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Total Reaction Cross Section in an Isospin-Dependent Quantum Molecular Dynamics Model *

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The isospin-dependent quantum molecular dynamics (IDQMD) model is used to study the total reaction cross section σ_R. The energy-dependent Pauli volumes of neutrons and protons have been discussed and introduced into the IDQMD calculation to replace the widely used energy-independent Pauli volumes. The modified IDQMD calculation can reproduce the experimental σ_R well for both stable and exotic nuclei induced reactions. Comparisons of the calculated σ_R induced by ^{11}Li with different initial density distributions have been performed. It is shown that the calculation by using the experimentally deduced density distribution with a long tail can fit the experimental excitation function better than that by using the Skyrme–Hartree–Fock calculated density without long tails. It is also found that σ_R at high energy is sensitive to the long tail of density distribution.

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The total reaction cross section σ_R has been extensively studied theoretically and experimentally.[1−10] There are two kinds of theoretical models to calculate σ_R. The first is the low-energy theory based on the interaction potential. Such models are not successful for the reaction beyond 10–15 MeV/nucleon above the Coulomb barrier. The second is the high-energy microscopic Glauber theory based on the individual nucleon–nucleon collisions in the overlap volume of the projectile and target. However, the roles of mean field and medium effect are difficult to be discussed in the Glauber-type model. In recent years, Ma *et al.* developed a new method to study σ_R with helps of transport theory and Glauber model.[5] Originally, the Boltzmann–Uehling–Uhlenbeck model[11] was taken as a tool to investigate σ_R.[5] Later, the quantum molecular dynamics (QMD) model was applied to study σ_R[13] in the same spirit as Ref. [5]. The reaction dynamics in transport theory at intermediate energy is mainly governed by the mean field, two-body collisions, and Pauli blocking. To investigate the isospin effects, the above three dynamical ingredients should include properly isospin degrees of freedom to obtain an isospin-dependent quantum molecular dynamics (IDQMD). It is also important that the samples of neutrons and protons in the phase space should be treated separately in the initialization of projectile and target nuclei. In this Letter, the IDQMD model is introduced to calculate σ_R. This model incorporates the isospin dependence of mean-field, nucleon–nucleon cross section, and Pauli blocking. It has been widely used to study the multi-fragmentation and the collective flow. In the IDQMD model, neutrons and protons are distinguishable in the initialization.

The density distributions for the initial projectile and target nuclei are determined from the Skyrme–Hartree–Fock (SHF) calculation[17] with a parameter set of the Skyrme modified force. The stability of the propagation of the initialized nuclei has been checked in details and can last at least 200 fm/c according to the evolutions of the average binding energies and the root mean square radii of the initialized nuclei.

In the IDQMD model, once the distance between the two nucleons is less than r_{nn}, the collision may occur, where r_{nn} is defined as

$$r_{nn} = \sqrt{\sigma_{nn}(\sqrt{s})/\pi},$$

with $\sigma_{nn}(\sqrt{s})$ representing the nucleon–nucleon reaction cross section and $\sqrt{s}$ representing the nucleon energy in the centre-of-mass system. Whenever a collision occurs, the final momenta of the scattering nucleons can be easily obtained as a consequence of momentum conservation and the coordinates are updated in terms of Newtonian equation (classical trajectory). Then we calculate and check the phase spaces around the final states of the scattering nucleons. Thus it is easy to determine the probabilities (P_1 and P_2) for each of the two scattering nucleons that their final phase spaces are already occupied by other nucleons by comparing with the defined Pauli volume, i.e. $4(\Delta P \Delta R)^3/3$, in six-dimensional phase space, where ΔR is the minimum radius which is allowed to be occupied by itself in coordinate space and ΔP is the same but in momentum space. The collision is then

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blocked with a probability

$$P_{\rm block} = 1 - [1 - \min(P_1, 1)][1 - \min(P_2, 1)].$$

Correspondingly, the collision is allowed with probability $(1 - P_{\rm block})$. Whenever a collision is blocked, the momenta of the scattering nucleons will be replaced by the values they are prior to scattering. More details could be found in Refs. [12,15].

