BRIEF REPORTS

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In-medium nucleon-nucleon cross section and its effect on total nuclear reaction cross section

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A phenomenological formula for in-medium nucleon-nucleon cross section is presented, in which nuclear matter density and incident energy dependencies are included. This formula is used to study total nuclear reaction cross section based on Coulomb-modified Glauber model. The calculated results can reproduce experimental total reaction cross section induced by the stable nuclei and the exotic nuclei over a wide energy range. [S0556-2813(98)03007-6]

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One of the most important physical quantities characterizing the properties of nuclear reaction is the total nuclear reaction cross section σ_R [1–10]. It is very useful for extracting fundamental information about the nuclear size and the density distributions of neutrons and protons in nucleus. In particular, the neutron halo has been found by measuring the total reaction cross section induced by radioactive nuclear beams [1,2]. A new Coulomb-modified Glauber model [3–5] is developed to explain the new phenomena of σ_R by considering the relation between surface diffuseness of neutron distribution and neutron separation energy of nuclei. In this model, the free-space nucleon-nucleon cross section $\sigma_{NN}^{\mathrm{free}}$ obtained by experimental measurement is used. But the real in-medium nucleon-nucleon cross section $\sigma_{NN}^{\text{in-medium}}$ is different from the free-space nucleon-nucleon cross section because of the effects of Pauli blocking and finite nuclear matter density in heavy-ion reactions. Theoretically, in-medium nucleon-nucleon cross section can be attained by solving the many-body Bethe-Goldstone (BG) equation, namely G matrix cross section [6,7]. However, up to now, most of the calculations were performed only at several values of nuclear matter density and incident energy. So it is valuable if one can present some new formula to calculate the in-medium nucleon-nucleon cross section over a wide energy range. As an attempt, a phenomenological formula for in-medium nucleon-nucleon cross section is presented in this article based on several recent theoretical studies, especially of Li and Machleidt's works [11,12]. Then it is applied to calculate the total reaction cross section and the results are discussed.

Many groups [11–27] have studied medium effect of nucleon-nucleon cross section. Based upon the Bonn A nucleon-nucleon interactive potential and Dirac-Brueckner approach for nuclear matter, in-medium nucleon-nucleon cross sections were calculated by Li and Machleidt [11,12] for the incident energies from 50 to 300 MeV in a laboratory frame and the matter densities up to $2\rho_0$ (where ρ_0 is the saturation density of normal nuclear matter in the range of 0.15–0.19 fm^{-3}; in this paper we use $\rho_0 = 0.17\ \mathrm{fm}^{-3}$). Results of their numerical calculation were fitted by a semiempirical formula (LM formula) including the dependence on incident energy and nuclear matter density. The analytic formula can be written as

$$\sigma_{\mathrm{nn}} = [23.5 + 0.002\,56(18.2 - E_{\mathrm{lab}}^{0.5})^4] \times \frac{1.0 + 0.1667 E_{\mathrm{lab}}^{1.05}\rho^3}{1.0 + 9.704\rho^{1.2}},$$

$$\sigma_{\mathrm{np}} = [31.5 + 0.092\,\mathrm{abs}(20.2 - E_{\mathrm{lab}}^{0.53})^{2.9}] \times \frac{1.0 + 0.0034 E_{\mathrm{lab}}^{1.51}\rho^2}{1.0 + 21.55\rho^{1.34}}, \qquad (1)$$

where σ_{nn} is the neutron-neutron (or proton-proton) cross section, σ_{np} is neutron-proton cross section, ρ is nuclear matter density in the unit of fm^{-3}, and E_{lab} is the incident energy in laboratory frame. In Eq. (1), the coefficient with the value 0.0256 in LM's publication should be 0.002 56 [28]. Recently, the LM formula has been applied to study some features of nuclear reaction [29,30].

