Probing the Isospin Dependent In-Medium Nucleon-Nucleon Cross Section by Nucleon Emissions

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Abstract. The effects of the symmetry potential and the isospin dependent in-medium nucleon-nucleon (NN) cross section on the number of proton(neutron) emissions $N_p(N_n)$ are studied respectively within an isospin-dependent quantum molecular dynamics (IQMD) model. The isospin dependent in-medium NN cross section is found to have a strong influence on $N_p(N_n)$ but $N_p(N_n)$ is not sensitive to the symmetry potential for the neutron-deficient colliding system at relatively high energies. We propose to make use of the $N_p(N_n)$ as a probe to extract information on the isospin dependent in-medium NN cross section.

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1 Introduction

With the rapid advance in radioactive beam physics a better understanding of the isospin degree of freedom in nuclear collision dynamics may provide us with useful hints on how to extract reliable information about the in-medium NN cross section and the symmetry potential [1-5]. To obtain this information several interesting isospin effects in heavy ion collisions have been explored both experimentally [6-16] and theoretically, e.g., [17-25] over the last few years. Bao-An Li et al. [19, 25] have found that information on the symmetry potential can be extracted by studying the neutron to proton ratio of preequilibrium emissions in the relative low energy heavy ion collisions (HIC). In contrast, in this paper our studies within IQMD found that the numbers of proton(neutron) emissions $N_p(N_n)$ depend sensitively on the isospin dependent in-medium NN cross section and weakly on the symmetry potential in the relatively high beam energy region for the neutron-deficient systems. In this case, $N_p(N_n)$ is a probe for extracting information about the isospin dependence of in-medium NN cross section in the relative high beam energy region for the neutron-deficient systems.
2 Theoretical Model

The dynamics of intermediate energy heavy ion collisions described by QMD contains two ingredients: density dependent mean field and in-medium N-N cross section. To describe isospin effects appropriately, QMD should be modified properly: the density dependent mean field should contain the correct isospin terms including symmetry potential and Coulomb potential, the in-medium N-N cross section should be different for neutron-neutron (proton-proton) and neutron-proton collisions in which Pauli blocking should be counted by distinguishing neutrons from protons. In addition, the initial condition of the ground state of two colliding nuclei should also contain isospin information. The main physics ingredients and their numerical realization in the IQMD model can be found in Refs. [3, 28, 30, 31, 34]. In the IQMD model, the density distributions of colliding nuclei were from the calculations of the Skyrme- Hatree-Fock with parameter set SKM [32] and 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 are the same as the experimental data. In the presence calculations the interaction potential in the IQMD were determined as follows:

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

\[ U^{Sky} \] is the density-dependent Skyrme potential,

\[ U^{Sky} = \alpha \left( \frac{\rho}{\rho_0} \right) + \beta \left( \frac{\rho}{\rho_0} \right)^2 \]  

\[ V_c \] is Coulomb potential. \( U^{Yuk} \) is the Yukawa potential,

\[ U^{Yuk} = t_3 \exp \left( \frac{|r_1 - r_2|}{m} \right) \]

\[ U^{MDI} \] is the momentum dependent interaction,

\[ U^{MDI} = t_4 \ln ^2 \left| t_5 (p_1 - p_2)^2 + 1 \right| \frac{\rho}{\rho_0} \]

\[ U^{Pauli} \] is the Pauli potential,

\[ U^{Pauli} = V_p \left( \frac{h}{p_0 q_0} \right)^3 \exp \left( - \frac{(r_1 - r_2)^2}{2q_0^2} - \frac{(p_1 - p_2)^2}{2p_0^2} \right) \delta_{p_i p_j} \]  

\[ \delta_{p_i p_j} = \begin{cases} 1 & \text{for neutron-neutron or proton-proton} \\ 0 & \text{for neutron-proton} \end{cases} \]

