Parameterfree account of quasielastic scattering of stable and radioactive nuclei

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Elastic and inelastic scattering cross sections of the system $^{12}C+^{12}C$ at several bombarding energies are calculated within a parameterfree model using the recently developed nonlocal energy-independent bare potential. Comparison with the data indicates that such a calculation gives accurately the average values of the cross sections. The system $^{12}C+^{11}Li$ is also discussed. [S0556-2813(98)01407-1]

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Recently, we have proposed an energy and density independent real bare interaction for the description of heavy ion scattering [1,2]. In Ref. [2], we subjected our potential (coined the NLM3Y potential) to a stringent test by confronting it with elastic scattering data of a wide range of systems and energies. The imaginary part of the potential was taken to be a Woods-Saxon one with three adjustable parameters (in fact the diffuseness was taken to be fixed with respect to energy). The good agreement with the data, especially in the refractive region, convinced us that the NLM3Y interaction captures the essentials of the physics. The purpose of this work is to develop a parameterfree model by using for the absorptive part a $t\rho_1\rho_2$-inspired form. The energy dependence of such an interaction is then completely determined by that of the effective nucleon-nucleon total cross section [3]. We calculate both the elastic and inelastic cross sections for the $^{12}C+^{12}C$ at several energies where data are available. We also compare our theory with the elastic scattering of the halo nucleus ^{11}Li off ^{12}C. There are no free parameters in our calculation. The NLM3Y interaction is given by

$$V(\vec{r},\vec{r}')=V_{\rm DF}\left(\frac{r+r'}{2}\right)\frac{1}{\pi^{3/2}b^3}\exp\left[-\frac{|\vec{r}+\vec{r}'|^2}{b^2}\right], \quad (1)$$

where $V_{\rm DF}(r)$ is the local energy- and density-independent (aside from the folding of the two densities) double folding potential and $b=0.85/\mu$ fm with μ being the reduced mass of the two colliding nuclei.

We have shown in Ref. [2] that the energy-dependent local equivalent potential of Eq. (1) is, to a very good approximation, given by

$$V_{\rm LE}(r;E)=\frac{1-\sqrt{1-4\gamma V_{\rm DF}(r)\exp\{-\gamma[E-V_c(r)]\}}}{2\gamma}, \quad (2)$$

where $\gamma=\mu b^2/2\hbar^2$ and $V_c(r)$ is the double folding Coulomb interaction. As for the imaginary part we employ here the Lax interaction

$$W(r,E)=-\frac{E}{k_N}\sigma_T^{NN}(E)\int dr'\,\rho_A(|\vec{r}-\vec{r}'|)\rho_B(|\vec{r}'|), \quad (3)$$

where $\rho_T^{NN}(E)$ is the average nucleon-nucleon total cross section with Pauli blocking [3].

We have solved the optical differential equation using Eq. (2) as the bare real interaction and W of Eq. (3) as the energy-dependent imaginary potential. The model and the method of solution are fully discussed in Ref. [2]. The systems we chose to discuss the model are $^{12}C+^{12}C$ at several bombarding energies and $^{11}Li+^{12}C$ at $E_{\rm lab}=637$ MeV. The value of $\sigma_T^{NN}(E)$ were taken from Ref. [4] and realistic densities were used in the double folding calculation. In the evaluation of the cross section for the inelastic transition $^{12}C+^{12}C\rightarrow{}^{12}C(E_{2+}=4.4\ \text{MeV})+^{12}C$ we used the distorted wave Born approximation (DWBA) with an appropriate collective form factor having the form

$$F(r)=\delta\left(\frac{dU}{dr}+i\frac{dW}{dr}\right), \quad (4)$$

with $\delta=\beta R_0$, $R_0=1.2A^{1/3}$, and $\beta=0.6$ [4].

The potentials U and W are the same as those of Eqs. (2) and (3). We ignore Coulomb excitation since the system is light and the bombarding energy is high. In Fig. 1 we show our result both for the elastic [Fig. 1(a)] and inelastic [Fig. 1(b)] cross sections for the $^{12}C+^{12}C$ system. The data points were taken from Ref. [4].

