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Isospin Effect on Nuclear Stopping in Intermediate Energy Heavy Ion Collisions *

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By using the isospin-dependent quantum molecular dynamics model, we study the dependence of nuclear stopping Q_{ZZ}/A and R in intermediate energy heavy ion collisions on system size, initial N/Z, isospin symmetry potential and the medium correction of two-body cross sections. We find the effect of the initial N/Z ratio and isospin symmetry potential on stopping is weak. The excitation function of Q_{ZZ}/A and R depends on the form of medium correction of two-body cross sections, the equation of state of nuclear matter. Our results show that the behaviour of the excitation function of Q_{ZZ}/A and R can provide clearer information of the isospin dependence of the medium correction of two-body cross sections.

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It is important to investigate whether an equilibrium is reached or not for a colliding system in order to obtain correctly the information of equation of state (EOS) and the reaction mechanism. This problem has been studied extensively both theoretically and experimentally.[1−6] Following the establishment of radioactive beam facilities in many laboratories, it has become possible to study neutron-rich (or proton-rich) nuclear collisions at intermediate energies. Therefore it is necessary to study the effect of isospin asymmetry on the equilibrium process in a colliding system. In Ref. [7] the sensitivity of nuclear stopping to the isospin dependence of the cross section was studied but the isospin dependence of the medium correction of two-body cross sections and the isospin asymmetry of the initial system were not tested. As expected, the degree of equilibrium is influenced by the mean field, the medium correction of two-body cross section as well as the size of the colliding system. To consider the influence of the isospin dependence of the medium correction of the two-body cross section, in this Letter we use four different forms of in-medium two-body cross sections as follows: (1) σ_0, the free nucleon-nucleon cross section which is isospin-dependent;[8] (2) σ_0^*,[9] which reads

$$\sigma^* = [1 + \alpha(\frac{\rho}{\rho_0})]\sigma^{\rm free}, \qquad (1)$$

where $\alpha = -0.2$; (3) σ_1 according to Ref. [10]; (4) σ_2, in which the medium correction is obtained based on the results of Ref. [11]. Li and Machleidt[10] calculated the in-medium neutron–proton, proton–proton (neutron–neutron) scattering cross section at energies up to 300 AMeV with the Dirac–Brueckner Hartree–Fock approach where the medium correction of the ρ meson mass was not taken into account. It was found that the in-medium cross sections decreased with the density and increased slightly when the density was higher than normal nuclear density and the energy was higher than about 125 AMeV (in the laboratory system). In Ref. [11] the in-medium binary scattering cross section has been derived based on a QHD-II type Lagrangian within the framework of the microscopic transport theory at energies up to 800 AMeV where the medium correction of the ρ meson mass was taken into account.[12] It was found that because of the medium correction of the ρ meson mass, the medium correction of the nucleon–nucleon cross section was also isospin-dependent, i.e. σ^*_{np} depends on the baryon density weakly while $\sigma^*_{nn(pp)}$ depends on the baryon density obviously. It was also shown that energy increased slightly when the density was higher than the normal density and the energy was higher than about 200 AMeV (in the laboratory system). The influence of the mean field is considered by taking the EOS to be the "soft" EOS ($K = 200$ MeV) and the "hard" EOS ($K = 380$ MeV) as well as with and without the isospin symmetry potential. In order to study the dependence of the degree of equilibrium on the nuclear size and the initial isospin asymmetry, we calculate two groups of colliding systems: (1) ^{58}Ni+^{58}Ni and its neighbouring nuclei with $A = 60$ and $Z = 24 - 32$; and (2) ^{120}Sn+^{120}Sn and its neighbouring nuclei with $A = 120$ and $Z = 47 - 55$.

We study the degree of equilibrium in momentum space by investigating the momentum quadrupole Q_{ZZ} and R, the ratio between perpendicular momentum and parallel momentum, which usually are called the nuclear stopping. Q_{ZZ} is defined as

$$Q_{ZZ} = \sum_i [2P_z(i)^2 - P_x(i)^2 - P_y(i)^2], \qquad (2)$$

and R is defined as

$$R = \frac{2}{\pi}\frac{\sum_i |P_\perp(i)|}{\sum_i |P_z(i)|}. \qquad (3)$$

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Here the summation runs over all nucleons in the projectile and target and the transverse momentum $P_\perp(i) = \sqrt{P_x(i)^2 + P_y(i)^2}$.

The isospin-dependent quantum molecular dynamics (QMD) model[13,14] is used in the calculations. For details, please see Ref. [15]. The used parameters of the EOS are shown in Table 1.

