Isospin effect of the in-medium nucleon-nucleon cross section in excited nuclear reactions*

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Abstract: Using relativistic mean field theory, the neutron and the proton density distribution of ^{56}Ni nuclei could be obtained in the ground state and the excited state. Based on the framework of the quantum molecular dynamics model, the ^{56}Ni nuclei have been simulated in ground state and in the neutron or proton excited state. We then used the three different states of ^{56}Ni to collide with the ^{56}Ni in the ground state. To discuss the evolution of the nuclear stopping in different reactions, two kinds of different excited nuclear reactions were studied at different reaction energies and at different impact parameters. Studies have shown that the nuclear stopping of an excited nuclear reaction is sensitive to the isospin-dependent in-medium nucleon-nucleon cross section, compared with the response value of the ground state nuclear reaction. So, it is better for the excited nuclei to extract the isospin dependence of nucleon-nucleon cross section information.

Key words: quantum molecular dynamics, excited state, nuclear stopping, isospin effect

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1 Introduction

The quantum molecular dynamics model (QMD) is a nuclear transport theory that has been extensively used to simulate intermediate energy heavy-ion collisions [1]. V. Zanganeh used the improved QMD to study the dynamical nucleus-nucleus potentials for some fusion reactions. They also investigated the influence of the range of nucleon-nucleon interaction and the nuclear matter incompressibility on the nucleus-nucleus dynamic potential [2]. Ying-Xun Zhang studied the in-medium N-N cross section, symmetry potential and impact parameters influencing the isospin sensitivity by the improved QMD in heavy-ion collisions. They found that the density of symmetric potential played a more important role in the double neutron-to-proton ratio and isospin transport ratio than the in-medium N-N cross section when the incidence velocity was higher than the Fermi velocity [3]. Feng-Shou Zhang made a contribution to the kinematic property of collision fragments by the isospin-dependent QMD and the statistical decay model. Based on classical theory, they extracted the single fragment temperature in the central heavy-ion collisions by using two models, and discussed the difference between the slope temperature and the quadrupole temperature. They also derived that the quantum temperature depends on the limited nuclear system of Fermi-Dirac nature [4].

The density dependence of nuclear symmetry energy plays an important role in understanding some astrophysical problems and in understanding the properties of exotic nuclei near drip lines. Bao-An Li analyzed the density, momentum and isospin-dependent nucleon effective masses of neutron-rich matter by a scaling model to study the N-N cross section. Compared with the free-space N-N cross section, it has been found that the in-medium N-N cross section was reduced and had different isospin dependence [5]. Based on isospin dependent and momentum dependent transport model, Lie-Wen Chen found that the isospin diffusion was influenced by the nuclear symmetry energy and the momentum dependent nucleon potential in heavy-ion collisions at intermediate energies [6]. Based on the framework of an isospin and momentum-dependent hadronic transport model, Yuan Gao concluded that the double charged pion ratio from the mirror systems might be a useful probe for the high-density behavior of nuclear symmetry energy [7].

Nuclear stopping has been widely used to research in-medium N-N cross section information. It can be used as a good parameter for making sure of the product in the reaction [8–10]. Jian-Ye Liu used the isospin-dependent QMD to study the isospin effects on the fragments and the dissipation in intermediate-energy heavy-ion

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collisions. He found that the momentum dependence enhanced the sensitivity to the isospin effect of the in-medium N-N cross section to high beam energies [11]. In this paper, we study the isospin effect of the in-medium N-N cross section in excited nuclear reactions.

