A Systematic Investigation of Light Heavy-Ion Reactions
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Abstract
We introduce a novel coupling potential for the scattering of deformed light heavy-ion reactions. This new approach is based on replacing the usual first-derivative coupling potential by a new, second derivative coupling potential in the coupled-channels formalism. The new approach has been successfully applied to the study of the $^{12}\text{C}+^{12}\text{C}$, $^{12}\text{C}+^{24}\text{Mg}$, $^{16}\text{O}+^{28}\text{Si}$ and $^{16}\text{O}+^{24}\text{Mg}$ systems and made major improvements over all the previous coupled-channels calculations for these systems. This paper also shows the limitations of the standard coupled-channels theory and presents a global solution to the problems faced in the previous theoretical accounts of these reactions.

1 Introduction
We investigate the elastic and inelastic scattering of light heavy-ions, which have stimulated a great deal of interest over the last 40 years. There has been extensive experimental effort to measure the elastic and inelastic scattering data as well as their $90^\circ$ and $180^\circ$ excitation functions. A large body of experimental data for these systems is available (see [1, 2, 3, 4] and references therein). A variety of theoretical accounts based on dynamical models or purely phenomenological treatments have been proposed to explain these data [4, 5]. The elastic scattering data have already been studied in detail using optical model and coupled-channels method.

Although most of these models provide reasonably good fits, no unique model has been proposed that explains consistently the elastic and inelastic scattering data over a wide energy range without applying any ad hoc approaches. Consequently, the following problems continue to exist for light heavy-ion reactions: (1) explanation of anomalous large angle scattering data, ‘ALAS’; (2) reproduction of the oscillatory structure near the Coulomb barrier; (3) the lack of the correct oscillatory structure between theoretical predictions and experimental data for the ground and excited states; (4) simultaneous fits of the individual angular distributions, resonances and excitation functions (for the $^{12}\text{C}+^{12}\text{C}$ system in particular); (5) the magnitude of the mutual-2$^+$ excited state data in the $^{12}\text{C}+^{12}\text{C}$ system is unaccounted for; (6) the deformation parameters ($\beta$ values): previous calculations require $\beta$ values that are at variance with the empirical values and are physically unjustifiable.

Therefore, in this paper, we are concerned with the measured experimental data for $^{12}\text{C}+^{12}\text{C}$, $^{16}\text{O}+^{28}\text{Si}$, $^{12}\text{C}+^{24}\text{Mg}$ and $^{16}\text{O}+^{24}\text{Mg}$ in an attempt to find a global model, which simultaneously fits the elastic and inelastic scattering data for the

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ground and excited states in a consistent way over a wide energy range, and which throws light on the underlying mechanism of the reactions and on the nature of the interactions involved.

2 Standard Coupled-Channels Model

Although we have considered and studied four different reactions, we will show some of the results for the $^{16}\text{O}+^{28}\text{Si}$ and $^{12}\text{C}+^{12}\text{C}$ reactions. The details of the models and a complete set of the results for all reactions can be found in references [3, 7, 10, 8].

We describe the interaction between $^{16}\text{O}$ and $^{28}\text{Si}$ nuclei with a deformed optical potential. The real potential is assumed to have the square of a Woods-Saxon shape:

$$V_N(r) = \frac{-V_0}{(1 + \exp(r - R)/a)^2}$$

with $V_0=706.5$ MeV, $R=r_0(A_p^{1/3}+A_t^{1/3})$ with $r_0=0.7490$ fm and $a=1.40$ fm. The parameters of the real potential were fixed as a function of energy and were not changed in the present calculations although it was observed that small changes could improve the quality of the fits.

The imaginary part of the potential was taken as in ref.[4] as the sum of a Woods-Saxon volume and surface potential:

$$W(r) = -W_V f_{(r,R_v,a_v)} + 4W_S a_S df_{(r,R_s,a_s)}/dr$$

$$f_{(r,R,a)} = \frac{1}{(1 + \exp((r - R)/a))}$$

with $W_V=59.9$ MeV, $a_V=0.127$ fm and $W_S=25.0$ MeV, $a_S=0.257$ fm. These parameters were also fixed in the calculations and only their radii increased linearly with energy according to the following formulae.

$$R_V = 0.06084E_{CM} - 0.442$$

$$R_S = 0.2406E_{CM} - 2.191$$

Since the target nucleus $^{28}\text{Si}$ is strongly deformed, it is essential to treat its collective excitation explicitly in the framework of the coupled-channels formalism. It has been assumed that the target nucleus has a static quadrupole deformation, and that its rotation can be described in the framework of the collective rotational model. It is therefore taken into account by deforming the real optical potential in the following way

$$R(\theta, \phi) = r_0 A_p^{1/3} + r_0 A_t^{1/3}[1 + \beta_2 Y_{20}(\theta, \phi)]$$

where $\beta_2=-0.64$ is the deformation parameter of $^{28}\text{Si}$. This value is actually larger than the value calculated from the known BE(2) value. However this larger $\beta_2$ was needed to be able to fit the magnitude for the $2^+$ data.
Figure 1: For $^{16}$O+$^{28}$Si, the comparison of the standard coupling potential which is the first derivative of the central potential and our new coupling potential which is parameterised as the 2nd derivative of Woods-Saxon shape and which has $V=155.0$ MeV, $R=4.160$ fm and $a=0.81$ fm.

