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A new coupling potential for the analysis of deformed light heavy-ion reactions

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Abstract

A number of serious problems has continued to plague the study of the $^{16}O + ^{28}Si$, $^{12}C + ^{24}Mg$ and $^{12}C + ^{12}C$ systems for the last 40 years. The explanation of anomalous large angle scattering data; the reproduction of the oscillatory structure near the Coulomb barrier; the out-of-phase problem between theoretical predictions and experimental data; the consistent description of angular distributions together with resonance and excitation functions data are just some of these problems. These are long standing problems that have persisted over the years and do represent a challenge calling for a consistent framework to resolve these difficulties within a unified approach. Traditional frameworks have failed to describe these phenomena within a single model and have so far only offered different approaches where these difficulties are investigated separately from one another. The present work offers a plausible framework where all these difficulties are answered. Not only it improves the simultaneous fits to the data of these diverse observables, achieving this within a unified approach for a number of nuclear systems over wide energy ranges, but it departs for its coupling potential from the standard formulation. This new feature could provide new insight in the dynamics of these reactions. It also leads to new predictions especially concerning resonance phenomena in these systems which could form the basis for some new experimental investigation.

1. Introduction

In this Letter, building on a previous paper [1], we introduce a new coupling potential that explains the scattering observables of the $^{16}O + ^{28}Si$, $^{12}C + ^{24}Mg$ and $^{12}C + ^{12}C$ systems over wide energy ranges in a consistent way.

These reactions have been extensively studied both theoretically and experimentally [2–6] and these investigations have resulted in a large body of experimental data and a great number of theoretical models. Although the theoretical models, based on dynamical or purely phenomenological treatments, provide reasonably good fits, no unique model has been proposed that addresses the problems of such reactions in a unified way.

Consequently, the following problems continue to exist for light heavy-ion reactions: (1) explanation of anomalous large angle scattering data; (2) reproduction of the oscillatory structure near the Coulomb barrier; (3) the out-of-phase problem between theoretical predictions and experimental data; (4) simultaneous

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fits of the individual angular distributions, resonances and excitation functions (for the $^{12}C + ^{12}C$ system in particular); (5) the magnitude of the mutual-2^+ excited state data in the $^{12}C + ^{12}C$ system is unaccounted for; (6) the deformation parameters (β values): previous calculations require β values that are at variance with the empirical values and are physically unjustifiable.

In the next section, we introduce the standard and new coupled-channels models. Sections 3–5 are devoted to the application of the new coupling potential to the analyzes of the $^{12}C + ^{12}C$, $^{16}O + ^{28}Si$ and $^{12}C + ^{24}Mg$ reactions. Finally, we conclude in Section 6.

2. The model

The three systems we study ($^{16}O + ^{28}Si$, $^{12}C + ^{24}Mg$ and $^{12}C + ^{12}C$) are quite different in many ways but they share two common features: (1) the elastic scattering data suggest that there is weak absorption in the entrance channel in each case and (2) each reaction involves at least one nucleus which is highly deformed.

2.1. The standard coupled-channels calculations

In the standard coupled-channels calculations, we describe the interaction between two nuclei with a deformed optical potential. For all the reactions considered, the real potential is assumed to have the square of a Woods–Saxon shape. The parameters of the real potential for the $^{16}O + ^{28}Si$ and $^{12}C + ^{24}Mg$ systems are fixed as a function of energy and are not changed in the present calculations. For the $^{12}C + ^{12}C$ system, it is slightly energy-dependent. The parameters are shown in Table 1.

The imaginary part of the potential is the standard Woods–Saxon shape. Only the depth or radius increased linearly with energy.

Since the target nuclei ^{28}Si, ^{24}Mg and ^{12}C are strongly deformed, it is essential to treat their collective excitations explicitly in the framework of the coupled-channels formalism. We assume that the target nuclei have static quadrupole deformations, and that their excitations can be described in the framework of the collective rotational model. The empirical values for the deformation parameters (β), derived from the known $B(E2)$ values, are used in the present calculations.

Using this standard coupled-channels method, we found, as other authors had found, that it was not possible to find a consistent solution over wide energy ranges to the above-mentioned problems (see the discussions of results and figures below).