2 The model

It is well known that relativistic mean field (RMF) theory is a very successful and widely used application microscopic theoretical model [12] that can be used to study the properties and structure of $N=Z$ nuclei [13]. It can also provide a good description of the nature of stable nuclei or the nuclides that are far away from the β-stablility line [14]. For example, it can describe the neutron and proton density distribution for a nucleus, and it can also give the spin orbit coupling. The starting point of RMF is the local Lagrangian density including nucleons, σ, ω, and ρ mesons and photons [15]:

$$\begin{aligned} L =& \overline{\psi}[\not{p}-g_{\omega}\not{\omega}-g_{\rho}\not{\boldsymbol{\rho}}\boldsymbol{\tau}-\frac{1}{2}e(1-\tau_3)\not{A}-g_{\sigma}\sigma-M_{\mathrm{N}}]\psi \\ &+\frac{1}{2}\partial_{\mu}\sigma\partial^{\mu}\sigma-U(\sigma)-\frac{1}{4}\Omega_{\mu\nu}\Omega^{\mu\nu}+\frac{1}{2}m_{\omega}^2\omega_{\mu}\omega^{\mu} \\ &-\frac{1}{4}\boldsymbol{R}_{\mu\nu}\boldsymbol{R}^{\mu\nu}+\frac{1}{2}m_{\rho}^2\boldsymbol{\rho}_{\mu}\boldsymbol{\rho}^{\mu}-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \end{aligned} \tag{1}$$

where the nucleus is regarded as the kinetic Dirac particle in the σ, ω, ρ meson field and photon field. This can be solved based on the Klein-Gordon equation to self-consistent iteration, and the wave function and energy of the single nucleon can be obtained. Based on the RMF, the density distributions of proton and neutron are given in the neutron excited nucleus and proton excited nucleus. The spin orbit coupling causes the energy level splitting in the nucleus. Then, one of the valence nucleons (neutron or proton) jumps to the outermost energy level. In this condition, the distributions for the neutron and proton excited nucleus are obtained. In this paper, the parameter TM1 is used in RMF.

Based on the classical molecular dynamics method that can handle the debris problem, the QMD [16, 17] is a very important model that is developed by considering the uncertainty principle and Pauli blocking principle [18]. It is a good model for studying low and intermediate-energy heavy-ion collisions. The collision reaction is simulated in the QMD, and the reaction considers the correlation between nucleus and the physical fluctuation of mean field. It can well show the information of nuclear structure and reaction, for example: the fragment formation, the dynamical fluctuations in heavy-ion collision, the multiple fracture and so on. In the QMD, based on the semi-classical theory the response single nucleon has wave-particle duality, so it is regarded as a Gaussian wave packet whose coordinate space and momentum space have a certain limit, and the density distribution function is:

$$f_{\mathrm{i}}(\boldsymbol{r},\boldsymbol{p},t)=\frac{1}{(\pi\hbar)^3}\exp\left[-\frac{(\boldsymbol{r}-\boldsymbol{r}_{\mathrm{i}}(t))^2}{2L}-\frac{(\boldsymbol{p}-\boldsymbol{p}_{\mathrm{i}}(t))^2\cdot 2L}{\hbar^2}\right]. \tag{2}$$

In this function $\boldsymbol{r}$ and $\boldsymbol{p}$ stand for the coordinates of nuclear space and the center position in momentum space, respectively. In the reaction, the evolution of this process changes over time; the corresponding time interval is 0.5 fm/c. In the evolution process, the spatial coordinates and the momentum coordinates of the single particle spread according to the canonical equations of motion. In the process of initialization, the nucleus density distribution is given by considering the binding energy and the nuclear root mean square radius based on experimental values. In the calculation, the following interaction potentials will be used [19]:

$$U(\rho)=U^{\mathrm{Sky}}+U^{\mathrm{Coul}}+U^{\mathrm{Yuk}}+U^{\mathrm{Pauli}}+U^{\mathrm{MDI}}+U^{\mathrm{Sym}}. \tag{3}$$

In this formula, U^{Sky} stands for the density-dependent Skyrme potential, U^{Coul} is the Coulomb potential, U^{Yuk} is the Yukawa potential, U^{Pauli} is the Pauli potential, U^{MDI} is the momentum-dependent interaction, U^{Sym} is the symmetric potential, and is defined as $U_0^{\mathrm{Sym}}=0.0$, $U_1^{\mathrm{Sym}}=32\frac{\rho}{\rho_0}\cdot\frac{\rho_{\mathrm{n}}-\rho_{\mathrm{p}}}{\rho}\tau_z$, where ρ and ρ_0 are the nuclear density and its normal value. ρ_{n} and ρ_{p} represent the neutron and proton densities. $\tau_z=1$ for neutron and $\tau_z=-1$ for proton.

