Isospin Effect of Coulomb Interaction on Momentum Dissipation in Intermediate Energy Heavy Ion Collisions *

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We investigate the isospin effect of Coulomb interaction on the momentum dissipation or nuclear stopping in the intermediate energy heavy ion collisions by using the isospin-dependent quantum molecular dynamics model. The calculated results show that the Coulomb interaction induces obviously the reductions of the momentum dissipation. We also find that the variation amplitude of momentum dissipation induced by the Coulomb interaction depends sensitively on the form and strength of symmetry potential. However, the isospin effect of Coulomb interaction on the momentum dissipation is less than that induced by the in-medium nucleon–nucleon cross section. In this case, Coulomb interaction does not change obviously the isospin effect of momentum dissipation induced by the in-medium two-body collision. In particular, the Coulomb interaction is preferable for standing up the isospin effect of in-medium nucleon–nucleon cross section on the momentum dissipation and reducing the isospin effect of symmetry potential on it, which is important for obtaining the feature about the sensitive dependence of momentum dissipation on the in-medium nucleon–nucleon cross section and weakly on the symmetry potential.

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The isospin effect at intermediate energy heavy ion collisions can be used to obtain the information for the in-medium N–N cross section and isospin-dependent mean field. Several interesting isospin effects in heavy ion collisions have been explored both experimentally and theoretically over the last few years.[1−9,16−19] However, the isospin-dependent in-medium N–N cross section and the symmetry potential in heavy ion collisions have not yet been well determined. As we know, nuclei offer an interesting isospin situation, where the symmetry potential, Coulomb interaction and isospin-dependent in-medium nucleon–nucleon collisions are simultaneously present. However, in general, the isospin effect of the Coulomb interaction is not studied separately in more detail, even though the study for the isospin effect of the isospin-dependent mean field in heavy ion collisions includes automatically the role of Coulomb interaction. As a matter of fact, the Coulomb interaction is an important asymmetry term, which can bring an important isospin effect into the observable quantities in the intermediate energy heavy ion collisions. The study for the isospin effect of Coulomb interaction on the momentum dissipation in the intermediate energy heavy ion collisions is important for exploring isospin physics and setting up the equation of state for the isospin asymmetry nuclear matter. Recently, studies by Lee and Mekjian,[20] Colonna *et al.*[21] and Gulminelli *et al.*[22] pointed out that the Coulomb interaction induced the reductions of chemical and mechanical instability domains. In this Letter, the isospin effects of Coulomb term and symmetry potential on the nuclear stopping at intermediate energy heavy ion collisions are studied respectively by using isospin-dependent quantum molecular dynamics model (IQMD). The calculated results show that the Coulomb interaction induces the reduction of stopping, i.e. the reduction of momentum dissipation. In particular, the variation amplitudes of stopping induced by the Coulomb term depend on the form and strength of symmetry potential. An interesting result is that the Coulomb interaction is preferable to standing up the isospin effect of in-medium N–N cross section on R and Q_{zz} and reducing the isospin effect of symmetry potential on them. Namely, Coulomb interaction is important for making nuclear stopping as a good probe for extracting the information about in-medium the nucleon–nucleon cross section.

In order to describe the isospin effects appropriately, the quantum molecular dynamics model (QMD)[11,12] should be modified properly to obtain the IQMD: the density-dependent mean field should contain correct isospin terms, including the symmetry potential and the 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 and protons. In addition, the initial condition of the ground state of two col-

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liding nuclei should also contain isospin information. In our IQMD model, the initial density distributions of the colliding nuclei are from the calculations of the Skyrme–Hartree–Fock with parameter set SKM*.[13] The initial code of the IQMD is used to determine the ground-state properties of the colliding nuclei, such as the binding energies and the rms radii, which are consistent with the experimental data. In the above-mentioned calculations, the interaction potential can be determined by

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

where $U^{\rm Sky}$, $U^{\rm Coul}$, $U^{\rm Yuk}$ and $U^{\rm Pauli}$ are the Skyrme potential, Coulomb potential, Yukawa potential and Pauli potential. $U^{\rm MDI}$ is the momentum-dependent interaction. $U^{\rm sym}$ is the symmetry potential. In the present study, three different forms of $U^{\rm sym}$ are used, i.e.[1,2]

$$U_1^{\rm sym} = cF_1(u)\delta\tau_z, \quad (2)$$

$$U_2^{\rm sym} = cF_2(u)\delta\tau_z + \frac{1}{2}cF_2(u)\delta^2, \quad (3)$$

$$U_3^{\rm sym} = cF_3(u)\Big[\delta\tau_z - \frac{1}{4}\delta^2\Big], \quad (4)$$

with

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

Here c is the strength of symmetry potential, with the value of 32 MeV, $F_1(u) = u$, $F_2(u) = u^2$ and $F_3(u) = u^{1/2}$ and, $u = \frac{\rho}{\rho_0}$; δ is the relative neutron excess $\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p} = \frac{\rho_n - \rho_p}{\rho}$; ρ, ρ_0, ρ_n and ρ_p are the total, normal, neutron and proton densities respectively.

