Isospin effects of the Skyrme potential and the momentum dependent interaction at intermediate energy heavy ion collisions*

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Abstract We improve the isospin dependent quantum molecular dynamical model by including isospin effects in the Skyrme potential and the momentum dependent interaction to obtain an isospin dependent Skyrme potential and an isospin dependent momentum interaction. We investigate the isospin effects of Skyrme potential and momentum dependent interaction on the isospin fractionation ratio and the dynamical mechanism in intermediate energy heavy ion collisions. It is found that the isospin dependent Skyrme potential and the isospin dependent momentum interaction produce some important isospin effects in the isospin fractionation ratio.

Key words heavy ion collision, isospin fractionation ratio, isospin effect, isospin dependent momentum interaction, isospin dependent Skyrme potential

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1 Introduction

In order to obtain information on the in-medium nucleon-nucleon cross section and isospin dependent mean field in heavy ion collisions, several interesting isospin effects in heavy ion collisions have been explored over the last few years[1—25], both, experimentally and theoretically. The effects of the momentum dependent interaction (MDI) and the Skyrme potential in heavy ion collisions have been studied for many years. However, the isospin dependence of the momentum interaction and Skyrme potential has not been studied in heavy ion collisions. Recently Das Gupta, Gale and Li investigated the isospin dependence of the momentum interaction and Skyrme potential in asymmetric nuclear matter and gave a formula with isospin dependence of the momentum interaction and Skyrme potential for Boltzmann-Uehling-Uhlenbeck (BUU) calculations and for heavy ion collisions induced by neutron-rich nuclei[26,27]. However the isospin dependence of the momentum interaction and Skyrme potential have not been taken into account in isospin dependent quantum molecular dynamical model (IQMD) . We improve the IQMD by including an isospin effect in the MDI and the Skyrme potential to obtain an isospin dependence of the momentum interaction and Skyrme potential for practical calculations. In this work we investigate the isospin effects of the MDI and Skyrme potential on the isospin fractionation ratio and its dynamical mechanism in intermediate energy heavy ion collisions. It is found that isospin dependence of the momentum interaction and Skyrme potential produce some important isospin effects in the isospin fractionation ratio.

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2 IQMD with isospin dependent momentum interaction and isospin dependent Skyrme potential

2.1 IQMD without isospin dependence in the momentum dependent interaction and Skyrme potential

The quantum molecular dynamics (QMD)[28,29] contains two dynamical ingredients: the density dependent mean field and the in-medium nucleon-nucleon cross section. In order to describe the isospin effects appropriately, the QMD should be modified properly. The density dependent mean field should contain correct isospin terms. This includes the isospin dependence momentum interaction, the isospin dependence Skyrme potential, the symmetry potential and the Coulomb potential. The in-medium nucleon-nucleon cross section should be different for neutron-neutron (proton-proton) and neutron-proton collisions, in which Pauli blocking should be taken into account treating neutrons and protons as distinct particles. In addition, the starting condition of the ground state of two colliding nuclei should also contain isospin information. The initial density distributions of the colliding nuclei are obtained from Skyrme-Hartree-Fock (SHF) calculations, and the initialization code of IQMD is used to determine the ground state properties of the colliding nuclei. In this way one achieves consistency of binding energies and the root mean square radii (rms) with the experimental data. In these calculations the interaction potential in IQMD is

$$U(\rho)=U^{\text{Sky}}+U^{\text{Coul}}+U^{\text{sym}}+V^{\text{Yuk}}+V^{\text{MDI}}+V^{\text{Pauli}}\,, \quad (1)$$

where V^{Yuk} and V^{Pauli} are the Yukawa and Pauli interactions, U^{Coul} is the Coulomb potential and U^{sky} is the Skyrme potential

$$U^{\text{Sky}}=\alpha\left(\frac{\rho}{\rho_0}\right)+\beta\left(\frac{\rho}{\rho_0}\right)^{\gamma}. \quad (2)$$

with α=−390 MeV, β=320 MeV, γ=1.14. In this work U^{sym} has been used in the form[1,2],