\( U^{sym} \) is the symmetry potential. In the present calculation, two different density dependent symmetry potentials [2, 3, 29] are used, i.e., \( U^{sym}_1 = c F_1(u) \delta \tau_z \) and \( U^{sym}_2 = c F_2(u) \delta \tau_z + \frac{1}{2} \delta^2 \), where \( \tau_z = 1 \) for neutron and \( \tau_z = -1 \) for proton, \( F_1(u) = u \) and \( F_2(u) = u^2 \), \( u \equiv \rho / \rho_0 \). \( \delta \) is the relative neutron excess \( \delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p} = \frac{\rho_n - \rho_p}{\rho} \). Here \( c \) is the strength of symmetry potential, taking the value of 32 or 0 MeV (the \( c=0.0 \) case is denoted by \( U^{sym}_0 \)). \( \rho_n \) and \( \rho_p \) are total density and its normal value, neutron density and proton density, respectively. It is worth mentioning that the recent studies on collective flow in HIC at intermediate energies have indicated a reduction of in-medium N-N cross sections. An empirical expression of the density dependent in-medium N-N cross section [26] is given by

\[ \sigma_{NN}^{med} = (1 + \alpha \frac{\rho}{\rho_0}) \sigma_{NN}^{free} \]  

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Where the parameter $\alpha \approx -0.2$ has been found to reproduce the flow data. $^{\text{free}}\sigma_{NN}$ is the experimental N-N cross section$^{[27]}$. The parameters of the interaction potentials are given in table 1.

| $\alpha$ (MeV) | $\beta$ (MeV) | $\gamma$ (MeV) | $t_3$ (MeV) | $t_4$ (MeV) | $t_5$ (MeV $^{-2}$) | $V_P$ (MeV) | $p_0$ (MeV/c) | $q_0$ (fm) |
|----------------|---------------|----------------|-------------|-------------|---------------------|-------------|-------------|-------------|
| -390.1         | 320.3         | 1.14           | 7.5         | 0.8         | 1.57                | 5 $\times$ 10$^{-4}$ | 30          | 400         | 5.64        |

Table 1. The parameters of the interaction potentials

The free neutron-proton cross section $^{\text{free}}\sigma_{NN}$ is about a factor of 3 times larger than the free proton-proton or free neutron-neutron cross section below about 400 MeV (in the Lab). It is worth to mentioning that the relationship between the neutron-proton cross section and neutron-neutron (proton-proton) cross section depends also on the modification of the nuclear density distributions during reactions. We construct clusters by means of the isospin-dependent modified coalescence model$^{[34]}$, in which particles with relative momentum smaller than $p_0 = 300$ MeV/c and relative distance smaller than $R_0 = 3.5$ fm are used. We make use of the restructuring aggregation model$^{[35]}$ to avoid the nonphysical clusters after constructing the clusters, until there are not any nonphysical clusters to be produced.

3 Results and Discussions

3.1 Checking the IQMD model

In order to check the IQMD code with the above parameters, the multiplicity of the intermediate mass fragments $N_{\text{imf}}$ for the reactions $^{58}\text{Fe} + ^{58}\text{Fe}$ and $^{58}\text{Ni} + ^{58}\text{Ni}$ at the beam energy $E = 75\text{MeV/u}$ has been calculated by using the IQMD code with the above parameters. The multiplicity of the intermediate mass fragments (IMFs) is defined as the number of fragments with charge numbers from 3 to 18. The calculated results are compared with the experimental data$^{[36]}$ on the same scale in Fig.1 which gives the correlation between the mean value of the intermediate mass fragment multiplicity $N_{\text{imf}}$ and the charged particle multiplicity $N_c$. The solid (open) circles represent the experimental data for the reaction $^{58}\text{Ni} + ^{58}\text{Ni}$ ($^{58}\text{Fe} + ^{58}\text{Fe}$) at $E = 75\text{MeV/u}$ and the solid line (dot line) denotes the IQMD results for $^{58}\text{Ni} + ^{58}\text{Ni}$ ($^{58}\text{Fe} + ^{58}\text{Fe}$). It is clear that the present IQMD predictions are in satisfactory agreement with general features of the experimental data which means that IQMD with the above parameters is a reasonable transfer theoretical model for simulating the dynamical process in intermediate energy heavy ion collisions.