The curvatures $K_{\rm sym}$ of $U_1^{\rm sym}$, $U_2^{\rm sym}$ and $U_3^{\rm sym}$ are -27 MeV, 61 MeV and -69 MeV respectively.

An empirical density-dependent expression of the in-medium N–N cross section with the parameter $\alpha \approx -0.2$ can be expressed by[14]

$$\sigma_{NN}^{\rm med} = \Big(1 + \alpha\frac{\rho}{\rho_0}\Big)\sigma_{NN}^{\rm free}, \quad (5)$$

which has been found to be better to reproduce the flow data. Here $\sigma_{NN}^{\rm free}$ is the experimental N–N cross section.[15] We make use of Eq. (5) to obtain the medium effect in the N–N collisions. The main physics ingredients and their numerical realization in the IQMD model can be found in Refs. [2,10–13]. The parameters in the IQMD model can be found in Ref. [17].

The isospin-dependent N–N cross section and the isospin-independent one in the medium are defined respectively by $\sigma^{\rm iso}$ and $\sigma^{\rm noiso}$. Here $\sigma^{\rm iso}$ indicates $\sigma_{np} \geq \sigma_{nn} = \sigma_{pp}$ and $\sigma^{\rm noiso}$ means $\sigma_{np} = \sigma_{nn} = \sigma_{pp}$. Where σ_{np}, σ_{nn}, σ_{pp} are neutron–proton, neutron–neutron and proton–proton cross sections in media, respectively.

The momentum dissipation or nuclear stopping in the intermediate energy heavy ion collisions is described by the transverse–parallel ratio of momentum R and the quadruple moment of nucleon momentum distribution Q_{zz}. The transverse–parallel ratio of momentum R is defined as $R = (2/\pi)(\sum_i^A \mid P_\perp(\mathrm{i})—)/(\sum_i^A \mid P_\parallel(i) \mid)$. The transverse and the parallel components of the momentum of the ith nucleon are $P_\perp(i) = \sqrt{P_x(i)^2 + P_y(i)^2}$ and $P_{//}(i) = P_z(i)$, respectively. The momentum quadruple of nucleon momentum distribution is defined as $Q_{ZZ} = \sum_i^A (2P_z(i)^2 - P_x(i)^2 - P_y(i)^2)$, where the total mass A is the sum of the projectile mass A_p and the target mass A_t. $P_z(i)$, $P_x(i)$ and $P_y(i)$ are the three momentum components of the ith nucleon, respectively.

The dependence of the isospin effect of R and Q_{zz}/Q_{zz0} induced by the Coulomb interaction on the beam energy is as follows. Figure 1 shows R (left window) and Q_{zz}/Q_{zz0} (right window) at freeze-out time as a function of beam energy for different symmetry potentials $U_3^{\rm sym}$ and $U_1^{\rm sym}$ and different N–N cross sections $\sigma^{\rm iso}$ and $\sigma^{\rm noiso}$ with and without Coulomb interactions. Here Q_{zz0} is the value at the beginning of time. The calculation is for the reaction ^{94}Mo+^{94}Mo at an impact parameter b of 2.0 fm. The line symbols with numbers and their meanings for eight lines of R or Q_{zz}/Q_{zz0} are shown in the left window of Fig. 1. The eight lines are separated into two groups of lines, i.e. the lines with the numbers 1, 3, 5, 7 without Coulomb term and corresponding to four lines 2, 4, 6, 8 with Coulomb term. We find that the Coulomb interaction induces the reduction of R and the enhancement of Q_{zz}/Q_{zz0} from four lines 2, 4, 6, 8 to corresponding to lines 1, 3, 5, 7. Namely, Coulomb interaction induces obviously the reduction of momentum dissipation, because the Coulomb term induces the reduction of the chemical instability and mechanical instability domains[20,21] due to the repulsion for the protons. It is worth noting that the reduction of R and the enhancement of Q_{zz}/Q_{zz0} indicate the same meaning for the reduction of momentum dissipation.

