Total Reaction Cross Section for $^{12}C+^{12}C$ with Glauber Model Using Finite Range Formalism

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In order to understand the halo-structure of unstable nuclei, it is important to develop a theoretical method of analyzing reaction cross sections of neutron-rich nuclei. In 1985, a simple relation between the radii of light nuclei and the reaction cross section was suggested by Tanihata *et al.*[1]. Since then, many studies have been done. Kox *et al.*[2] showed that a good result can be obtained with the microscopic formalism of Karol[3]. This model has its base in the scattering theory of Glauber[4]. Ogawa *et al.*[5] made a careful analysis of the case of ^{11}Li. They used the Glauber model and the finite range formalism for nucleon-nucleon interaction. The fit between theory and experimental data was good over a wide energy range. Recently, the experimental cross sections for 24 nuclei were compared with Glauber model calculation by Ozawa *et al.*[6]. Their calculations were done with the zero range approximation for nucleon-nucleon interaction and the optical limit approximation for phase shift. Further, they included a correction for the coulomb force. The fit between theory and experimental data was not good at the lower energy. In order to get more information from the cross section measurements, it is important that a simple model is demonstrated to provide the energy dependence of cross sections.

Our purpose in this study is to investigate a model which is able to describe the energy dependence of cross sections for collisions of stable nuclei in the wide energy range. For this study, we take the Glauber theory with the finite range effect.

In general, the total reaction cross section can be calculated from Glauber theory in the following expression,

$$\sigma_R = \int \left(1 - \left|e^{i\chi_{PT}(\boldsymbol{b})}\right|^2\right) d\boldsymbol{b}, \tag{1}$$

where $\chi_{PT}(\boldsymbol{b})$ is the phase shift function from scattering theory.

Now, we want to consider the model including the effect of the finite range in the nucleon-nucleon interaction. In the optical limit, $\chi_{PT}(\boldsymbol{b})$ describes the scattering of the projectile and target and is given by

$$i\chi_{PT}(\boldsymbol{b}) = \int d\boldsymbol{s} \int d\boldsymbol{t} \sum_{ik} \rho^z_{P_i}(\boldsymbol{s})\rho^z_{T_k}(\boldsymbol{t})\Gamma_{ik}(\boldsymbol{b}+\boldsymbol{s}-\boldsymbol{t}) \tag{2}$$

where Γ_{ik} is the form factor and the thickness function of the projectile. $\rho^z_{P_i}(\boldsymbol{s})$ is written as,

$$\rho^z_{Pi}(\boldsymbol{s}) = \int_{-\infty}^{\infty} \rho_{Pi}\left(\sqrt{\boldsymbol{s}^2+z^2}\right) dz, \tag{3}$$

and similar one for target nucleus. The summation is made over the four nucleon contributions; pp, pn, np and nn. The form factor of the finite range formalism is usually parameterized in the form[5],

$$\Gamma_{ik}(\boldsymbol{b}) = \frac{1-i\alpha}{4\pi\beta^2_{ik}}\sigma_{ik}\mathrm{exp}\left(-\frac{\boldsymbol{b}^2}{2\beta^2_{ik}}\right), \tag{4}$$

where σ_{ik} is the total cross section of the nucleon-nucleon collision. In the optical limit, α disappears in the calculation of σ_R. β is real parameter.

A simple correction for the effect of coulomb force between the projectile and target was proposed by Kox *et al.*[2]. This correlation is based on the fact that at low energy the projectile trajectory is modified by the coulomb force between the projectile and the target. The corrected σ_R is expressed as follows:

$$\sigma_R^{corrected} = \left(1 - \frac{B_c}{E_{cm}}\right) \sigma_R^{uncorrected}, \tag{5}$$

where B_c is the coulomb barrier given by

$$B_c = \frac{Z_t Z_p e^2}{4\pi\epsilon_0 \left(A_t^{1/3} + A_p^{1/3}\right) r_c}, \tag{6}$$

and E_{cm} is the total center-of-mass energy.