In the QMD, the free-space N-N cross section is given by [20]:

$$\sigma_{\mathrm{np}}^{\mathrm{free}}=\begin{cases} -\dfrac{5067.4}{E^2}+\dfrac{9069.2}{E}+6.9466(\mathrm{mb}), & E\leqslant 40(\mathrm{MeV}); \\ \dfrac{239380}{E^2}+\dfrac{1802.0}{E}+27.147(\mathrm{mb}), & 40<E\leqslant 400(\mathrm{MeV}); \\ 34.5(\mathrm{mb}), & 400<E\leqslant 800(\mathrm{MeV}). \end{cases} \tag{4}$$

$$\sigma_{\mathrm{nn}}^{\mathrm{free}}(\sigma_{\mathrm{pp}}^{\mathrm{free}})=\begin{cases} -\dfrac{1174.8}{E^2}+\dfrac{3088.5}{E}+5.3107(\mathrm{mb}), & E\leqslant 40(\mathrm{MeV}); \\ \dfrac{93074}{E^2}-\dfrac{11.148}{E}+22.429(\mathrm{mb}), & 40<E\leqslant 310(\mathrm{MeV}); \\ \dfrac{887.37}{E}+0.05331E+3.5475(\mathrm{mb}), & 310<E\leqslant 800(\mathrm{MeV}) \end{cases} \tag{5}$$

where E represents the incident energy. The in-medium N-N cross section is defined as:

$$\sigma_{\mathrm{NN}}^{\mathrm{med}}=\left(1-0.2\frac{\rho}{\rho_0}\right)\sigma_{\mathrm{NN}}^{\mathrm{free}}. \tag{6}$$

In this formula, $\sigma_{\mathrm{NN}}^{\mathrm{free}}$ is the free-space N-N cross section. If the N-N cross section is calculated without isospin effect, it will be defined as $\sigma_{\mathrm{np}}=\sigma_{\mathrm{nn}}=\sigma_{\mathrm{pp}}$.

3 Results

The density distribution for three different states of ^{56}Ni is analyzed based on relativistic mean field theory. These three kinds of nuclei are used as projectiles to collide with the target by QMD and extract the nuclear stopping information in the reaction. The nuclear stopping is the ratio of vertical component and parallel component of the momentum $\left(R=(2/\pi)\left(\sum_i^A|P_\perp(i)|\right)\Big/\left(\sum_i^A|P_{//}(i)|\right)\right)$.

The root-mean-square radius (r_{rms}), binding energy (E_{b}), proton excitation energy (E_{ze}) and neutron excitation energy (E_{ne}) of the incident nuclear calculated by RMF are shown in Table 1. It is shown that the r_{rms} of excited nuclei are bigger than the r_{rms} of ground-state nucleus, and the excited nuclear binding energies are smaller than the ground-state binding energies. The proton (neutron) excitation energy of a proton (neutron) excited nucleus is smaller than the excitation energy of the ground-state nuclei. Because the structure of the excited nuclei is diffuse, we forecast that the nuclear stopping of the excited nuclear reaction is larger than the ground-state reaction.