From Fig. 1, we can see that, in each group of lines, the gap between the values of R or Q_{zz} induced by different N–N cross sections $\sigma^{\rm iso}$ and $\sigma^{\rm noiso}$ but the same symmetry potential $U_3^{\rm sym}$ or $U_1^{\rm sym}$ is larger in the beam energy region from 50 MeV/nucleon to about 300 MeV/nucleon. However, the gap between the values of R or Q_{zz}/Q_{zz0} induced by different symmetry potentials $U_3^{\rm sym}$ and $U_1^{\rm sym}$ with the same $\sigma^{\rm iso}$ or $\sigma^{\rm noiso}$ is smaller. This feature means that R and Q_{zz}/Q_{zz0} in this energy region depend sensitively on the in-medium N–N cross section and weakly on the symmetry potential with and without Coulomb interactions. However, this feature with Coulomb interaction is better than that without the Coulomb term. For example, the gap between lines 1 and 3 is less than

that between 2 and 4. Similarly, the gap between 5 and 7 is less than that between 6 and 8. This feature means that the Coulomb interaction is preferable to standing up the feature for the sensitive dependence of momentum dissipation on the two-body collision and weakly on the symmetry potential.

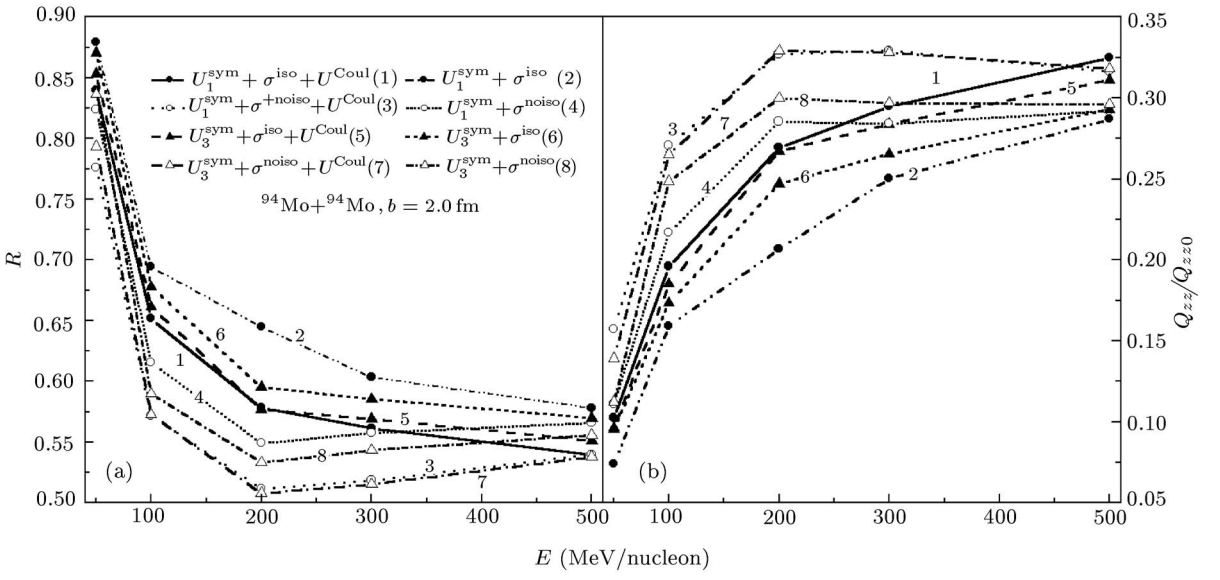


Fig. 1. R (a) and Q_{zz}/Q_{zz0} (b) versus beam energy in the reaction ^{94}Mo+^{94}Mo at impact parameter b of 2 fm for the two cases with and without Coulomb terms.

