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LETTER TO THE EDITOR

Modified Glauber-model description for $^{12}C + ^{12}C$ elastic scattering

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Abstract. A nuclear-modified Glauber model for heavy-ion elastic scattering is presented by taking into account the deflection effect of the trajectory due to the real nuclear potential in addition to the Coulomb potential in the Coulomb-modified Glauber model. It has been applied satisfactorily to elastic scatterings of the system $^{12}C + ^{12}C$ at $E_{lab} = 1016$ and 1449 MeV.

In recent years much theoretical effort has been invested in describing elastic and inelastic scattering processes between heavy ions within the framework of the optical limit to the Glauber model [1–7]. In the simple Glauber approach to heavy-ion elastic scattering [1, 2], it is assumed that the flux attenuation of the elastic channel occurs by means of nucleon–nucleon collisions along a classical straight line trajectory. The standard form of the Glauber model was modified to account for the Coulomb distortion of the trajectory occuring in the case of heavy-ion scattering [3–6]. In a previous paper [8], we have presented a semiclassical phase-shift analysis of the elastic scattering data for $E_{lab} = 1503$ MeV ^{16}O beams on ^{40}Ca and ^{90}Zr nuclei [9] based on the Coulomb-modified Glauber model. However, the Coulomb-modified Glauber model neglects the deflection in the orbit of heavy ions due to the real nuclear potential. In this paper we present a nuclear-modified Glauber model to take into account the deflection effect of the trajectory due to the real nuclear potential, in addition to the Coulomb effect in the usual modified Glauber model.

In the Glauber optical limit, the nuclear **S**-matrix S_l^N is expressed as [1]

$$S_l^N = \exp\left[\frac{2\pi i}{K_{NN}} \Omega_l f_{NN}(0)\right] \tag{1}$$

where the scattering amplitude $f_{NN}(0)$ for nucleon–nucleon scattering is related to the average nucleon–nucleon total cross section σ_{NN} through

$$f_{NN}(0) = \frac{k_{NN}}{4\pi} \sigma_{NN}(\alpha_{NN} + i) \tag{2}$$

where α_{NN} is the ratio of real-to-imaginary parts of the forward nucleon–nucleon scattering amplitude. Ω_l is the overlap integral of the nuclear densities along a straight line characterized by the impact parameter $b = (l + \frac{1}{2})/k$. Usually, a Gaussian distribution of the nuclear density [1, 3] is commonly used in order to evaluate the overlap integral. In the Coulomb-modified Glauber model, the impact parameter b is replaced by the distance of closest approach d_0

$$d_0 = \frac{1}{k}\{\eta + [\eta^2 + (l+\tfrac{1}{2})^2]^{1/2}\} \tag{3}$$

where η is the Sommerfeld parameter.

Equation (3) assumes point charges interacting via the Coulomb field alone. It therefore does not include the deflection in the trajectory of the heavy ion due to the real nuclear potential. As is shown by Wong and Low [10], the deflection effects due to the Coulomb and the real nuclear potentials can be included in the manner of Brink and Satchler [11]. If the real part of the total potential is written as

$$\mathrm{Re}[V(r)] = \frac{Z_1 Z_2 e^2}{r} - \frac{V_0}{1+\mathrm{e}^{(r-R)/a}} + \frac{(l+\frac{1}{2})^2\hbar^2}{2\mu r^2} \tag{4}$$

then the closest approch d_0 can be replaced by d [10, 12]

$$d = d_0 - \left\{\frac{\mathrm{Re}[V_n(d_0)]}{\mathrm{Re}[V'(d_0)]}\right\} \tag{5}$$

where $R = r_0(A_1^{1/3} + A_2^{1/3})$, the prime denoting the first derivative of the potential and $V_n(d_0)$ the real part of the nuclear potential at $r = d_0$. The elastic scattering amplitude for spin-zero particles via Coulomb and short-range central forces

$$f(\theta) = f_\mathrm{R}(\theta) + \frac{1}{\mathrm{i}k}\sum_{l=0}^{\infty}(l+\tfrac{1}{2})\exp(2\mathrm{i}\sigma_l)(S_l^\mathrm{N} - 1)P_l(\cos\theta) \tag{6}$$

can then be used to calculate the differential cross sections. In equation (6), $f_\mathrm{R}(\theta)$ is the usual Rutherford scattering amplitude and σ_l is the Coulomb phase shift.

We have applied the nuclear-modified Glauber model formalism to the elastic scatterings of $^{12}\mathrm{C} + {}^{12}\mathrm{C}$ at $E_\mathrm{lab} = 1016$ and 1449 MeV. Table 1 shows the input values in the Coulomb-modified Glauber model and in the nuclear-modified Glauber model to calculate the differential cross sections. In figures 1(a) and (b), the broken curves represent the cross sections obtained from the Coulomb-modified Glauber optical limit (equations (1)–(3) and (6)) and the full curves denote the results from our nuclear-modified Glauber optical limit (equations (1)–(2) and (4)–(6)). It is seen that the agreement of the nuclear-modified Glauber model results with the experimental values is remarkably good for $^{12}\mathrm{C} + {}^{12}\mathrm{C}$ at $E_\mathrm{lab} = 1016$ MeV and slightly good for $^{12}\mathrm{C} + {}^{12}\mathrm{C}$ at $E_\mathrm{lab} = 1449$ MeV compared to the Coulomb-modified Glauber model. We can see in table 1 that values of χ^2/N apparently decrease in the nuclear-modified Glauber model compared with the results in the Coulomb-modified Glauber model.