The input data needed for the calculation of the reaction cross section are density distributions for nucleon of projectile and target, the total cross section of nucleon-nucleon collisions and the value of β parameter.

One difficult problem is to find values of the β parameter in (4). Ray[7] published values of β_{pp} and β_{pn}. In the literature β values for lower energies are not found. In ref.[5], these values had big uncertainties. There may be several ways to get β values, for possible examples, to use the phase shift function given from the nucleon-nucleon potential[4], to use published values of T_{NN} matrix elements of nucleon-nucleon scattering[8], or the *de Broghie* wavelength of projectile particle.

We calculate the total cross section for ^{12}C+^{12}C collision by using.(1)-(6). The densities of ^{12}C are constructed from the simplest harmonic-oscillator shell model. The free total cross sections are given by experimental data as $\sigma_{pp} = \sigma_{nn}$ and $\sigma_{pn} = \sigma_{np}$. As for the range parameter β, we take values by fitting a simple function to the existing data on β[7].

We show the numerical result of the total cross section calculated by Glauber model using finite range formalism in Fig.1. We also show the result of the zero range approximation for comparison. This approximation can be obtained by replacing Gaussian function by the delta function in (4).

At high energy, we see that the agreement is perfect and the results agree with those of ref.[5]. At low energy, however, our calculations are not satisfactory.

The fit between experimental data and calculated values in our studies is not sufficient. However, we can make a number of conclusions for this result. First of all, it seems that the finite range formalism is quite important method in the calculation of cross section. Secondly, at lower energies it is important to include corrections of the effect of coulomb force. Third, although we have used uncertain values in this study, we need more careful treatments of β-parameter in the nucleon-nucleon form factor. In order to solve this problem, it is necessary that those values are found experimentally.

Furthermore, if this model is applied to unstable nuclei with the halo-structure, it is necessary not only to take the optical limit approximation but also to include higher order contributions [5].

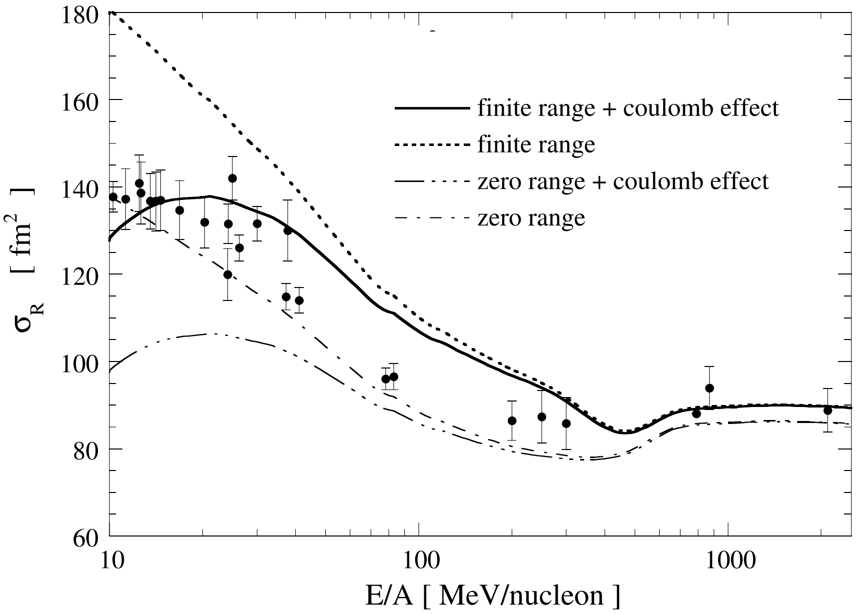

Figure 1: The total reaction cross section for $^{12}C+^{12}C$ collision. Black dotes with error bars are experimental data taken from ref.[9]-[12]

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