Klakow *et al.* [13] calculated the balance energy by the Boltzmann-Uehling-Uhlenbeck (BUU) model with a soft equation of state. They found that the calculated balance energy could fit experimental data best when the in-medium nucleon-nucleon cross section equals to 80% of the free-space nucleon-nucleon cross section. Haar and Malfliet [14,15] got the same conclusion after studying the property of higher energy nucleons interaction and reflection particle at dense medium by taking advantage of the relativistic Dirac-Brueckner approach. This conclusion now is often used in the transport model such as the BUU equation [9,16,17] and quantum-molecular-dynamics (QMD) [18].

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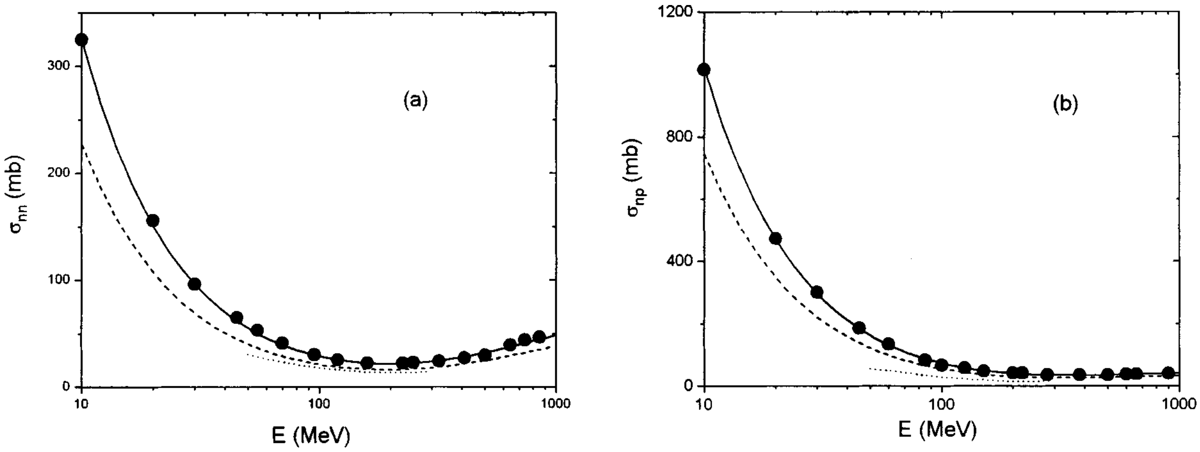

FIG. 1. Nucleon-nucleon cross section as a function of incident energy. (a) Neutron-neutron interaction cross section. (b) Neutron-proton interaction cross section. Solid circles indicate experimental free-space nucleon-nucleon cross section. Solid and dashed curves indicate the result of present formula at $\rho=0$ and ρ_0, respectively. For comparison, results of the LM formula at $\rho=\rho_0$ are shown by dotted lines.

But, in fact, the medium effect is different in various incident energy ranges and matter densities. So it seems that the conclusion of Klakow *et al.* overlooks the energy dependence of medium effect and describes the density dependence too simply.

Combing the energy dependence of free-space nucleon-nucleon cross section of Charagi and Gupta [8] with the LM formula, a new phenomenological formula for in-medium nucleon-nucleon cross section is proposed by the following expression:

$$\sigma_{\rm nn}=(13.73-15.04\beta^{-1}+8.76\beta^{-2}+68.67\beta^{4})\times\frac{1.0+7.772E_{\rm lab}^{0.06}\rho^{1.48}}{1.0+18.01\rho^{1.46}},$$

$$\sigma_{\rm np}=(-70.67-18.18\beta^{-1}+25.26\beta^{-2}+113.85\beta)\times\frac{1.0+20.88E_{\rm lab}^{0.04}\rho^{2.02}}{1.0+35.86\rho^{1.90}}, \tag{2}$$

$$\beta=\sqrt{1.0-\frac{1.0}{\gamma^2}},\quad \gamma=\frac{E_{\rm lab}}{931.5}+1.0, \tag{3}$$

where β is the ratio of projectile velocity to light velocity and the meanings of the other variables are the same as in Eq. (1). Coefficients in Eq. (2) are obtained by a least squares fit to the experimental total reaction cross section data over a wide incident energy range from 10 MeV to 1 GeV. In Eq. (2) the first part describes the free-space nucleon-nucleon cross section [8] and the second part describes the incident energy and nuclear matter effects of in-medium nucleon-nucleon cross section. It can be seen from Eq. (2) that the nucleon-nucleon cross section in nuclear medium decreases with increasing energy, but the medium effect does not vanish even at higher energies.