$$U^{\text{sym}}=cu\delta\tau_z\,, \quad (3)$$

with

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

Here c is the strength of the symmetry potential (c=32 MeV has been used). $u=\rho/\rho_0$ and $\delta=(\rho_{\text{n}}-\rho_{\text{p}})/(\rho_{\text{n}}+\rho_{\text{p}})=(\rho_{\text{n}}-\rho_{\text{p}})/\rho$ is the relative neutron excess. ρ, ρ_0, ρ_{n} and ρ_{p} are the total, normal, neutron and proton densities, respectively. U^{MDI} is the isospin independent momentum interaction[29]

$$U^{\text{MDI}}=t_4\ln^2[t_5(\boldsymbol{p}_1-\boldsymbol{p}_2)^2+1]\frac{\rho}{\rho_0}\,. \quad (4)$$

Here t_4=1.57 MeV and t_5=0.0005 MeV^{-2}. An empirical density dependent expression of the in-medium nucleon-nucleon cross section[30] has been used.

$$\sigma_{\text{NN}}^{\text{med}}=\left(1+\alpha\frac{\rho}{\rho_0}\right)\sigma_{\text{NN}}^{\text{free}}\,. \quad (5)$$

In the above equation the parameter α=−0.2 has been found to reproduce the current available data. Here $\sigma_{\text{NN}}^{\text{free}}$ is the experimental nucleon-nucleon cross section. We use Eq. (5) to obtain the medium effects in nucleon-nucleon collisions. The main physics and its numerical realization in the IQMD model can be found in Refs. [1, 2, 28, 29, 31, 32].

2.2 IQMD with isospin dependent momentum interaction and isospin dependent Skyrme potential

The isospin independent MDI, Eq. (4) is extracted from an optical potential[29]. In order to include isospin effects in MDI, we insert an isospin degree of freedom into the MDI to obtain an isospin dependent momentum interaction. The latter should include the interactions between the same kinds of nucleons τ-τ (neutron-neutron, proton-proton) and that between different kinds of nucleons τ-τ' (neutron-proton, proton-neutron), in which each nucleon interacts with all other nucleons. In this way we can write an isospin dependent momentum interaction as follows:

$$\begin{aligned}U_{\tau}^{\text{IMDI}}(\boldsymbol{p}_{\tau},\tau) =\; & t_4\ln^2[t_5(\boldsymbol{p}_{\tau}-\boldsymbol{p}'_{\tau})^2+1]C_{\tau\tau}\frac{\rho_{\tau}}{\rho_0}+\\ & t_4\ln^2[t_5(\boldsymbol{p}_{\tau}-\boldsymbol{p}'_{\tau'})^2+1]C_{\tau\tau'}\frac{\rho_{\tau'}}{\rho_0}\,. \end{aligned}\quad (6)$$

τ and τ' indicate neutron and proton, $\tau\neq\tau'$. $\boldsymbol{p}'$ and $\boldsymbol{p}$ are the different nucleon momenta, $C_{\text{nn}}=C_{\text{pp}}=C_{\tau\tau}$ and $C_{\text{np}}=C_{\text{pn}}=C_{\tau\tau'}$.

The isospin independent Skyrme potential as shown in Eq. (2) can be modified in the following way

$$U_{\tau}^{\text{ISKY}}=\alpha_{\tau\tau}\left(\frac{\rho_{\tau}}{\rho_0}\right)+\alpha_{\tau\tau'}\left(\frac{\rho_{\tau'}}{\rho_0}\right)+\beta\left(\frac{\rho}{\rho_0}\right)^{\gamma}. \quad (7)$$

In the above equation $\alpha_{\tau\tau}$ ($\alpha_{\tau\tau'}$) are the coefficients for the nucleon-nucleon interaction between nucleons of the same (different) kind ($\tau\neq\tau'$). The new one-body potential (U_{τ}) is now given by

$$U_{\tau}=U_{\tau}^{\text{ISKY}}+U_{\tau}^{\text{IMDI}}+U_{\tau}^{\text{sym}}\,. \quad (8)$$

The parameters of U_{τ} in Eq. (8) (including the isospin dependent momentum interaction and Skyrme potential) are determined by a comparison with the one-body Gogny potential (U_{Gogny}) in