Figure 1 shows the neutron (left) and proton (right) density distribution for the three states of ^{56}Ni gotten by the RMF. It can be obviously seen that the three states of ^{56}Ni have different neutron and proton radial distribution because their states are different (ground state, and neutron excited state, and proton excited state). The radial distribution of the neutron excited nuclei is very diffuse in the left figure. Consequently, it has a larger root-mean-square radius. But in the right figure, the range of the proton density distribution is wide for the proton excited nuclei. The proton excited nuclei have a big root-mean-square radius. So, there is a skin structure for density distribution in the excited nuclei. We forecast that the excited nuclear reaction is more violent and sensitive to isospin-dependent N-N cross section.

Table 1. The r_{rms}, E_{b}, E_{ze} and E_{ne} of the incident nuclear calculated by RMF.

nuclear	r_{rms}/fm	E_{b}/MeV	E_{ze}/MeV	E_{ne}/MeV
Ni	3.637	−8.570	−6.95	−16.36
Ni(n)	3.655	−8.433	−6.67	−8.76
Ni(z)	3.657	−8.461	−1.33	−16.01

Figure 2 shows that the ground state, neutron and proton excited state of ^{56}Ni collides with the ground ^{56}Ni at an energy of 100 MeV/u. The curves stand for the nuclear stopping evolution over time. In the figure, the solid line and dashed line are the results that are calculated with isospin-dependent N-N cross section. The solid line and dotted line represent the results calculated with U_1^{Sym}. We can obviously see that the results of the above two lines consider the isospin-dependent N-N cross section from the figure. The distance between these two groups of lines is very big because of the influence of the isospin effects. Every group's lines have little difference

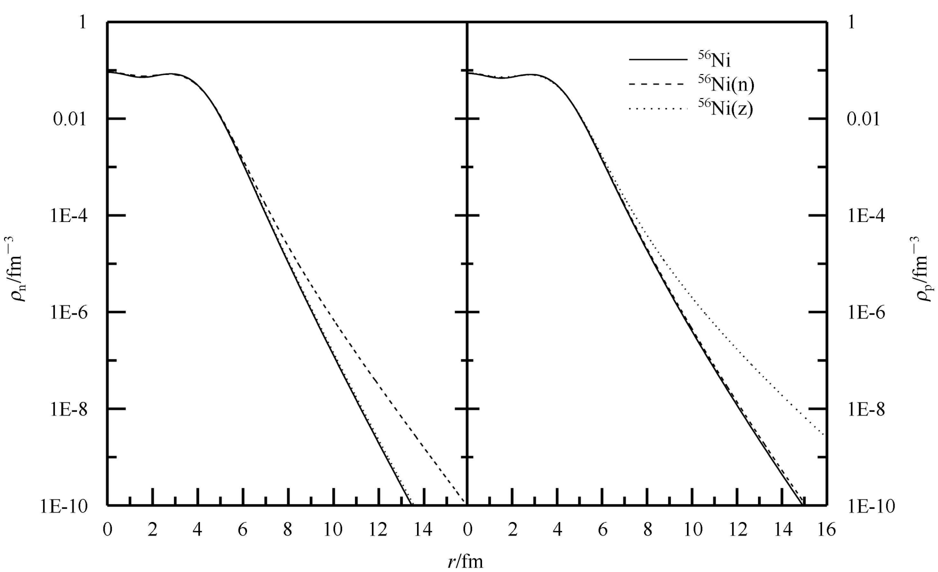

Fig. 1. The neutron (left) and proton (right) density distributions for the ground state, and neutron excited state, and proton excited state of ^{56}Ni.