Figure 1 shows the energy dependence of nucleon-nucleon cross section. The solid circles describe the experimental values of free-space nucleon-nucleon cross section, which are taken from Ref. [8]. The solid lines describe results of Eq. (2) at $\rho=0$. The dashed lines describe results of Eq. (2) at $\rho=\rho_0$. The results of LM formula at $\rho=\rho_0$ are plotted as dotted lines. From Fig. 1 one can see that our new calculations presented by the solid lines can fit the experimental values well over the energy range from 10 MeV to 1 GeV. Note that the LM formula is only valid in the energy range 50–300 MeV [11,12].

In order to examine the effects of in-medium nucleon-nucleon cross section on physical observable, the total nuclear reaction cross section is investigated as an example. A basic tool used here to calculate the total nuclear cross section is the Coulomb-modified Glauber model [3–5]. In this model the total nuclear reaction cross section can be written as

$$\sigma_R=2\pi\int b\,db[1-T(b)]. \tag{4}$$

Using surface-normalized Gaussian density distribution of nucleons in the target and projectile for a finite range nuclear interaction, an analytic expression for the transparency $T(b)$ is obtained as

$$T(b)=\exp\left[-\pi^2\sum_{i=n,z}\sum_{j=n,z}\frac{\sigma_{ij}\rho_{Ti}(0)\rho_{Pj}(0)\alpha_{Ti}^3\alpha_{Pj}^3}{\alpha_{Ti}^2+\alpha_{Pj}^2+\gamma_0^2}\times\exp\left(-\frac{b'^2}{\alpha_{Ti}^2+\alpha_{Pj}^2+\gamma_0^2}\right)\right], \tag{5}$$

$$b'^2=\frac{b^2}{1-V_c/E_{\rm c.m.}}=\frac{b^2}{1-1.44Z_TZ_P/(R_{\rm int}E_{\rm c.m.})}, \tag{6}$$

where $\rho_{Ti}(0)$, $\rho_{Pj}(0)$, α_{Ti}, and α_{Pj} are the parameters of surface-normalized Gaussian distributions of the protons and neutrons in the target and projectile, respectively. They are adjusted to reproduce the nuclear surface texture by requiring the Gaussian distribution at $b=c$ and $b=c+\frac{1}{2}t$ to be identical to the values calculated from the realistic two parameter Fermi distribution (with c as the half central density and t as the surface diffuseness of the neutron and proton distributions, respectively). b is the impact parameter. $\gamma_0=1$ fm is the range parameter. Details can be found in