Ref. [26]. The $U_{\rm Gogny}$ can be obtained from the Gogny effective interaction used in nuclear many-body theory. The adjustable parameters in U_τ are t_4, t_5, $C_{\tau\tau}$, $C_{\tau\tau'}$, $\alpha_{\tau\tau}$, $\alpha_{\tau\tau'}$, β and γ. The determination of these parameters is subject to the following constraints. The results of the original IQMD model should be recovered if the difference between neutron and proton is neglected in Eq. (8). On the other hand, under all circumstances, should U_τ, the nuclear symmetry energy and the curvature of the symmetry energy at normal density be in accord with $U_{\rm Gogny}$ for all energies and densities. From these conditions the following values of the parameters of U_τ have been obtained: t_4=1.57 MeV, t_5=0.00056 MeV^{-2}, $C_{\tau\tau}$=0.5, $C_{\tau\tau'}$=1.78, $\alpha_{\tau\tau}$=−388 MeV, $\alpha_{\tau\tau'}$=−382 MeV, β = 313 MeV, γ=1.15. Fig. 1 shows U_τ (thick lines) and $U_{\rm Gogny}$ (thin lines) as a function of momentum at densities $\rho/\rho_0 = 0.5$, 1.0 and 1.5 for neutrons (solid line) and protons (dashed line). From Fig. 1 we can see that the two solid lines and the two dashed lines are close to each other. It means that the potentials U_τ for neutrons and protons are in accord with those from $U_{\rm Gogny}$,except in case of the neutron potential at ρ/ρ_0=1.5. The isospin fractionation process occurs mainly in the lower density (region below ρ/ρ_0=1.0) which we represent quite good. The starting code of IQMD with isospin dependent momentum interaction and isospin dependent Skyrme potential is also used to determine the ground state properties of the colliding nuclei. During this starting calculations, all parameters of the interactions with isospin dependent momentum interaction and isospin dependent Skyrme potential are defined as the input data for dynamical calculations.

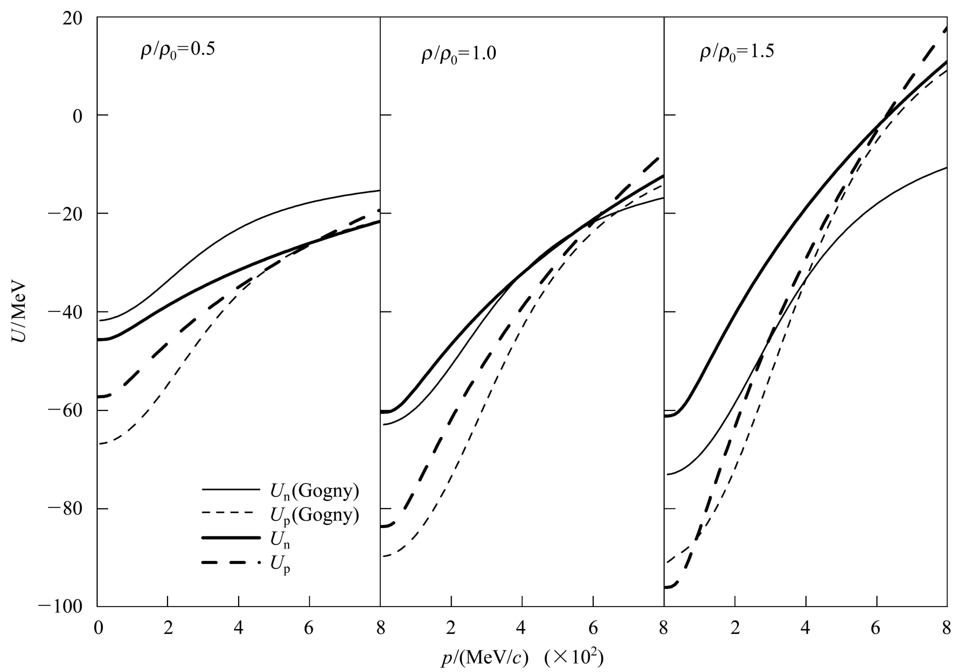

Fig. 1. The correspondence between the one-body potential U_τ and the one-body Gogny potential as a function of momentum p at densities $\rho/\rho_0 = 0.5$, 1.0 and 1.5 for neutrons (solid line) and protons (dashed line).