The above feature for the linear momentum dissipation is due to the fact that the dynamics is dominated by N–N collisions and the role of the mean field is less important in this energy region. In particular,in this energy region, we can see that the gap between lines 1 and 2 with the filled circularity symbol is larger than the difference between lines 5 and 6 with the filled triangle symbol, while the gap between lines 3 and 4 with the open secularity symbol is larger than the difference between lines 7 and 8 with the open triangle symbol for the R and Q_{zz}/Q_{zz0}. Namely, the reduction amplitude of R and the enhancement amplitude of Q_{zz}/Q_{zz0} with U_1^{sym} induced by the Coulomb interaction are larger than those with U_3^{sym}, even though the form of Coulomb interaction, in-medium nucleon–nucleon cross section and entrance channel condition are the same for U_3^{sym} and U_1^{sym}. This feature means that the momentum dissipation induced by the Coulomb interaction depends sensitively on the strength and the form of symmetry potential because the curvature of U_1^{sym} is stronger than that of U_3^{sym}. In this case, we have to investigate the effect of the Coulomb interaction on the momentum dissipation. In addition, it is obvious that the value of R decreases and the value of Q_{zz}/Q_{zz0} increases with the increasing beam energy, i.e. momentum dissipation decreases with the increasing beam energy. At the same time, the features of the sensitive dependence of R and Q_{zz}/Q_{zz0} on the in-medium two-body collisions and weakly on the symmetry potential disappear gradually with the enhancement of beam energy above 300 MeV/nucleon, because on the one hand, two-body collision is enhanced and the role of mean field is reduced as the enhancement of the beam energy. On the other hand, the degree of momentum dissipation decreases and the degree of transparency between the two colliding nuclei increases, so that it leads to the disappearance for the above two features with the enhancement of beam energy.

In order to give explanations separately for the dependence of momentum dissipation induced by the Coulomb interaction, in the form and strength of symmetry potential in more detail, Fig. 2 shows the time evolution of R for three forms of symmetry potentials U_1^{sym}, U_2^{sym} and U_3^{sym} with and without the Coulomb interactions in the reaction ^{94}Mo+^{94}Mo at an impact parameter b of 2.0 fm and a beam energy of 100 MeV/nucleon. It is apparent that the gap between thick dotted line and thin dotted line for U_2^{sym} is the largest, but the gap between thick dashed line and thin dashed line for U_3^{sym} is the least because the curvatures K_{sym} of U_1^{sym}, U_2^{sym} and U_3^{sym} are -27 MeV, 61 MeV and -69 MeV respectively; i.e., the strength for U_2^{sym} with 61 MeV is the largest but that of U_3^{sym} with -69 MeV is the smallest. It is worth mentioning that the form and the strength of symmetry potential have not been determined in a very wide variation region of the curvature K_{sym}. Therefore, we have to investigate and analyse systematically the competition and mechanism among the Coulomb interaction, the possible forms of symmetry potentials and in-medium N–N cross section by making the comparisons between

theoretical results and experimental data, to determine the form and strength of the symmetry potential.

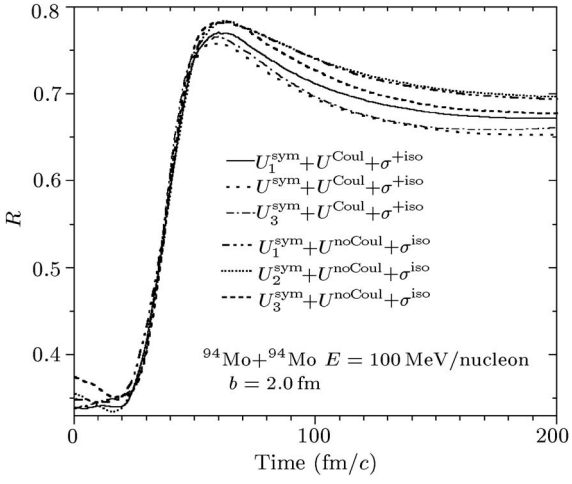


Fig. 2. Time evolutions of R for three forms of the symmetry potentials $U_1^{\rm sym}$, $U_2^{\rm sym}$ and $U_3^{\rm sym}$ in the two cases with and without the Coulomb interactions in the reaction ^{94}Mo+^{94}Mo at impact parameter b of 2 fm.

In conclusion, the Coulomb interaction can induce the reduction of momentum dissipation. The momentum dissipation decreases with the increasing beam energy. The momentum dissipation depends sensitively on the in-medium N–N cross section and weakly on the symmetry potential with and without Coulomb interactions in the definite beam energy region, but the Coulomb interaction does not change this isospin effect obviously. In particular, the variation amplitude of momentum dissipation induced by the Coulomb interaction depends on the form and strength of the symmetry potential. The Coulomb interaction is preferable to standing up the isospin effect of in-medium N–N cross section on R and Q_{zz} and to reducing the isospin effect of symmetry potential on them.

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