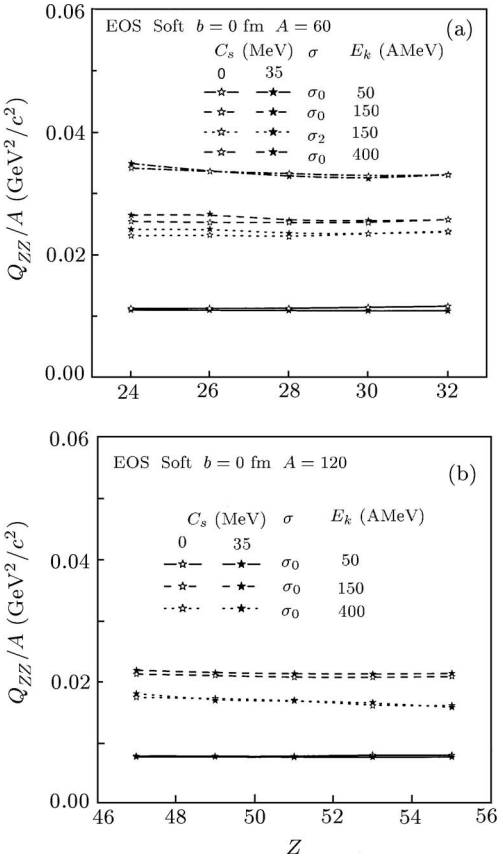


Fig. 1. Average Q_{ZZ} as a function of Z for projectile and target taken to be (a) $A = 60$, and Z ranging from 24 to 32 and (b) $A = 120$, and Z ranging from 47 to 55, at beam energies of 50, 150 and 400 AMeV with $C_S = 0$ and 35 MeV. The two-body cross section is taken to be σ_0 and σ_2 (see text), respectively.

First of all, we investigate the effect of the symmetry potential and isospin dependence of the medium correction of the two-body cross section as well as the isospin asymmetry of the initial system on Q_{ZZ}. Figure 1 shows the average Q_{ZZ} as a function of Z for projectile and target taken to be (a) $A = 60$, with Z ranging from 24 to 32 and (b) $A = 120$, with Z ranging from 47 to 55, at beam energies of 50, 150 and 400 AMeV with $C_S = 0$ and 35 MeV. The two-body cross section is taken to be σ_0 and σ_2, respectively. As a whole, we can find that the effects of the symmetry potential and the initial isospin asymmetry on Q_{ZZ} are weak for both in-medium cross sections taken to be σ_0 (no medium correction) and σ_2 (with isospin-dependent medium correction) cases.

In Figs. 2(a) and 2(b) we present the excitation function of average Q_{ZZ} with different EOS ("soft" and "hard") and cross sections (σ_0, σ_0^*, σ_1 and σ_2) for (a) ^{58}Ni+^{58}Ni and (b) ^{120}Sn+^{120}Sn. It is shown that Q_{ZZ}/A first increases with beam energy then it is saturated at about 150 – 300 AMeV depending on the in-medium cross section used. Different forms of medium correction of two-body cross sections significantly affect the behaviour of the excitation function of Q_{ZZ}/A. From a comparison of Figs. 2(a) and 2(b) we find that for the ^{58}Ni+^{58}Ni case the influence of different EOS on Q_{ZZ}/A is much weaker than that of different forms of cross section, while for the ^{120}Sn+^{120}Sn case it is comparable with that of different cross sections. Thus, from the above study, we may conclude that the behaviour of the excitation function of Q_{ZZ}/A for a medium size system such as ^{58}Ni+^{58}Ni can provide clearer information of isospin dependence of the medium correction of cross sections.

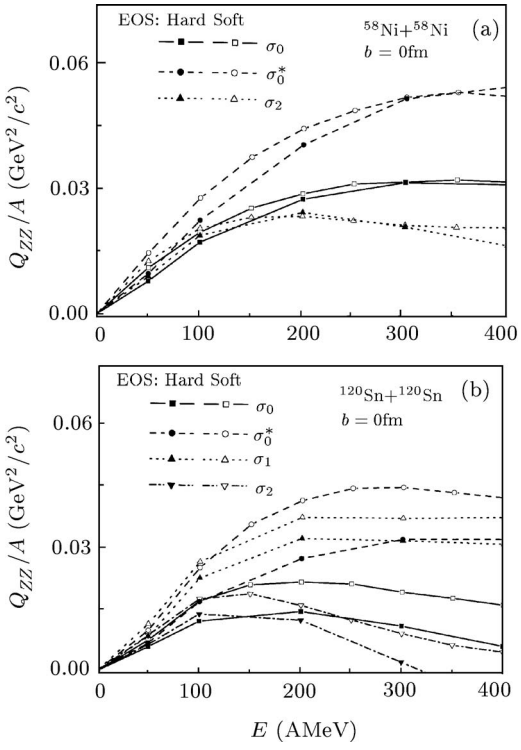


Fig. 2. Average Q_{ZZ} as a function of beam energy for (a) ^{58}Ni+^{58}Ni and (b) ^{120}Sn+^{120}Sn at $b = 0$ fm with different EOS and two-body cross sections σ (see text).