3 Results and discussions

It is well known that the calculated isospin fractionation ratio ($(N/Z)_{\rm gas}/(N/Z)_{\rm liq}$) in neutron rich systems[23,25] depends sensitively on the symmetry potential and only weakly on the isospin dependent in medium nucleon-nucleon cross section. $(N/Z)_{\rm gas}$ is the neutron to proton ratio for nucleon emissions and $(N/Z)_{\rm liq}$ is the ratio of neutrons to protons in the emitted fragments. Here all fragments with mass number $A \geqslant 2$ are included. Because the isospin fractionation ratio depends simultaneously both, on the mass and the neutron-proton ratio of the colliding system, we investigate the dependence of $(N/Z)_{\rm gas}/(N/Z)_{\rm liq}$ on the neutron-proton ratio of a system with fixed mass number. We have chosen the four colliding systems ^{94}Kr$+^{94}$Kr, ^{94}Zr$+^{94}$Zr, ^{94}Mo$+^{94}$Mo and ^{94}Ru$+^{94}$Ru, all with the same mass number ($A = A_{\rm p} + A_{\rm t} = 188$). The corresponding neutron-proton ratios are 1.61, 1.35, 1.24 and 1.14, respectively. This allows one to ignore the effect of the mass of the system.

The left window of Fig.2 shows $(N/Z)_{\rm gas}/(N/Z)_{\rm liq}$ at freeze-out time as a function of the neutron-proton ratio of the colliding system at a beam energy of

50 MeV/nucleon and an impact parameter of 2.0 fm. In both of the cases shown, the isospin dependent momentum interaction was used. The upper curve corresponds to a calculation with the usual Skyrme interaction (U^{Sky}), whereas in the lower curve the isospin dependent Skyrme potential (U_{τ}^{ISKY}) has been used. Because the isospin fractionation ratio reaches its saturation value after about 150 fm/c, the freeze-out time is 300 fm/c. Clearly the use of U_{τ}^{ISKY} leads to a significant reduction of $(N/Z)_{\mathrm{gas}}/(N/Z)_{\mathrm{liq}}$ for all colliding systems. We know that the variation of the chemical potential with the nuclear density is different for neutrons and protons. The isospin fractionation depends mainly on the decrease of the chemical potential with density. The isospin dependent Skyrme potential enters into the chemical potential. Being different for neutrons and protons, it leads to a decrease in the chemical potential which is different for neutrons and protons. The right window in Fig. 2 shows the difference between the neutron and proton potentials $(U_{\mathrm{n}}-U_{\mathrm{p}})/2$ when U_{τ}^{ISKY} or U^{Sky} as a function of nuclear density ρ/ρ_0 is included for momenta k=1 fm^{-1} and 2 fm^{-1}. It can be seen that the solid line for $(U_{\mathrm{n}}-U_{\mathrm{p}})/2$ (with isospin independent U^{Sky}) is higher and steeper than that with the isospin dependent U_{τ}^{ISKY}. The latter leads for all colliding systems to a reduction of $(N/Z)_{\mathrm{gas}}/(N/Z)_{\mathrm{liq}}$. Therefore we can say that the isopin dependent Skyrme potential brings an important isospin effect into the isospin fractionation ratio.