3.2 A probe of isospin dependent in-medium NN cross section by nucleon emissions

The isospin effects of the in-medium NN cross section on the physical quantities arise from the difference between isospin dependent in-medium NN cross section denoted by $^{\text{iso}}\sigma_{NN}$ in which $\sigma_{np} \geq \sigma_{nn}=\sigma_{pp}$ and isospin independent NN cross section denoted by $^{\text{noiso}}\sigma_{NN}$ in which
\[ \sigma_{np} = \sigma_{nn} = \sigma_{pp}. \] Here \( \sigma_{np}, \sigma_{nn}, \) and \( \sigma_{pp} \) are the neutron-proton, neutron-neutron and proton-proton cross sections respectively.

Here \( N_p(N_n) \) includes all of protons(neutrons) emitted during the nuclear reaction. To identify free nucleons, a phase-space coalescence method has been used at 200 fm/c (when \( N_p(N_n) \) becomes nearly a constant) after the initial contact of the two nuclei. A nucleon is considered as free if it is not correlated with other nucleon within a spatial distance of \( \Delta r=3 \text{fm} \) and a momentum distance of \( \Delta p=300 \text{MeV/c} \). Otherwise, it is bound in a cluster. In addition to the nucleon emissions we also calculated all of the fragments during the same reaction. Fig.2 shows the time evolutions of the \( N_n \) (top windows) and \( N_p \) (bottom windows) for the colliding systems \( ^{76}\text{Kr}+^{40}\text{Ca}, ^{74}\text{Kr}+^{74}\text{Se}, ^{76}\text{Kr}+^{76}\text{Kr} \) and \( ^{74}\text{Se}+^{74}\text{Se} \) with neutron-proton ratios 1.04, 1.06, 1.11 and 1.18 respectively at impact parameter \( b=4.0 \text{ fm} \) and beam energy \( E=150 \text{ MeV/nucleon} \). To identify the isospin effects of the two-body collision on the \( N_p(N_n) \) we compare the cases when the isospin dependence of in-medium NN cross section is either turned on (\( \sigma_{iso} \)) or off (\( \sigma_{noiso} \)). Turning on the isospin-dependent NN cross section is seen to enhance the momentum dissipation as expected, leading to a larger number of proton(neutron) emissions. The isospin effects of the one-body dissipation and two-body collision on the \( N_n(N_p) \) are identified by using five cases: \( U_1^{sym} + \sigma_{iso} \) (solid lines), \( U_0^{sym} + \sigma_{iso} \) (dot lines), \( U_2^{sym} + \sigma_{iso} \) (dashed lines), \( U_1^{sym} + \sigma_{noiso} \) (dashed-dot lines), \( U_2^{sym} + \sigma_{noiso} \) (dashed-dot-dot lines). From Fig.2 it is clear to see that the variations among the values of \( N_p(N_n) \) with the same \( \sigma_{iso} \) or the same \( \sigma_{noiso} \) but different symmetry potentials are smaller but the gaps between the \( N_p(N_n) \) with \( \sigma_{iso} \) and \( N_p(N_n) \) with \( \sigma_{noiso} \) are larger, i.e., the values of \( N_p(N_n) \) depends sensitively on the isospin dependence of in-medium NN cross section and weakly on the symmetry potentials for the neutron-deficient systems. This situation is contrary to the neutron-proton ratio of the preequilibrium emissions in relatively low energy regions, where the neutron-proton ratio of the preequilibrium emissions depends sensitively on the symmetry potential and weakly on the isospin dependence of the in-medium NN cross section [19]. With decreasing beam energy the role of two-body collision is reduced. In particular, the symmetry potential is repulsive for the neutrons and attractive for the protons which tends to make more neutrons than protons unbound i.e., the role of symmetry potential on the nucleon emissions at low energies results in the sizeable differences between neutron emissions and proton emissions, but the two-body collision produces about the same probability for gaining enough energy to become unbound for the the neutrons and protons. As a result, the isospin dependence of in-medium NN cross section has a small affect on the neutron-proton ratio of the preequilibrium emissions but the role of the symmetry potential on it is strengthened in regions of relatively low beam energy. But with increasing beam energy the role of two-body collisions increases while the role of the mean field is reduced i.e., in the relatively high energy region the two-body collision is dominant. Especially in this paper we calculated the neutron emissions and the proton emissions not the ratio of them. Finally we can get the results as in Fig.2. In Fig.3 is shown the impact parameter-averaged asymptotic values of \( N_n \) (top window) and \( N_p \) (bottom window) as a function of beam energy for the systems \( ^{76}\text{Kr}+^{40}\text{Ca} \) and \( ^{78}\text{Kr}+^{70}\text{Kr} \) in the five cases considered as the same as Fig.2. From Fig.3 it is very clear to see the same conclusion as Fig.2 in the beam energy region from about 50 to 400 MeV/nucleon. But as the beam energy is decreased to about 50 MeV/nucleon the \( N_p(N_n) \) depends on both the isospin dependence of in-medium NN cross section and the symmetry potential. It is worth mentioning that the minimum energies for remaining above property are small different for the systems with the variation of the neutron-proton
ratios and mass asymmetries of the colliding systems.