In the present calculations, the first two excited states of the target nucleus $^{28}$Si: 2$^+$ (1.78 MeV) and 4$^+$ (4.62 MeV) were included and the 0$^+$-2$^+$-4$^+$ coupling scheme was employed. The reorientation effects for 2$^+$ and 4$^+$ excited states were also included. The calculations were performed with an extensively modified version of the code CHUCK [12].

Using the standard coupled-channels theory, we found, as other authors had found, that it was impossible to describe consistently the elastic and inelastic scattering of this and other reactions we considered.

3 New Coupling Potential

The limitations of the standard coupled-channels theory in the analyses of these reactions compelled us to look for another solution. Therefore, a second-derivative coupling potential, as shown in figure 1, has been used in the place of the usual first-derivative coupling potential. The interpretation of this new coupling potential is given in reference [9]. We employed the same method with small changes in the potential parameters. The empirical deformation parameter ($\beta_2$) is used in these new calculations.
4 Results

4.1 $^{16}\text{O} + ^{28}\text{Si}$

The first system we consider is $^{16}\text{O} + ^{28}\text{Si}$, which shows anomalous large angle scattering (ALAS). In the present work, we consider an extensive simultaneous investigation of the elastic and the inelastic scattering of this system at numerous energies from $E_{\text{Lab}} = 29.0$ MeV to 142.5 MeV over the whole angular range up to $180^\circ$. In this energy range, the excitation functions for the ground and $2^+$ states are also analysed [6, 11].

Several *ad hoc* models have been proposed to explain these data, but no satisfactory microscopic models have been put forward yet. The most satisfactory explanation proposed so far is that of Kobos and Satchler [1] who attempted to fit the elastic scattering data with a microscopic double-folding potential. However, these authors had to use some small additional *ad hoc* potentials to obtain good agreement with the experimental data.

Using the standard coupled-channels method, some of the results obtained for the $180^\circ$ excitation functions for the ground and $2^+$ states of the $^{16}\text{O} + ^{28}\text{Si}$ reaction are shown in figure 2. The magnitude of the cross-sections and the phase of the oscillations for the individual angular distributions are given correctly at most angles. However, there is an out-of-phase problem between the theoretical predictions and the experimental data towards large angles at higher energies. This problem is clearly seen in the $180^\circ$ excitation functions which are shown in the figure. A number of models have been proposed, ranging from isolated resonances to cluster exchange between the projectile and target nucleus to solve these problems (see ref. [1] for a detailed discussion).

We have also attempted to overcome these problems by considering: (i) changes in the real and imaginary potentials, (ii) inclusion of $6^+$ excited state, (iii) changes in the $\beta_2$ value, (iv) the inclusion of the hexadecapole deformation ($\beta_4$). These attempts failed to solve the problems at all [8, 11]. We were unable to get an agreement with the elastic and the $2^+$ inelastic data as well as the $180^\circ$ excitation functions simultaneously within the standard coupled-channels formalism. However, as shown in figure 2, the new coupling potential has solved the out-of-phase problem for the $180^\circ$ excitation functions and fits the ground state and $2^+$ state data simultaneously.

4.2 $^{12}\text{C} + ^{24}\text{Mg}$ and $^{16}\text{O} + ^{24}\text{Mg}$

The second and third examples we have considered are $^{12}\text{C} + ^{24}\text{Mg}$ and $^{16}\text{O} + ^{24}\text{Mg}$. Fifteen complete angular distributions of the elastic scattering of $^{12}\text{C} + ^{24}\text{Mg}$ system were measured at energies around the Coulomb barrier and were published recently [3]. We have studied these fifteen complete elastic scattering angular distributions as well as some inelastic scattering data measured by Carter et al. some twenty years ago [8, 11]. Excellent agreement with the experimental data was
obtained by using this new coupling potential. Our model has also solved some problems in $^{16}$O+$^{24}$Mg scattering [10].

4.3 $^{12}$C+$^{12}$C

The final system we have considered is that of $^{12}$C+$^{12}$C, which has been studied extensively over the last 40 years. There has been so far no model, which fits consistently the elastic, inelastic scattering data and mutual excited state data as well as the resonances and excitation functions. Another problem is the predicted magnitude of the excited state cross-sections, in particular for the mutual-2$^+$ channel. The conventional coupled-channels model underestimates its magnitude by a factor of at least two and often much more [13, 10, 17]. We have also observed this in our conventional coupled-channels calculations as shown in figure 3 with dashed lines. There are also resonances observed at low energies, which have never been fitted by a potential, which also fits either the angular distributions or the excitation functions. Therefore, the experimental data at many energies between 20.0 and 126.7 MeV in the laboratory system have been studied simultaneously to attempt to find a global potential. Using this new coupling potential, we have been able to fit the energy average of all the available ground, single-2$^+$, mutual-2$^+$ and the backgrounds in the integrated cross-sections as well as the main gross features of the 90$^\circ$ excitation function, as shown in figures 3 and 4, simultaneously. Our preliminary calculations of resonances using no imaginary potential are promising but there are problems
Figure 3: $^{12}$C+$^{12}$C system: The integrated cross-section of the single and mutual-2$^+$ states. The solid lines are the results of the new coupling potential, while the dashed lines are the results of standard coupled-channels model.

with the widths of the resonances.

To summarise while these four systems show quite different properties and problems, a unique solution has come from a new coupling potential. Although the origin of this new coupling potential is still speculative and needs to be understood from a microscopic viewpoint, the approach outlined here is universal and applicable to all the systems. Studies using this new coupling potential are likely to lead to new insights into the formalism and the interpretation of these systems. Therefore, this work represents an important step towards understanding the elastic and inelastic scattering of light deformed heavy-ion systems.

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