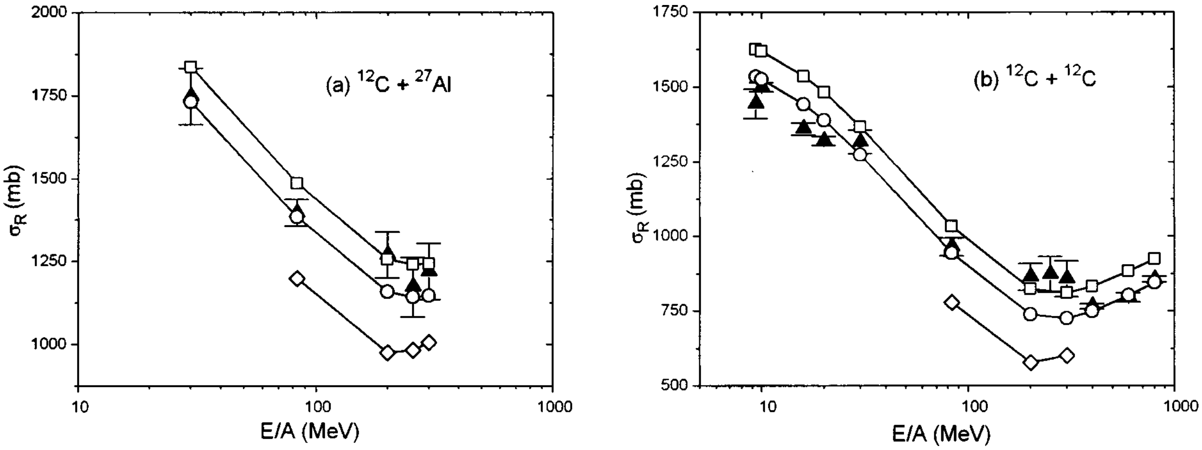

FIG. 2. Energy dependence of total reaction cross section. (a) For the $^{12}C+^{12}C$ reaction. (b) For the $^{27}Al+^{12}C$ reaction. Solid triangles denote experimental values. Solid line connecting circles is from this work. Solid line connecting boxes is based on the calculation without considering the medium effect. Solid line connecting the diamonds is based on the calculations using the LM formula at $\rho=\rho_0$. All the calculations used the same Glauber model.

Refs. [3–5]. In-medium nucleon-nucleon cross section in the present calculation for Eq. (2) is used in $\rho=\rho_0$.

The total nuclear reaction cross sections of four different reaction systems, which are calculated by the above model, are shown in Fig. 2 and Fig. 3. In these figures, the solid triangles are the experimental data of σ_R from Refs. [1,6,8,31–35]. The circles describe our calculated results by using Eq. (2) at $\rho=\rho_0$. The calculated results without considering the medium effects are given in these figures via boxes. The calculated results via the LM formulas at $\rho=\rho_0$ are given by diamonds. The lines in the Fig. 2 and Fig. 3 are only for guiding the eyes.

Seeing from the energy dependence of total reaction cross section of a ^{12}C projectile on ^{27}Al and ^{12}C targets, as shown in Figs. 2(a) and 2(b), the results of our calculation provide a very reasonable fit and the calculated results considering LM formula at $\rho=\rho_0$ underestimate the experimental values. For the $^{12}C+^{12}C$ system in Fig. 2(b), all the three calculated results underestimate the experimental values at intermediate energy. The calculations for other systems also show that the present formula at $\rho=\rho_0$ underestimates the experimental total reaction cross section at incident energy around several hundreds MeV/nucleon. The reason, maybe, is that the reaction mechanism is very complicated at this energy range. It is difficult to use the Glauber model to estimate the role of mean field, the Pauli blocking effect, and the nucleon-nucleon interaction simultaneously. Using some dynamical models, which incorporate these effects simultaneously, like BUU or QMD can solve this problem [9].

Figures 3(a) and 3(b) give the nuclear reaction cross sections of radioactive nuclear beam Be and Li isotopes at 790 MeV/nucleon on ^{12}C target. Present calculation with Eq. (2) reproduces experimental results fairly well and improves a lot comparing to the free-space nucleon-nucleon cross section. The large increase of σ_R for ^{11}Be and ^{14}Be stems from the small separation energy of outside neutrons from the core. In the case of Li isotopes, σ_R varies smoothly with mass until ^{9}Li. There is a rapid increase in σ_R between ^{9}Li and ^{11}Li. Present calculation can reproduce this trend reasonably. But there are still some deviations between calculation results and experimental results like ^{6}Li, ^{7}Li, and ^{7}Be because of similar reason for ^{12}C on ^{12}C at several hundreds MeV/nucleon.