The above results show strongly that \( N_p(N_n) \) during the neutron-deficient nuclear reaction can be used as a sensitive probe for extracting information on the isospin dependent in-medium NN cross section. Here the above behaviour has been shown for the neutron emissions and proton emissions separately, of course, there is also the same behaviour as a probe for the sum of them.

It is worth mentioning that in general, the correction effect of the sequential decays on the dynamical process of HIC and the number of the nucleon emissions should be considered. For example M.B. Tsang et al’s studies show that the apparent temperatures measured with double ratios of fragment isotope yields display fluctuations that can be attributed to the sequential decay of heavier particle unstable nuclei \(^{37}\). However, the number of nucleon emissions in our calculations is the final total number of nucleon emissions after colliding system has reached at equilibrium which includes the original nucleon emissions and sequential decays leading above conclusion. Namely the final total number of nucleon emissions depends sensitively on the isospin effect of in-medium NN cross section and insensitively on the symmetry potential as a probe for extracting information on the isospin dependent in-medium NN cross section in HIC at the relatively high beam energies for neutron-deficient colliding systems. Even though the dynamical mechanisms for the original nucleon emissions and the sequential decays are different which produces the correction effect on the total number of nucleon emissions but this difference and the correction effect of sequential decays on the total number of nucleon emissions do not influence our final conclusion.

4 Summary and conclusions

In summary, within the IQMD we studied the isospin effects of one-body dissipation and two-body collision on the number of protons (neutrons) emitted during the nuclear reaction. The calculated results show strongly that the isospin-dependent in-medium NN cross section has a much stronger influence on \( N_p(N_n) \) but the effects of the symmetry potential on them are smaller for the neutron-deficient systems in the relatively high energy region. Studies of \( N_p(N_n) \) during the nuclear reactions are proposed to extract information on the isospin-dependent in-medium NN cross section in HIC based on systematic comparisons between the theoretical simulations and experimental studies.

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**Figure captions**

**Fig. 1** The correlation between the mean intermediate mass fragment multiplicity $N_{imf}$ and the charged particle multiplicity $N_c$. Filled (unfilled) circles represent the experimental data [36] for the reactions $^{58}Ni+^{58}Ni(^{58}Fe+^{58}Fe)$ at E=75 MeV/u and the solid line (dot line) indicates the IQMD results for $^{58}Ni+^{58}Ni(^{58}Fe+^{58}Fe)$. The charge number of $N_{imf}$ is taken from 3 to 18.
**Fig. 2** The time evolutions of the $N_n$ (top windows) and $N_p$ (bottom windows) for the colliding systems $^{76}\text{Kr}+^{40}\text{Ca}$, $^{74}\text{Kr}+^{74}\text{Se}$, $^{76}\text{Kr}+^{76}\text{Kr}$ and $^{74}\text{Se}+^{74}\text{Se}$ with neutron-proton ratios 1.07, 1.11, 1.11 and 1.18 respectively at impact parameter $b=4.0\text{fm}$ and beam energy $E=150\text{MeV/nucleon}$ for five cases (see text).

**Fig. 3** The impact parameter-averaged values of $N_n$ (top window) and $N_p$ (bottom window) as a function of the beam energies for the systems $^{76}\text{Kr}+^{40}\text{Ca}$ and $^{76}\text{Kr}+^{76}\text{Kr}$ in the five cases as the same as Fig. 2.