2.2. New coupling potential

The limitations of the standard coupled-channels method, on the one hand, and the resulting shape of the compound nucleus created by the projectile and target nuclei, on the other hand, have motivated us to use a second-derivative coupling potential. If we consider two ^{12}C nuclei approaching each other, the double-folding model will generate an *oblate* potential which is correct at large distances. When these two nuclei come close enough, they create the compound nucleus ^{24}Mg which is a *prolate* nucleus in its ground state. In the standard method, the folding model yields an oblate (attractive) potential for such a configuration. It is not clear how well the double-folding model de-

Table 1
The parameters of the central and coupling potentials for the reactions studied

	Central			Coupling		
	V	r_0	a	V	r_0	a
$^{16}O + ^{28}Si$	750.5	0.749	1.4	155.0	0.748	0.81
$^{12}C + ^{24}Mg$	427.0	0.865	1.187	185.0	0.710	0.62
$^{12}C + ^{12}C$	~ 290.0	~ 0.8	~ 1.28	210.0	~ 0.67	~ 0.68

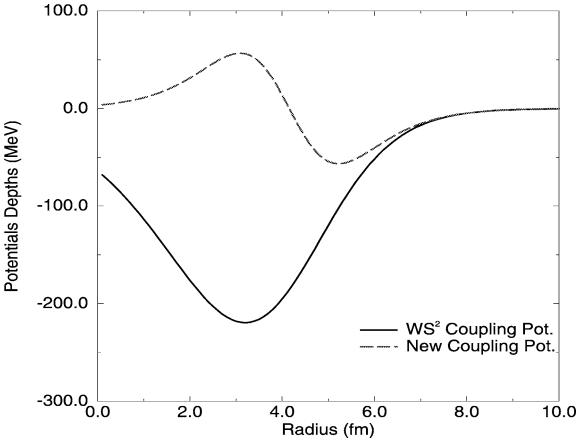

Fig. 1. For $^{16}O + ^{28}Si$, the comparison of the *standard* and *new* coupling potentials, parameterized as the 2nd derivative of Woods–Saxon shape.

scribes a prolate nucleus with this oblate potential and this may be the reason why the earlier calculations using a double-folding model in the coupled-channels method were unable to provide a consistent solution to the problems of such reactions. In order to describe the above-mentioned configuration, the coupling potential must be *oblate* (attractive) when two ^{12}C nuclei are at large distances and must be *prolate* (repulsive) when they are at short distances [1].

The standard and new coupling potentials are compared in Fig. 1. In the new calculations, we employed the same method with the same potentials. The parameters are shown in Table 1. The empirical deformation parameter (β_2) is used in these calculations.

3. $^{12}C + ^{12}C$

The first system we consider is the $^{12}C + ^{12}C$, which has been studied extensively over the last 40 years. Our analysis consists of a *simultaneous* investigation of the elastic scattering, single-2^+ and mutual-2^+ excitation inelastic scattering data from $E_{Lab} = 20.0$ MeV to 126.7 MeV. In such a large energy range, we also consider the 90° elastic and inelastic excitation functions.

The conventional folding model potentials fail to reproduce certain aspects of the data such as the reproduction of the gross structure in the 90° elastic scattering excitation function and a simultaneous consistent description of the elastic, single-2^+ and mutual-2^+ states data. So far, no model has been able to predict the magnitude of the mutual-2^+ state data correctly over a wide energy range. The standard coupled-channels model using double-folding potentials underestimates its magnitude by a factor of 3 to 10 and the single-2^+ state results are too oscillatory with respect to experimental data [4,7–10]. These problems have remained unsolved so far. Clearly, the $^{12}C + ^{12}C$ system has numerous problems to which no consistent global solution has been provided yet.

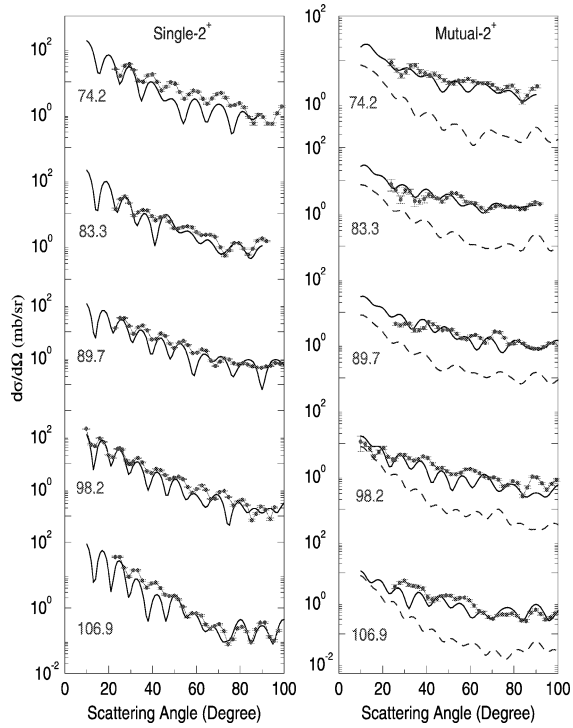

Fig. 2. The $^{12}C + ^{12}C$ system: the results of the single and mutual-2^+ states. The *solid* lines are the results of *the new coupling potential*, while the *dashed* lines are the results of *standard coupled-channels model*.