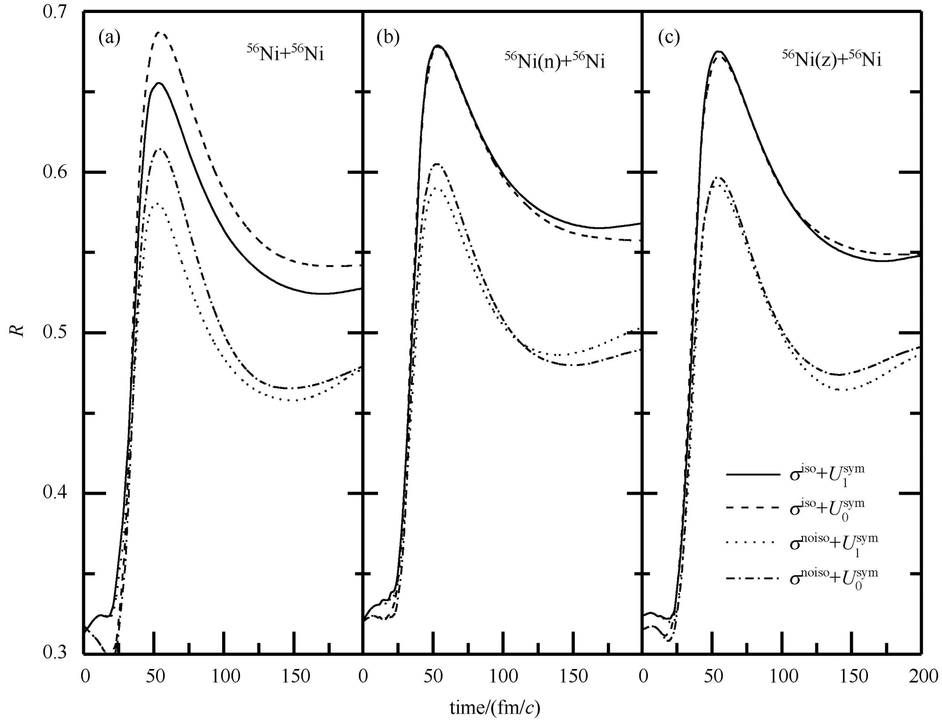

Fig. 2. The relationship between the nuclear stopping in ground-state nuclear reaction (a), neutron (b) or proton (c) excited nuclear reaction and time.

because of the influence of the symmetry potential, which means that the nuclear stopping strongly depends on the isospin effects of the in-medium N-N cross section. The neutron or proton radial distribution of the excited nuclei is very big, which makes the reaction ratio greater, so the nuclear stopping of the excited nuclear reaction is larger than the ground-state reaction. It can be seen that the dashed lines are close to the solid lines for the excited nuclear reaction. We think that the excited nuclear reactions have good sensitivity for the isospin effects of the in-medium N-N cross section and serve as a good probe to extract isospin-dependent N-N collision reaction information.

Figure 3 presents the ratio of considered and unconsidered isospin-dependent N-N cross section changing with the incident energy. The lower part of Fig. 3 illustrates the calculations with isospin-dependent N-N cross section. In Fig. 3, the straight line is a standard line ($R(U_1^{\rm Sym}/U_0^{\rm Sym})$=1), and the three curves stand for the results of ^{56}Ni+^{56}Ni with different states nuclei as projectile. It is obviously shown that the fluctuation of the ratio in the ground state is big while the fluctuation of the ratio is small in neutron excited state, which happens because the reaction with neutron or proton excited state is violent in these systems. In other words, the symmetric potential has little effect on nuclear stopping in the neutron excited reaction. Consequently, it indirectly explains that neutron excited reactions can well extract isospin-dependent N-N cross section information.

This figure shows the reaction at an energy of 100 MeV/u with different impact parameters (b=0, 2, 4, 8) in the left with $U_1^{\rm Sym}$. In this figure the ordinate stands for the ratio of nuclear stopping ($R(\sigma^{\rm iso})/R(\sigma^{\rm noiso})$). It is noticed that the ratio has greater difference at the small impact parameter b (0–4 fm), while as the impact parameter increases the difference becomes smaller. This happens because in the condition of small