The following formula of in-medium reaction cross section is used in the present IDQMD calculation,

$$\begin{aligned}\sigma_{nn} =& (13.73 - 15.04\beta^{-1} + 8.76\beta^{-2} + 68.67\beta^{4}) \\ & \cdot \frac{1.0 + 7.772E_{lab}^{0.006}\rho^{1.48}}{1.0 + 18.01\rho^{1.46}} \\ \sigma_{np} =& (-70.67 - 18.18\beta^{-1} + 25.26\beta^{-2} + 113.85\beta) \\ & \cdot \frac{1.0 + 20.88E_{lab}^{0.04}\rho^{2.02}}{1.0 + 35.86\rho^{1.90}}, \\ \beta =& \sqrt{1 - \frac{1.0}{\gamma^2}}, \quad \gamma = \frac{E_{lab}}{931.5} + 1.0. \end{aligned} \tag{1}$$

This formula includes both effects of incident energy E_{lab} and nucleon matter density ρ. It shows that the medium effect is important at intermediate energies and becomes smaller at higher energies but does not vanish.[18,19]

The cross section σ_R can be written as[5]

$$\begin{aligned}\sigma_R =& 2\pi \int b[1 - T(b)]{\rm d}b, \\ =& 2\pi \int b[1 - \exp(-N)]{\rm d}b, \end{aligned} \tag{2}$$

where the transport function $T(b)$ can be obtained from the average n − n collision number N as a function of the impact parameter b. More details could be found in Ref. [5].

In the previous IDQMD model, the volume occupied by nucleon in the projectile and target (Pauli volume) was a constant $(\hbar^3/2)$. This constant could be deduced from the lowest limit of the uncertain relationship between the momentum and the coordinate.[14] Recently, it was found that the Pauli volume is sensitive to the incident energy and should not be a constant qualitatively.[20] Calculation of the average collision number N of the ^{12}C+ ^{12}C system at high incident energy shows that the average collision number still has an uptrend after the evolution time of 200 fm/c. However, other studies indicated that the average collision number has been saturated after 50 fm/c at high incident energy.[13] This indicates that the invariable Pauli volume used in the previous IDQMD model may not be suitable and the Pauli volume may be energy-dependent. From formula (2) we know that σ_R can be decided by the average collision number N. It is also clear that N is sensitive to the probability of the Pauli blocking in the collisions. Thus, the energy dependence of the Pauli volume becomes very important in the calculation of σ_R. Up to now, there has not yet been parametrized formula to describe the energy-dependent Pauli volume.

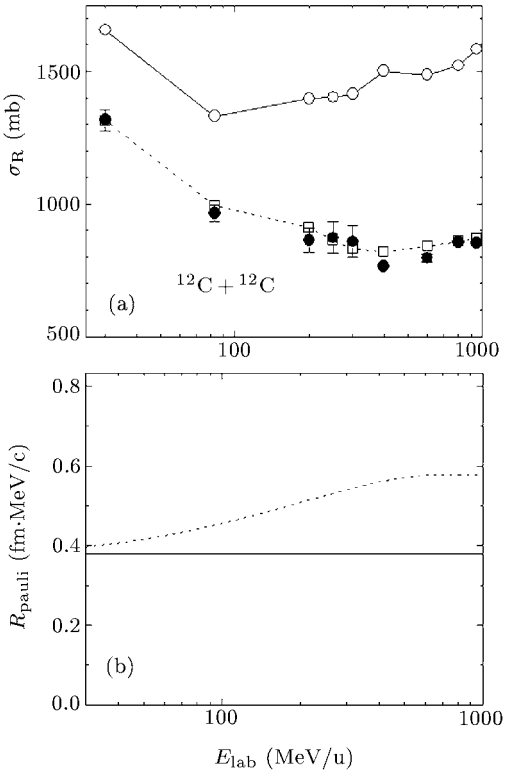

Fig. 1. (a) Total reaction cross section σ_R of ^{12}C on a ^{12}C target. The solid line with open circles shows the calculated results with the constant Pauli volume values, the dashed line with open squares represents the calculated results with the changeable Pauli volume values, the closed circles are experimental data from Ref. [4]. (b) Solid line is the constant Pauli radius R_0 taken in the previous IDQMD model and the dashed line shows the energy-dependent Pauli radius R in this work.

