>_b$, we have gotten the same conclusion as $<N_{imf}>_b$ in Fig.6.
3.3 Explanations for the medium correction of two-body collision and the role of MDI on the $N_{imf}$ and $N_n$.

Why does the medium correction of nucleon nucleon cross section and MDI enhance the dependences of multiplicity of intermediate mass fragments $N_{imf}$ and the number of nucleon emission $N_n$ on the isospin effect of two-body collision? Physically there are three mechanisms at work here. (1) The average momentum of a particle in medium is higher in a heavy ion collision than in cold nuclear matter at the same density. (2) MDI induces the transporting momentum more effectively from one part of the system to another, in which particles also move with a higher velocity in the medium than in free space for a given momentum. (3) As well know that the isospin dependent in-medium nucleon nucleon cross section is a sensitive function of the nuclear density distribution and beam energy as shown in Eq. (7). Fig. 7 shows the time evolution of the ratio of nuclear density to normal one, $\frac{\rho}{\rho_0}$, for four cases: they are $\rho(\sigma^{iso}, \alpha = -0.2)$ (solid line), $\rho(\sigma^{noiso}, \alpha = -0.2)$ (dotted line), $\rho(\sigma^{iso}, \alpha = 0.0)$ (dashed line) and $\rho(\sigma^{noiso}, \alpha = 0.0)$ (dot-dashed line) for the reaction $^{76}$Kr $+$ $^{76}$Kr with symmetry potential $U_1^{sym}$ at $E=150$ MeV/nucleon and $b=4.0$fm. From the values of peak for $\frac{\rho}{\rho_0}$ in the insert in Fig. 7 it is clear to see that $\rho(\sigma^{iso}, \alpha = -0.2)$ (solid line) is larger than $\rho(\sigma^{noiso}, \alpha = -0.2)$ (dot line) and $\rho(\sigma^{iso}, \alpha = 0.0)$ (dashed line) is larger than $\rho(\sigma^{noiso}, \alpha = 0.0)$ (dot-dashed line) because the larger collision number from $\sigma^{iso}$ increases the nuclear stopping and dissipation, which enhances the nuclear density, compared to the case with $\sigma^{noiso}$. From Fig. 7 we can also see that $\frac{\rho}{\rho_0}$ decreases quickly with increasing the time after the peak of $\frac{\rho}{\rho_0}$. During above process the larger compression produces quick expanding process of the colliding system and the small compression induces slow expanding process, at the same time, the $\frac{\rho}{\rho_0}$ decreases quickly with expanding process of system. But the decreasing velocity of $\frac{\rho}{\rho_0}$ is larger for the quick expansion system than that for the slow expansion system, up to about after 70 fm/c, on the contrary, $\rho(\sigma^{noiso}, \alpha = -0.2)$ (dot line) is larger than $\rho(\sigma^{iso}, \alpha = -0.2)$ (solid line) and $\rho(\sigma^{noiso}, \alpha = 0.0)$ (dot-dashed line) is larger than $\rho(\sigma^{iso}, \alpha = 0.0)$ (dashed line). In particular, the gap between two lines for $\alpha = -0.2$ is larger than that for $\alpha = 0.0$ after about 70 fm/c. This property is very similar to the
$N_{imf}$ and $N_n$, which means that the medium correction of an isospin dependent nucleon nucleon cross section enhances also the dependence of $\rho$ on the isospin effect of two-body collision, which induces the same effects on $N_{imf}$ and $N_n$ through the nucleon nucleon cross section as a function of the nuclear density as shown in Eq.(7).

4 Summary and conclusion

We studied the influences of the medium correction of the isospin dependent nucleon nucleon cross section and MDI on the fragmentation and nucleon emission in the heavy ion collisions at intermediate beam energies by using the IQMD. From the calculation results we can get the following conclusions:

(1) $\langle N_n \rangle_b$ and $\langle N_{imf} \rangle_b$ depend sensitively on the isospin effect of nucleon nucleon cross section and weakly on the symmetry potential.

(2) In particular, the medium correction of nucleon nucleon cross section enhances the dependence of $\langle N_n \rangle_b$ and $\langle N_{imf} \rangle_b$ on the isospin effect of nucleon nucleon cross section in the intermediate beam energy region.

(3) MDI produces an important role for enhancing the isospin effect of two-body collision on the $\langle N_n \rangle_b$ and $\langle N_{imf} \rangle_b$ due to the medium correction.

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Figure captions

**Fig. 1** The nucleon emission number \( N_n \) as a function of the beam energy for systems \( ^{76}Kr + ^{76}Kr \) and \( ^{112}Sn + ^{40}Ca \) for six cases (see text).

**Fig. 2** The time evolution of \( \Delta N_n(\Delta \sigma, \alpha) \) for the systems as the same as Fig.1 at \( E=100 \) MeV/nucleon (top panels) and 200 MeV/nucleon (bottom panels) for two symmetry potentials (see text).

**Fig. 3** \( \Delta N_n(\Delta \sigma, \Delta \alpha) \) as a function of the beam energy for the systems as the same as Fig.1 in two cases (see text).

**Fig. 4** The impact parameter average value of the number of nucleon emission \( < N_n >_b \) as a function of beam energy for the same incident channel conditions and line symbols as Fig.1 (see text).

**Fig. 5** The impact parameter average values of the multiplicity of intermediate mass fragment, \( < N_{imf} >_b \) as a function of the beam energy for the same incident channel conditions and line symbols as Fig.4.

**Fig. 6** The time evolution of the \( N_{imf} \) with MDI (solid line) and NOMDI (dot line) for systems \( ^{76}Kr + ^{76}Kr \) at \( E=100 \) MeV/nucleon and \( b=4.0 \) fm(see text).

**Fig. 7** The time evolution of the ratio of nuclear density to normal density \( \frac{\rho(\sigma_{iso}, \alpha)}{\rho_0} \) for four cases(see text).