Pauli-Blocking and Nuclear Potential Effects in the Glauber Model *

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ABSTRACT

In order to investigate the effects of the Pauli blocking and internuclear potential on the total reaction cross section, we apply a microscopic simulation method called Antisymmetrized Molecular Dynamics to the optical limit of the Glauber model. We have analyzed reactions induced by d, ^{3}He and α projectiles on ^{12}C target over an energy range from 10 MeV/A to 1GeV/A, are the calculated results show good agreement with experimental data. It is shown that each of these effects, which are ignored in the usual Glauber-type calculation, amounts to about 20 % at low energy regions, however, large cancellations occur when we include both effects.

1. Introduction

In these years, the total reaction cross section (TRCS) of heavy-ion collisions is extensively studied in a wide energy range — from a few ten MeV per nucleon to a few GeV — as a tool to study nuclear sizes and structures, especially, of unstable nuclei [1].

Until now, TRCS has been extensively studied based on the Glauber model, and this model has succeeded in reproducing the data of various kind of reactions and in a wide range of incident energies. In most of the Glauber-type calculations, the optical limit has been usually used [2, 3, 4]. In the Glauber model, since two-nucleon collisions give rise to reactions, the Pauli blocking and internucleus potential are important at incident energies lower than or comparable to the Fermi energy. However, these effects are ignored in the Glauber model, and it has not been known whether this success is only due to accidental cancellations or there exists some mechanism which supports the Glauber theory.

In nucleon-nucleus reactions, there have been some works which aim at the inclusion of these effects [5], In the case of nucleus-nucleus reactions, however, the estimation of the Pauli blocking becomes more complex. In addition to the fact that we have to treat two Fermi spheres, it has been pointed out that the dynamical change of the distribution function in the phase space plays an essential role [6]. In order to include these dynamical effects, it is necessary to rely on the microscopic simulation models. Microscopic simulation methods, such as Boltzmann-Uehling-Uhlenbeck (BUU) model [6, 7],

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Quantum Molecular Dynamics (QMD) [8, 9] or Antisymmetrized Molecular Dynamics (AMD) [10], have been a standard tool for the study of heavy-ion collisions. They usually contain the effects of the mean field and the Pauli blocking, thus they are considered to be the candidates to investigate above effects also on TRCS.

On the other hand, internucleus potentials between light heavy-ions have been successfully studied by the use of models based on the cluster theory. For example, Canonical Moving Wave Packet (CMWP) model gives us a reliable optical potential between heavy-ions [11, 12]. Although CMWP method is a semi-classical model, it has succeeded also below the Fermi energy region. Therefore, it is desirable to extend this model to include all the nucleonic degrees of freedom for the study of TRCS.

The aim of this study is to investigate the role of the Pauli blocking and internucleus potential on TRCS in the Glauber model by the use of AMD. AMD is one of the microscopic simulation method which exactly takes into account the fermionic nature of nucleons. Therefore, quantum features such as nuclear shell effects are automatically included in the dynamics, and it is suitable for the study of the Pauli blocking during the dynamical evolution. In addition, since AMD is considered to be an extended version of CMWP, it reasonably takes into account the modification of nuclear paths due to the nuclear potential from the straight-line which is assumed in most of the Glauber-type models.

2. Two-Nucleon Collision Probability Based on the Glauber Model in AMD

AMD is one of the microscopic simulation method which describes the time-evolution of the many-body wave function itself. In this model, the many-body wave function of the system is described by a Slater determinant of Gaussian wave packets which are parameterized by time-dependent complex variables $\boldsymbol{z}_i$. The time evolution of these parameters are determined by the time-dependent variational principle (TDVP) and the two nucleon collision term. Since the resultant equations of TDVP for complex parameters are not of canonical form, we cannot interpret them as physical positions and momenta of nucleons. Therefore, two-nucleon collision term is incorporated by the use of approximate canonical variables [10, 11, 12].

In the optical limit of the Glauber model within the zero range approximation, we can calculate TRCS by the following equations.

$$\sigma_{R} = 2\pi \int d^2b \; [\; 1 - \mathrm{e}^{-\chi(\boldsymbol{b})} \;] \; , \quad \chi(\boldsymbol{b}) = \sigma_{NN} \int d^2r \; \rho_z^P(\boldsymbol{r}) \; \rho_z^T(\boldsymbol{r}-\boldsymbol{b}) \; , \tag{1}$$

where σ_{NN} is the N-N cross section, $\boldsymbol{b}$ is the impact parameter, and ρ_z^P and ρ_z^T are the thickness functions of projectile and target nuclei, respectively.