We calculate the cross section σ_R of the ^{12}C+ ^{12}C reaction system in an IDQMD framework in a wide energy range as shown in Fig. 1(a). Here soft equation of state and in-medium σ_{nn} are used. The initialized density distribution of ^{12}C comes from the SHF calculation. The solid line with open circles shows the calculated results with the constant Pauli volume. It is obvious that they cannot reproduce the experimental data. With adjusted Pauli volume values in the IDQMD calculation we fit the experimental data at different energies [see the dashed line with open squares in Fig. 1(a)]. From these fits, the Pauli volume values were obtained in a wide energy range as shown in Fig. 1(b). Obviously, the Pauli radius R increases generally at intermediate energy and becomes saturated above 400 MeV/u. By using this energy-dependent Pauli volume, it is found that the average collision number N will be a constant after 50 fm/c at

high energy and after 100 fm/c at intermediate energy, which is consistent with the other studies.[13]

In order to test the modified IDQMD model, we use it to study σ_R for other reaction systems. In Fig. 2, the solid line shows the experimental matter density distribution with a long tail and the dashed line shows the one calculated with the SHF density distribution. The experimental density distribution of ^{11}Li is introduced into the IDQMD model to replace the SHF one. Figure 3(a) shows the calculated results of σ_R for the ^{11}Li + ^{12}C reaction system with different density distributions as shown in Fig. 2. Clearly, the calculation with the experimental density distribution of ^{11}Li can fit the experimental σ_R better. For the reaction induced by halo nucleus ^{11}Li, the results with the SHF density distribution are lower than the experimental ones at high incident energy for about a few per cent since the SHF calculation of ^{11}Li does not give the long tail as experimental one, which is expected to play an important role in the calculation of σ_R. This indicates that the density distribution calculated with the SHF density distribution is not appropriate to those halo nuclei[21] in the IDQMD calculation. It is obvious that the calculated σ_R at several hundreds of MeV/u is more sensitive to the long-tail density distribution. Since the central densities are also different between them, more conclusions about the density effect on σ_R can be obtained by further studies. The research along this line is in progress.

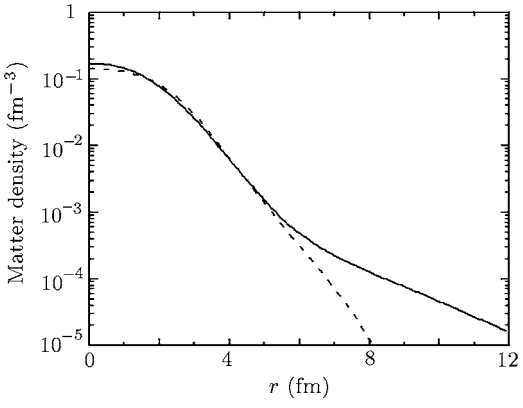

Fig. 2. Experimental density distribution (solid) of ^{11}Li (ρ_1)[21] and the calculated one (dashed) with the Skyrme–Hartree–Fock density distribution ρ_0.

Figure 3(b) shows the calculated results of excitation function of σ_R for the ^{12}C+ ^{27}Al reaction system. In Fig. 3, all the filled circles represent the experimental data.[4,22] The solid line with open squares shows the calculated results with the IDQMD, where the initialized density distribution of ^{27}Al and ^{12}C are calculated by using the SHF model. Figure 3 shows that the IDQMD calculation with the energy-dependent Pauli volume and the density distribution of the SHF model gives a good trend of excitation function of σ_R. For reaction induced by stable nuclei, the calculated results can fit the experimental values well in a wide energy range. With the experimental density distribution the IDQMD model can also give the fine results of σ_R induced by halo nuclei.