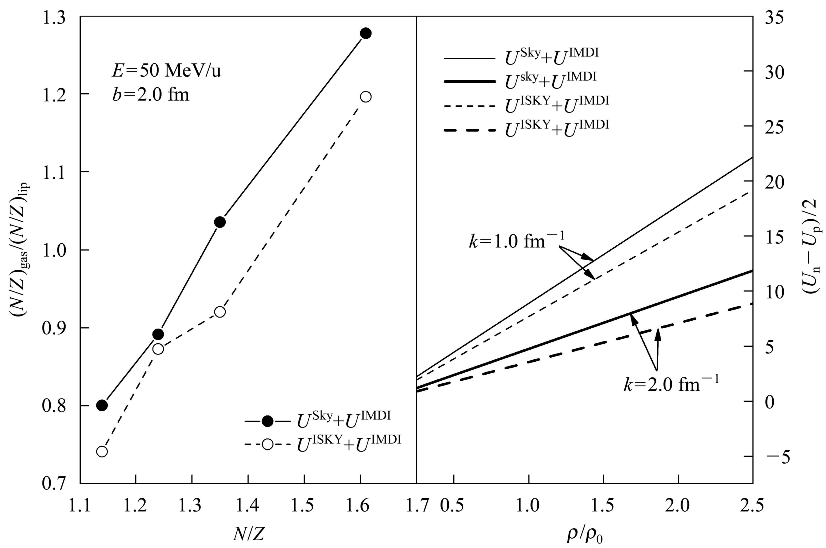

Fig. 2. $(N/Z)_{\mathrm{gas}}/(N/Z)_{\mathrm{liq}}$ as a function of the neutron-proton ratio of the system (left window) and $(U_{\mathrm{n}}-U_{\mathrm{p}})/2$ as a function of density ρ/ρ_0 for U^{ISKY} or U^{Sky} (right window).

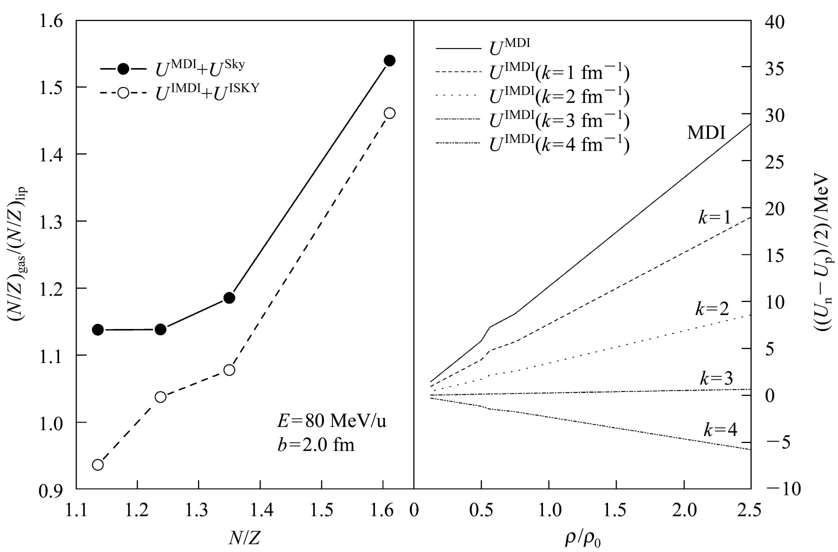

Fig. 3. $(N/Z)_{\mathrm{gas}}/(N/Z)_{\mathrm{liq}}$ as a function of the neutron-proton ratio of the system (left window) and $(U_{\mathrm{n}}-U_{\mathrm{p}})/2$ including U^{IMDI} or U^{MDI} as a function of density ρ/ρ_0 (right window).

The left side of Fig. 3 shows $(N/Z)_{\rm gas}/(N/Z)_{\rm liq}$ as a function of the neutron-proton ratio for systems satisfying the same conditions as in Fig. 2. Here the beam energy is 80 MeV/nucleon. It is evident that isospin dependent momentum interaction induces a significant reduction in $(N/Z)_{\rm gas}/(N/Z)_{\rm liq}$ for all colliding systems. The reason is the same as before, namely that the isospin dependent momentum interaction $U_{\tau}^{\rm IMDI}$ (part of the chemical potential), is different for neutrons and protons. From the right window in Fig. 3 we can see that $(U_{\rm n}-U_{\rm p})/2$ calculated with the isospin independent $U^{\rm MDI}$ is higher and steeper than that calculated with isospin dependent interaction $U_{\tau}^{\rm IMDI}$. From this we can conclude that the isospin dependent momentum interaction brings an important isospin effect into the isospin fractionation ratio.

4 Summary and conclusions

We improve the isospin dependent quantum molecular dynamical model by including isospin effects in the Skyrme potential and the momentum dependent interaction. By a comparison with the Gogny effective interaction, the parameters of the one-body potential are determined. We investigate the isospin dependent momentum interaction and Skyrme potential on the isospin fractionation ratio and the dynamical mechanism in intermediate energy heavy ion collisions. It is found that the isospin dependent momentum interaction and Skyrme potential leads some important isospin effects in the isospin fractionation ratio and induce a significant reduction of the isospin fractionation ratio for different neutron-proton ratios of the colliding systems.

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