It is noteworthy to rewrite this profile function $\chi(\boldsymbol{b})$ by the use of the Wigner function.

$$\chi(\boldsymbol{b}) = \int dt \; \frac{d\boldsymbol{r} d\boldsymbol{p}_1 d\boldsymbol{p}_2}{(2\pi\hbar)^6} \; v\sigma_{NN} \; f^P(\boldsymbol{r}-\boldsymbol{R}(t), \boldsymbol{p}_1) \; f^T(\boldsymbol{r}, \boldsymbol{p}_2) \; P_{coll}(\Omega) \; , \tag{2}$$

where $\boldsymbol{R} = (\boldsymbol{b}, z)$ represents the relative coordinate between projectile and target, f is the Wigner function, and $P_{coll}(\Omega)$ denotes the Pauli-allowed probability. In the Glauber model, the Pauli blocking is ignored ($P_{coll} = 1$) and straight-line path for the relative motion is assumed. In this case, this χ-function gives the same expression as the average number of N-N collisions $< N_{coll} >$ in the Intranuclear Cascade model. Thus, we can apply more sophisticated microscopic simulations which include the effects of the Pauli blocking and nuclear potentials for the estimation of $< N_{coll} >$ [7].

In AMD, TRCS can be calculated by replacing $\chi(\boldsymbol{b})$ by the average number of N-N collisions $< N_{coll} >$. Since we have to count the ratio escaping from the elastic channel for the estimation of TRCS, it is reasonable to fix the Wigner functions f^α to those in the elastic channel in Eq.2. Therefore, in this work, we count the number of two-nucleon collisions but we have not changed the momenta of collided nucleons in the simulation calculation. This is the essential difference between this work and Ref.6.

In the actual calculation, we count the number of collision in the simulation, instead of integrating Eq.2. There is almost no ambiguity in the TDVP part of AMD, however, there exist some algorithms in the treatment of two-nucleon collision term. For example, in BUU and QMD models, two-nucleons are usually made to scatter stochastically when their spatial relative distance is smaller than $\sqrt{\sigma_{NN}/\pi}$. This is nothing but a geometrical interpretation of the two-nucleon collision. In this work, we choose two-nucleon collision probability so as to reproduce the Glauber model when we ignored the Pauli-blocking factor and the straight-path nuclear orbitals are assumed. We start from Eq.1, and after some manipulation we get another representation of χ-function, in which the probability of each N-N collision is given by the density overlap.

$$\frac{dP_{ij}}{dt} = v\sigma_{NN} \int d\boldsymbol{r}\rho_i(\boldsymbol{r} - \boldsymbol{R})\rho_j(\boldsymbol{r}) \simeq v\sigma_{NN} \left(\frac{\eta\nu}{\pi}\right)^{3/2} \exp[-\eta\nu(\boldsymbol{r}_i - \boldsymbol{r}_j)^2] \,, \qquad (3)$$

where $\boldsymbol{r}_i$ and $\boldsymbol{r}_j$ represent the physical positions of colliding nucleons, which are the real parts of the above mentioned approximate canonical variables, and a parameter $\eta = 1.2$ is introduced in order to fit the overlap density of two nuclei. In this work, we adopt this expression as the collision probability for each pair, By this selection of two-nucleon collision probabilities, the effects of nuclear diffuseness is properly included compared with the previous geometrical treatment.

3. Results and Discussions

We have calculated TRCS in the reaction of $X+^{12}$C where $X = d$, ^{3}He and ^{4}He over an energy range from 10 MeV/A to 1GeV/A. As an effective nucleon-nucleon interaction, Volkov No.1 force is adopted. We have fixed model parameters to fit the binding energy data of α particle and ^{12}C , and the sum of RMS radii data of projectile and target nuclei. As for the two-nucleon cross section and the angular distribution, we have followed Charagi et al. [4] and Cugnon [6, 13], respectively.