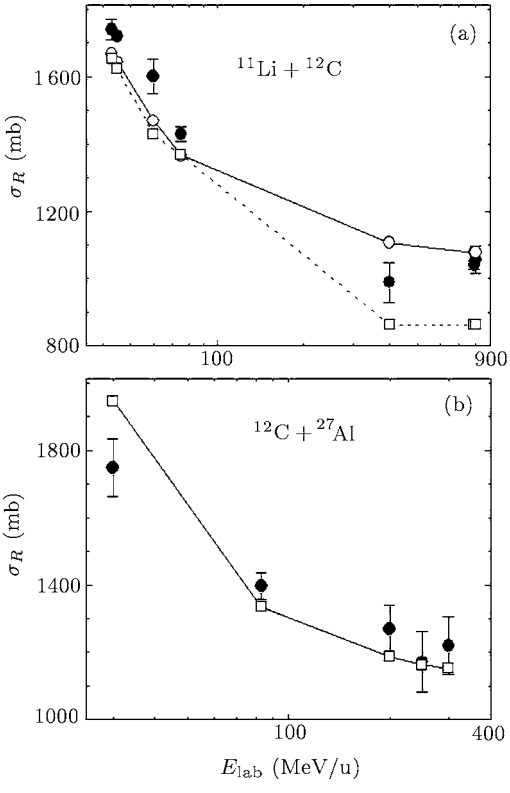

Fig. 3. (a) Calculation of σ_R for ^{11}Li on ^{12}C target. The dashed line with open squares shows the calculated results with ρ_0 and the solid line with open circles represents the calculated results with ρ_1. (b) The solid line with open square shows the energy dependence of σ_R for the ^{12}C + ^{27}Al. The closed circles are the experimental data from Refs. [4,22].

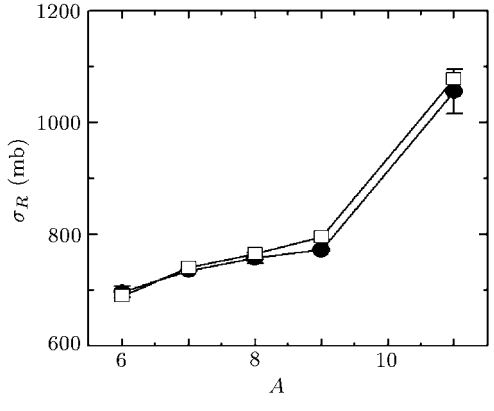

Fig. 4. Total reaction cross section σ_R of Li isotopes on a ^{12}C target at 790 MeV/u. The solid line with open squares shows the calculated results and the solid line with filled circles represents the experimental data taken from Refs. [10,23].

Figure 4 gives the calculation of σ_R of Li isotopes on the ^{12}C target at 790 MeV/u. The density distribution of ^{11}Li is from the experiment and the others are calculated with the SHF model. It shows that σ_R varies smoothly with mass number up to ^{9}Li. There is a sudden increase of σ_R between ^{9}Li and ^{11}Li which is corresponding to the halo structure in ^{11}Li. Our calculation results reproduce both the experimental values and the sudden change between ^{9}Li and ^{11}Li fairly well.

In conclusion, the IDQMD model has been introduced to study the total reaction cross section σ_R by using the energy-dependent Pauli volume which is deduced from the excitation function of σ_R of ^{12}C+ ^{12}C. The calculated results can reproduce the experimental σ_R quite well. It is interesting to investigate further the energy and isospin effects of Pauli volume in collision. For halo nuclei, the calculated results by using experimental density distribution are better than that by using the SHF density distribution. It is suggested that the long tail of the density distribution plays an important role for the halo nuclei and σ_R at high energy is sensitive to the long tail distribution of halo nuclei. Since the IDQMD model incorporates the isospin dependences of mean-field, nucleon–nucleon cross section, and Pauli blocking, it is also interesting to study each isospin-effect on σ_R and other physical quantities. In the IDQMD calculation, the clusters can be judged by the relative momenta and coordinates with an isospin-dependent modified coalescence model and the momentum distribution of the projectile fragments can be obtained easily. Thus, the IDQMD model can be used to study the total reaction cross section, fragmentation cross sections and momentum distribution of fragment of halo nuclei simultaneously. It can be used to give a more comprehensive and reliable criterion of halo structure, which is of great significance. These works are in progress.

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