Although the calculated cross section shows stronger oscillatory behavior, the magnitude, however, is in good agreement with the data. We consider this a very positive aspect of our parameterfree model. Clearly, space is available for improvement since what is at stake is not so much the energy dependence, which we believe to be well accounted for, but the geometry of the imaginary part.

In Table I we present a comparison of the calculated total reaction cross sections and the ones obtained directly or indirectly from the data. The agreement is excellent.

We consider next the scattering of a typical halo nucleus ^{11}Li. A measurement of the differential, inclusive, quasielastic cross section for $^{11}Li+^{12}C$ at $E_{\rm lab}=637$ MeV has already been reported [5]. Several attempts to account for the data were made [6,7]. Here our aim is not so much to get a better fit to the data, but rather to test the parameterfree NLM3Y interaction.

In the case of the scattering of ^{11}Li we have learned in the last few years that two competing effects come into play due to the extended size of the system: the enhanced probability for the breakup into $^{9}Li+2n$ (due to the very small separation energy of the $2n$) and the longer tail in the attractive bare potential due to the halo. The first effect brings in a

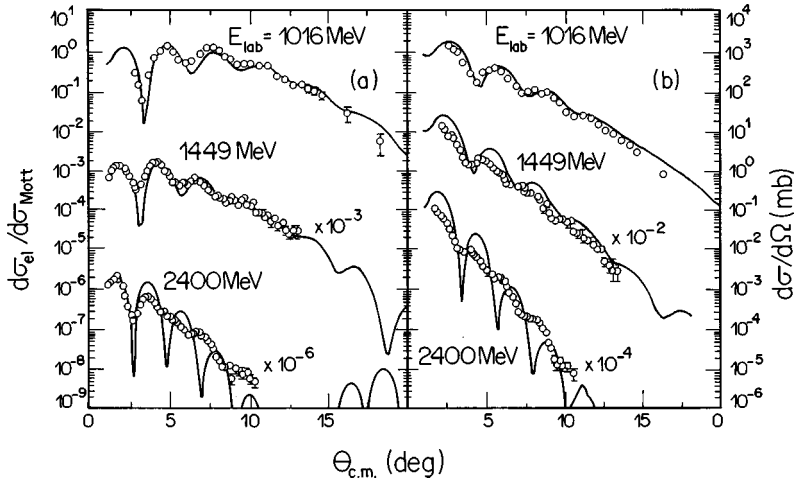

FIG. 1. Elastic (a) and inelastic (b) differential cross sections for the $^{12}C+^{12}C$ system. The data points are from Ref. [4] and also from Ref. [11].

long-range absorption to be added to W while the second adds to refraction. There is a third effect which is inherent in our NLM3Y interaction and that is the nonlocality range b.

On general ground and from the arguments given in Ref. [8], a slightly different (smaller) value of b is expected for the halo nucleus-stable nucleus NLM3Y interaction. To be precise, the value of b adapted for our analysis of the stable projectile-stable target NLM3Y interaction, namely, $b=0.85/\mu$ fm, is in fact obtained by Jackson and Johnson in the limit of an infinite size projectile or target (zero binding energy). This is not so bad an approximation, since relaxing this approximation by using Gaussian form for the density of the projectile or target, gives rise to a reduction in b by [8]

$$b\rightarrow\overline{b}=b\left[1+\left(\frac{0.85}{2R}\right)^2\right]^{-1/2}. \tag{5}$$

Thus the larger R is, the closer b would be to the value used above, $0.85/\mu$ fm.