In order to investigate the effects of the Pauli blocking and the internucleus potential separately, we have made two types of calculation. The first one is the simulation in which straight line paths of relative motion are assumed (SPAMD). In this calculation, nuclear potential effects are neglected but Coulomb effect is approximately included as in the case of Coulomb-modified Glauber model [4]. The second one is the full simulation, in which effects of the internucleus potential are included, as in the case of CMWP model. Since we have not changed the momenta of collided nucleons (*i.e.*, two-nucleon collisions are treated perturbatively) as mentioned before, we call this treatment as PTAMD. We show the comparison of calculate results and the data in Fig.1.

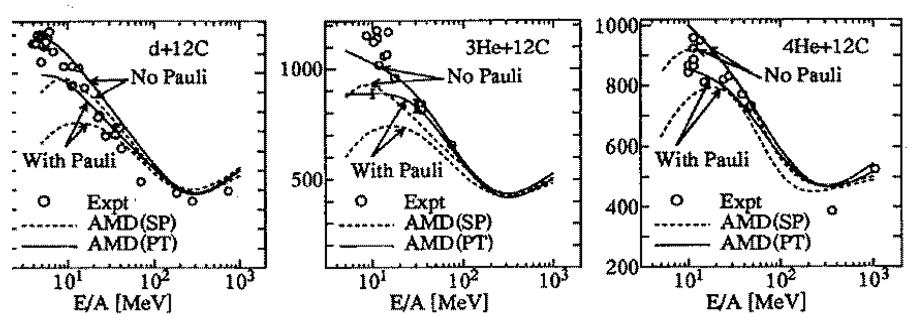

Figure 1. Total Reaction Cross Section

Solid and dashed lines show the calculated results with PTAMD and SPAMD, respectively. Upper (lower) lines show those without (with) the Pauli blocking. The Glauber-type calculation corresponds to SPAMD without the Pauli blocking. Circles show the experimental data.

Now we can discuss the effects of the Pauli blocking and the nuclear potential. It is clear from Fig.1 that the Pauli blocking reduces TRCS, and the nuclear potential increases TRCS. Since at a touching distance of two nuclei the internucleus potential is attractive, the projectile nucleus passes closer to the target than in the case of no potential. Thus the overlap density increases, and two-nucleon collisions are enhanced.

It is noteworthy that each of the above effects amount to about 20 % at low energy regions, however, when we include both effects, they almost cancel with each other. (Note that the usual Glauber model results correspond to those with SPAMD without the Pauli blocking.) This is the reason why the Glauber-type model have succeeded also below the Fermi energy. It is known that at low energy regions the depth of the internucleus potential is comparable to that determined by the Pauli forbidden region [11]. This means that nucleons in projectile pass outside of the Fermi sphere of target, and two-nucleon collisions become possible even at the low incident energy, when we ignore the shell effects.

One of the exception is α+^{12}C reaction, where the shell effect of α particle is so strong. In this case, the colliding nucleons have to lose large kinetic energy in order to break α particle. Thus they cannot find the final states of two-nucleon collisions in which the total energy is conserved. We note that the PTAMD results with the Pauli blocking fit the experimental data better than in the case of the Glauber-type model, except the resonance energy region ($E_{inc} \simeq 10\text{MeV}/A$), where the other effects rather than two-nucleon collision are considered to largely affect TRCS.

In this work, we have studied the Pauli blocking and internuclear potential effects in the optical limit of the Glauber model by the use of Antisymmetrized Molecular Dynamics (AMD). The model used here can be regarded as an extension of the Glauber model including the Pauli blocking and nuclear potential effects, and also as an extended version of Canonical Moving Wave Packet (CMWP) model with the estimation of escaping ratios from the elastic channel by two-nucleon collisions. The calculated results show good agreement with the experimental data and show that a large cancellation between above two effects can be seen at low incident energies. However, when the shell effects are strong as in the case of $\alpha+^{12}$C reaction, the Pauli blocking effects overcome those of the internucleus potential. When we see that the usual Glauber-type calculation overestimates TRCS data in this reaction [2, 3], the above effect is one of the possible and natural source for this overestimation.

We have limited our attention to the reactions only with stable nuclei. In the case of unstable nuclear reactions, since the spatial width of last nucleon(s) wave function is large and the separation energy is small, there is a possibility that the above cancellation would not occur.

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