We have also observed such results in our standard coupled-channels calculations, as shown only for the mutual-2^+ case in Fig. 2 with dashed lines. Varying the parameters and changing the shape of the real and imaginary potentials and some other attempts do not provide a complete solution to the problems of this reaction [1].

Using the new coupling potential, we have been able to obtain excellent agreement with all the available ex-

perimental data for the ground, single-2^+ and mutual-2^+ states as well as the 90° elastic scattering excitation function. This new approach also solves the magnitude problem of the mutual-2^+ excitation inelastic scattering data, which has been outstanding problem of this reaction. Some of the results for the single-2^+ and mutual-2^+ states are shown in Fig. 2 in comparison with the standard ones. All results can be found in Ref. [1].

4. $^{16}O + ^{28}Si$

The second system we consider is $^{16}O + ^{28}Si$, which shows anomalous large angle scattering (ALAS). In the present work, we consider an extensive *simultaneous* investigation of the elastic and inelastic scattering of this system at numerous energies from $E_{Lab} = 29.0$ to 142.5 MeV. In this wide energy range, the excitation functions for the ground and single-2^+ states are also analyzed [11].

Several ad hoc models have been proposed to explain the experimental data, but no satisfactory microscopic models have been put forward yet. The most satisfactory explanation proposed so far is that of Kobos and Satchler [6] who attempted to fit *only* the elastic scattering data with a microscopic double-folding potential. However, these authors had to use some small additional ad hoc potentials, which create a deepening in the surface region of the potential, to obtain a good agreement with the experimental data. Without the additional small potentials, they could not reproduce the experimental data. We have shown that this deepening of the real potential in the surface region takes into account the coupling effect in an ad hoc way [11].

Using the standard coupled-channels method, we obtained a very good agreement with the elastic scattering data. However, for the single-2^+ state data, the theoretical predictions were too oscillatory and in particular, towards large angles at *higher* energies, the out-of-phase problem between the theoretical predictions and the experimental data is observed. This problem is clearly seen in the 180° excitation function results, shown in Fig. 3b. A number of models have been proposed, ranging from isolated resonances to cluster

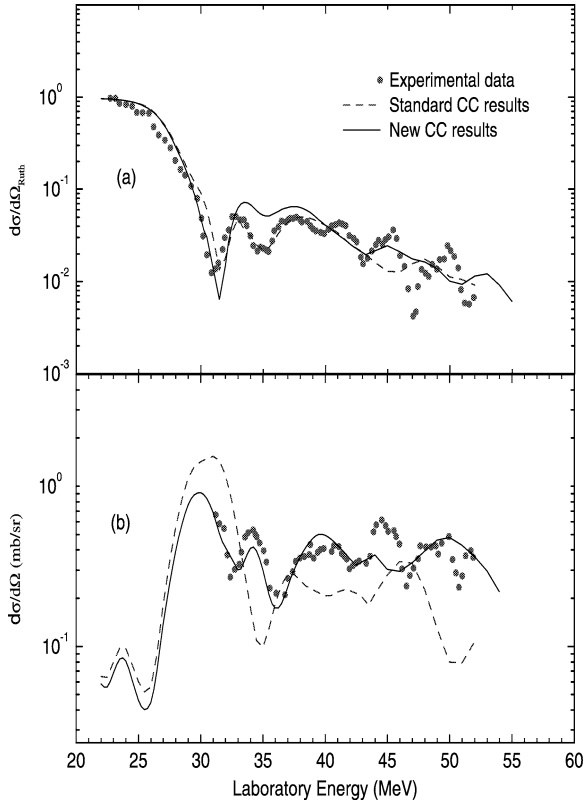

Fig. 3. The $^{16}O + ^{28}Si$ system: 180° excitation function for (a) ground and (b) 2^+ states, respectively. The *dashed* lines are the results of *standard* coupled-channels calculations and *solid* lines are the results obtained using new coupling potential.

exchange between the projectile and target nucleus, to solve these problems (see Ref. [2] 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 β_2 value and some other attempts failed to solve the problems [11]. We were unable to get an agreement with the elastic and the 2^+ inelastic data as well as the 180° excitation functions simultaneously within the standard coupled-channels formalism.