Table 1. Input values of the Coulomb-modified Glauber model (CGM) and nuclear-modified Glauber model (NGM) for $^{12}\mathrm{C} + {}^{12}\mathrm{C}$. We have used a Gaussian form for the nuclear densities [1] with R_RMS (^{12}C) = 2.442 fm. The average nucleon–nucleon total cross sections σ_NN were obtained from equations (22) and (23) by Charagi *et al* [5] rather than experimental values

E_lab (MeV)	σ_NN (mb)	α_NN	V_0 (MeV)	r_0 (fm)	a (fm)	CGM χ^2/N	NGM χ^2/N
1016	60.636	0.917	28.5	1.26	0.27	35.0	23.1
1449	42.839	0.748	24.7	1.30	0.12	53.7	49.5

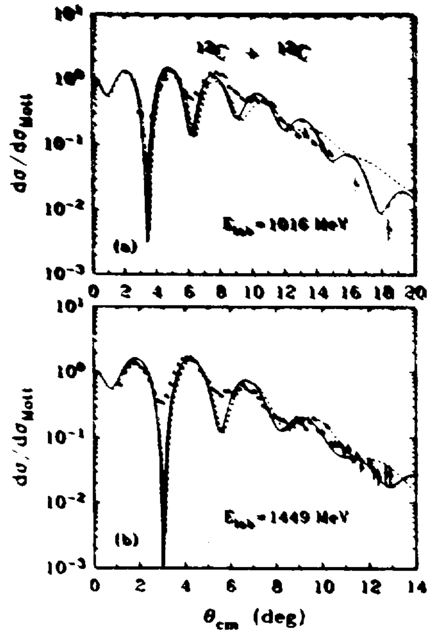

Figure 1. Elastic scattering angular distributions for the $^{12}C + ^{12}C$ system at (a) $E_{lab} = 1016$ and (b) 1449 MeV. The solid circles denote the observed data taken from Hostachy *et al* [13]. Full and broken curves are the calculated results from the nuclear-modified Glauber model and the Coulomb-modified Glauber model, respectively.

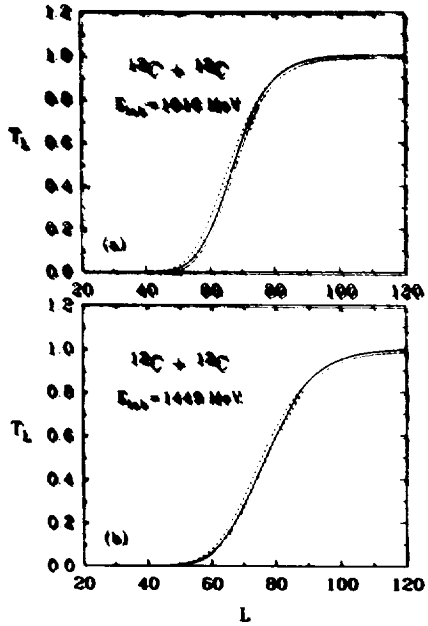

Figure 2. Transparency functions for the $^{12}C + ^{12}C$ system at (a) $E_{lab} = 1016$ and (b) 1449 MeV plotted against the orbital angular momentum. Full and broken curves are the calculated results from the nuclear-modified Glauber model and the Coulomb-modified Glauber model, respectively.

In figure 2, we plot a curve of the transparency function $T_l = |S_l|^2$ for the scattering of $^{12}C + ^{12}C$ at $E_{lab} = 1016$ and 1449 MeV. It can be seen that our extended formula raises the value of the orbital angular momentum for a given transparency function compared to one for the Coulomb-modified Glauber model. As seen in table 2, such a movement is reflected in the values obtained for the reaction cross sections. In this table $l_{1/2}$ is the critical angular momentum corresponding to the strong absorption radius $r_{1/2}$, for which $T(d = r_{1/2}) = \frac{1}{2}$. We can notice that the strong absorption radius gives a good measure of the reaction cross section in terms of $\sigma_R^{1/2} = \pi r_{1/2}^2$.

In this letter, we have presented a nuclear-modified Glauber model for heavy-ion

Table 2. Total reaction cross sections (σ_R obtained from the transparency function and $\sigma_R^{1/2} = \pi r_{1/2}^2$ from the strong absorption radius) of the Coulomb-modified Glauber model, nuclear-modified Glauber model and optical-model analysis (OM). Also given in parentheses is the critical angular momentum $l_{1/2}$. The optical-model nucleus–nucleus σ_R for $E_{lab} = 1016$ and 1449 MeV were obtained from Buenerd *et al* [14] and Hostachy *et al* [13], respectively.

	σ_R(mb)			$\sigma_R^{1/2}$(mb)	
E_{lab}(MeV)	CGM	NGM	OM	CGM	NGM
1016	1014	1042	$1000 \pm ^{50}_{250}$	970 (66)	1029 (68)
1449	933	954	907 ± 50	896 (76)	919 (77)

elastic scattering to take into account the deflection effect in the trajectory due to the real nuclear potential, in addition to the Coulomb effect in the Coulomb-modified Glauber model. It has been applied satisfactorily to the elastic scattering of the $^{12}C + ^{12}C$ system at $E_{lab} = 1016$ and 1449 MeV by using the nuclear-modified Glauber model.

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