Another, potentially important, consequence of the finite size of the nucleus is a reduction factor that multiplies the double folding potential, viz.

$$U_{\rm DF}\rightarrow\overline{U}_{\rm DF}=\left(\frac{\overline{b}}{b}\right)^3 U_{\rm DF}=\left[1+\left(\frac{0.85}{2R}\right)^2\right]^{-3/2} U_{\rm DF}. \tag{6}$$

The effects represented by Eqs. (5) and (6), are appreciable in the case of tightly bound (small) nuclei such as α particles. Thus, at most, the smaller value of $\overline{b}$ and the reduced strength of the double folding potential for halo nuclei result in few percent effects. This, coupled with the need to take into account the breakup channel, suggests the use of a model for elastic scattering following the line of Ref. [9], which uses the adiabatic approximation and takes into account the breakup effects to all orders, viz.,

$$\frac{d\sigma}{d\Omega}=|F(Q)|^2\frac{d\sigma_{\rm core}}{d\Omega}, \tag{7}$$

where $d\sigma_{\rm core}/d\Omega$ is the core (^{9}Li) $+^{11}$C elastic scattering differential cross section, while $F(Q)$ is the form factor related to the ground state wave function of ^{11}Li. This form factor has a value of unity at $Q=0$ and drops gradually with increasing Q, thus simulating the effect of breakup coupling. At the small angles (Q) involved in the measurement of Ref. [5] we set for the time being $F(Q)=1$. With this we are approximating the combined effect of smaller $\overline{b}$ and breakup damping by considering the ^{11}Li$+^{12}$C cross section, to be roughly the ^{9}Li$+^{12}$C cross section. In the following we give a description of our calculation for the system ^{11}Li$+^{12}$C.

Although a slightly different W from Eq. (3) should be used, owing to the loosely bound two neutrons halo, we have simply employed Eq. (3) for the imaginary part. We calculated the elastic and inelastic cross section for the 2^+ and 3^- states in ^{12}C. The result of the calculation is shown in Fig. 2, together with the data of Kolata *et al.* [5]. The summed cross section comes a bit short of accounting for the data in the

TABLE I. Calculated and experimental reaction cross sections of the $^{12}C+^{12}C$ system.

$E_{\rm lab}$ (MeV)	$\sigma_{\rm theory}$ (mb)	$\sigma_{\rm experimental}$ (mb)	$\sigma_{\rm inelastic}$ (mb)
1016	958	960±25 [a]	29
1449	886	907±50 [b]	24
2400	825	860±50 [a]	15

[a]Data taken from Refs. [12,13].

[b]Data taken from Ref. [4].

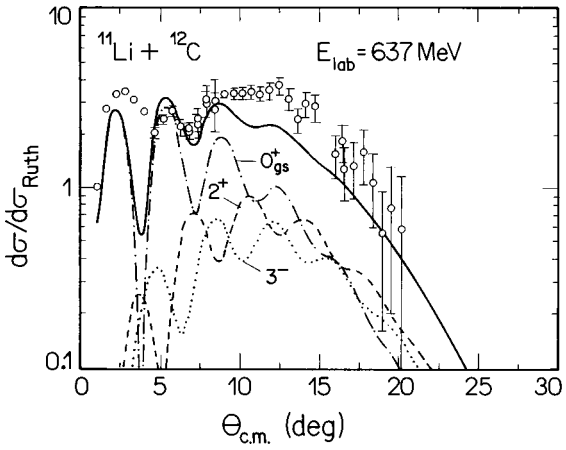

FIG. 2. The calculated summed quasielastic cross section for ^{11}Li$+^{12}$C at $E_{\rm lab}=637$ MeV (see text for details). The data points are from Ref. [5].

angular region $10° < \theta < 15°$ and also in the region around $\theta = 4°$. This latter region is also missed by most other calculations reported in the literature [6]. The total reaction cross section comes out to be $\sigma_R = 1.41$ b, in good agreement with the deduced one [5]. This result is very similar to the one obtained by Khoa, Satchler, and von Oertzen [6] where a three-parameter Woods-Saxon imaginary potential was employed. We stress here that we do not have in our model any adjustable parameter. We consider our result reasonable and certainly there is room for improvement such as considering higher-order terms in the multiple scattering theory-inspired form for W. It is also quite possible that other inelastic cross-sections may have to be added, such as the transition to the ''3α'' 0^+ state at $E^* = 7.68$ MeV [10].

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