Figures 3(a) and 3(b) show the excitation function of R for (a) ^{58}Ni+^{58}Ni and (b) ^{120}Sn+^{120}Sn with different EOS ("soft" and "hard"), and cross sections (σ_0, σ_0^*, and σ_2). For both the ^{58}Ni+^{58}Ni and ^{120}Sn+^{120}Sn cases, R decreases when the beam energy is less than $\sim$ 100 AMeV and there is a change of the decreasing slope at 50 AMeV. Then R increases with the further increase of the beam energy. For the ^{58}Ni+^{58}Ni case, the slope of the excitation function of R is dominated by the form of in-medium cross sections and its dependence on the mean field is very weak. While for the ^{120}Sn+^{120}Sn case, the slope of the excitation function of R depends on both the form of medium correction of the two-body cross section and

Table 1. Parameters used in calculations.

EOS	α (MeV)	β (MeV)	γ	ρ_0 (fm^{-3})	K (MeV)	L (fm)	C_{Yuk} (MeV)
Soft	-356	303	7.0/6.0	0.168	200	2.1	-5.5
Hard	-124	70.5	2.0	0.168	380	2.1	-5.5

the EOS of nuclear matter. This behaviour of R depending on the system size is the same as that of the Q_{ZZ}/A case shown in Figs. 2(a) and 2(b). It implies that the measurement of the excitation function of the stopping in a medium sized system such as ^{58}Ni+^{58}Ni can provide clearer information of the medium correction of the two-body cross section.

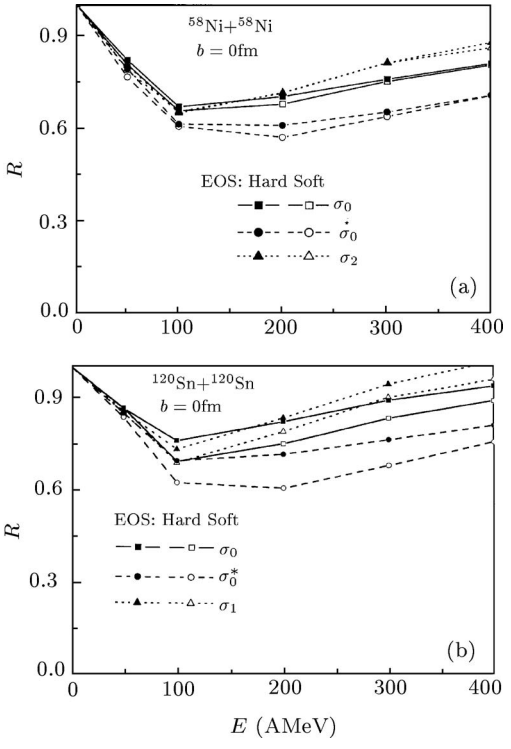


Fig. 3. R as a function of beam energy at different EOS and two-body cross sections σ (see text).

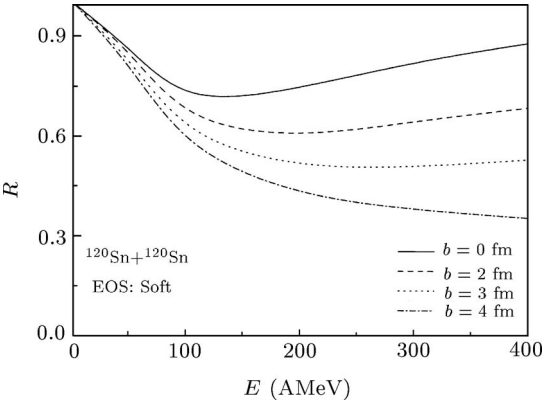


Fig. 4. R as a function of beam energy with different input parameters b.

Figure 4 shows the excitation function of R for ^{120}Sn+^{120}Sn at different impact parameters. The behaviour of R as a function of energy changes quickly for different impact parameters. The slopes of R as a function of beam energy change from negative to positive at $E \sim 100$ AMeV for $b = 0$ fm - $b = 3$ fm cases. For low beam energy, the slope of excitation function depends weakly on the impact parameter. This implies that, for the lower energy case, the stopping does not depend on the impact parameter strongly but on the impact parameter strongly as energy increases.

In summary, we have studied the dependence of nuclear stopping Q_{ZZ}/A and R on the isospin asymmetry of the initial system, the isospin dependence of the medium correction of the two-body scattering cross section and the EOS of nuclear matter (isospin-dependent part and incompressibility). We find that the dependence of stopping on the initial isospin asymmetry and isospin-dependent part of nuclear potential is weak and the dependence on the different forms of the medium correction of the two-body cross section is strong. By studying the excitation function of Q_{ZZ}/A and R we find that the influence of different EOS (incompressibility) on stopping is comparable with that of different medium corrections of two-body cross sections for ^{120}Sn+^{120}Sn. But it is much weaker for the ^{58}Ni+^{58}Ni case at the energy range studied in this work. Therefore the measurement of the excitation function of nuclear stopping for collisions of medium sized nuclei is a better means to extract the information of the medium correction of the two-body cross section. We also find that the dependence of nuclear stopping on the impact parameter is weak at low energy and it becomes stronger at an energy higher than $\sim 50 - 100$ AMeV.

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