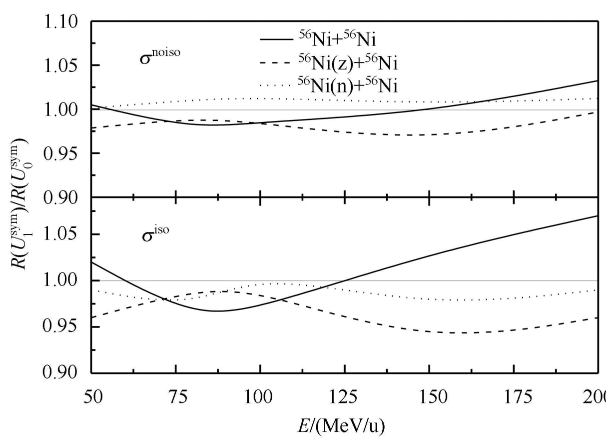

Fig. 3. The ratio of considered and unconsidered isospin-dependent N-N cross section changes with the incident energy.

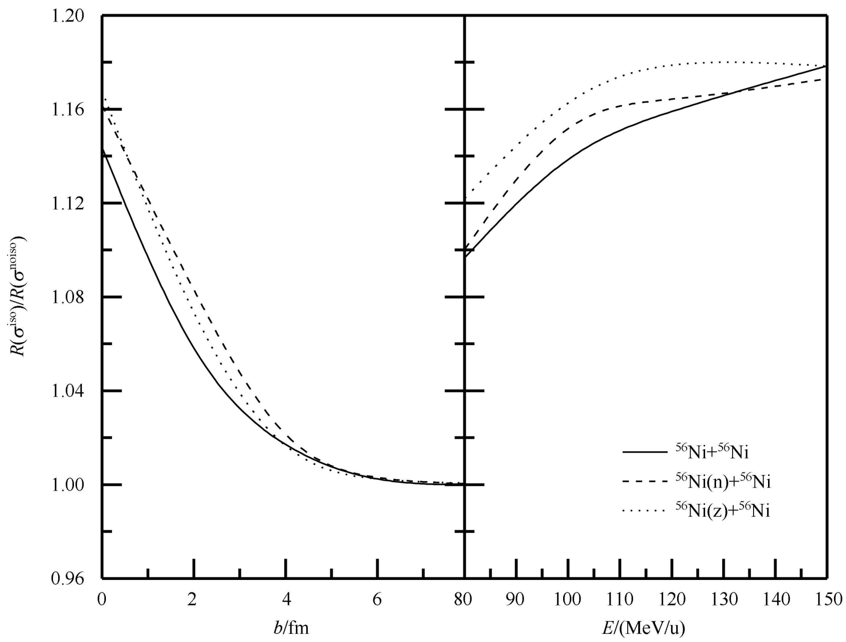

Fig. 4. The ratio $(R(\sigma^{\rm iso})/R(\sigma^{\rm noiso}))$ changes with the impact parameter and the incident energy.

impact parameters the N-N collision reaction is very intense, leading to a relatively larger collision number. Thus, it is sensitive for reaction with small impact parameters. In the right hand figure, the results of three curves are greater than one, which shows that the excited nuclear reactions are sensitive to isospin-dependent N-N cross section. At low incident energy, there are fewer collisions, so the difference is small in the results, both with and without isospin effect. At high energy, the excited energy of the nuclei is not obvious in the reaction, so the results of the excited nuclear reactions are close to the ground-state line. Consequently, the nuclear stopping of the excited nuclear reactions is sensitive to the isospin-dependent N-N cross section at energies from 80 MeV to 130 MeV.

4 Conclusions

^{56}Ni is a doubly magic nucleus, which is the isospin-symmetric nucleus. The symmetry potential of ^{56}Ni is small. Based on the above conditions, we use the ^{56}Ni nuclei with different states to study the collision reaction. With nuclei in different states as projectiles, the colliding systems of ^{56}Ni+^{56}Ni have been researched with the QMD at different energies with different impact parameters. We conclude that the excited nuclear reactions can extract the information of isospin-dependent in-medium N-N cross section. Consequently, we think that the nuclear stopping in the neutron-deficient system with the reaction energy from 80 MeV to 130 MeV is better for extracting cross section information.

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