The value of χ^2 is calculated as follows:

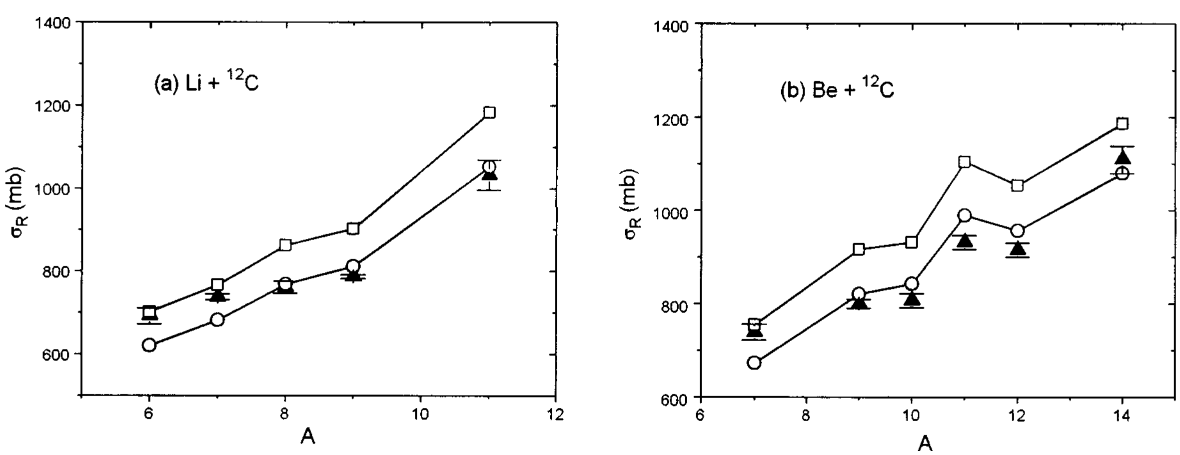

FIG. 3. Total reaction cross section of Li [Fig. 3(a)] and Be [Fig. 3(b)] isotopes on a ^{12}C target at bombard energy 790 MeV/A. Triangles show experimental values. Solid line connecting boxes shows results with free nucleon-nucleon cross sections. Present work is marked as solid line connecting circles.

$$\chi^2 = \sum_n \frac{(\sigma_{\mathrm{exp}} - \sigma_{\mathrm{cal}})^2}{\sigma_{\mathrm{exp}}^2}, \tag{7}$$

where σ_{exp} is the experimental data of the total nuclear reaction cross section and σ_{cal} is the calculated values of the Glauber model. The χ^2 is 0.035 for the present calculation and 0.17 for the case without introducing the medium effect. It indicates that the calculations with this analytic formula can reproduce the experimental values better than others.

Besides the above reaction systems, the total reaction cross sections of the other forty reaction partners induced by the stable nuclei or the exotic nuclei were also calculated in this work. The total χ^2 is 0.91 and 1.54, respectively, in the case of Eq. (2) and the case without the medium effect.

In summary, a new analytic formula is proposed to calculate the in-medium nucleon-nucleon cross section over a wide energy range. This formula describes the effect of nuclear density and incident energy on nucleon-nucleon cross section. The nucleon-nucleon cross section in nuclear medium is predicted to decrease with increasing density. The energy dependence is sensitive at low energies and becomes smaller at higher energies gradually. Introducing the present formula into the Coulomb-modified Glauber model, systematic calculations of nuclear reaction cross section for both stable and exotic nuclei induced reactions are presented and a good agreement has been obtained with experimental values. Actually, lots of important physical quantities, e.g., transverse collective flow, the rotational flow, their disappearance energy (balance energy), and π-meson production cross section, etc., are sensitive to the in-medium nucleon-nucleon cross section. The work to involve the nuclear matter density dependence and interactive energy dependence of in-medium nucleon-nucleon cross section into the transport model such as BUU will be considered. A first try will be the calculation of system mass dependence of balance energy by introducing this in-medium nucleon-nucleon cross section into BUU.

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