However, as shown in Fig. 3, the new coupling potential has solved the out-of-phase problem for the 180° excitation functions and fits the ground state and 2^+ state data simultaneously. To our knowledge, this has not been achieved over such a wide energy range.

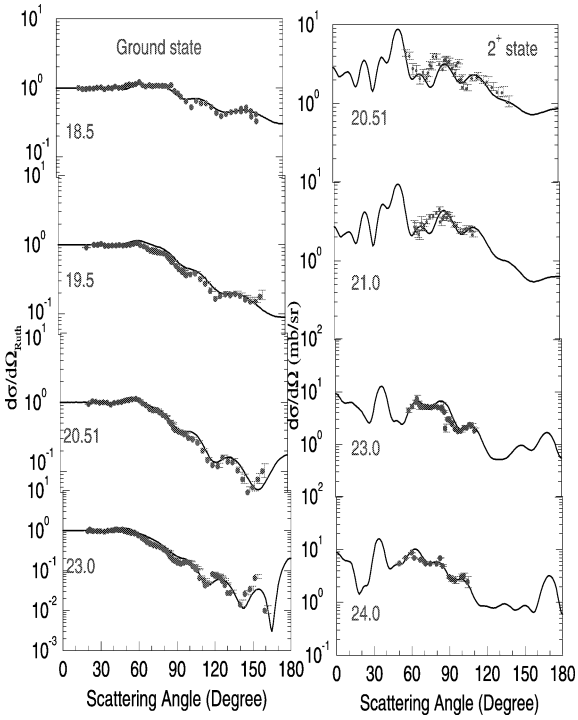

Fig. 4. The $^{12}C + {}^{24}Mg$ system: the ground and 2^+ states results, obtained using the new coupling potential.

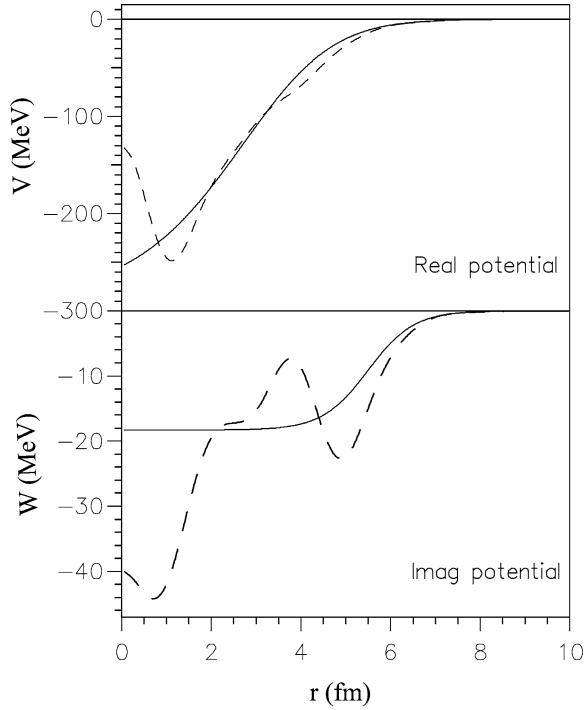

Fig. 5. The comparison of the bare potentials (*solid*) and the total inverted potentials (*dashed* lines), found by inverting S-matrix of the new coupled-channels calculations at $E_{Lab} = 126.7$ MeV for the $^{12}C + {}^{12}C$ system.

5. $^{12}C + {}^{24}Mg$

The final example we consider is the $^{12}C + {}^{24}Mg$ system. The angular distributions oscillate strongly near the Coulomb barrier and the data manifest ALAS. Our analysis consists of a *simultaneous* investigation of the elastic and inelastic scattering data at numerous energies from $E_{Lab} = 16.0$ to 24.0 MeV [12].

The most extensive study for this system was carried out by Sciani et al. [3]. The authors could only fit these data with Q-value dependent potential parameters in a rather ad hoc fashion. Without Q-dependent potentials, they observed that the theoretical predictions and the experimental data for the elastic and inelastic scattering data were completely out-of-phase.

In the present calculations, we have studied the data of Ref. [3] as well as some inelastic scattering data of Ref. [13]. In the standard coupled-channels calculations, we also found the out-of-phase problem which was in conformity with the findings of Sciani et al. However, using our new coupling potential, we obtained excellent agreement with the experimental data. Some of the individual angular distribution fits for the ground and 2^+ states are shown in Fig. 4 (see Ref. [12] for all the results).

6. Discussion and summary

The effect of this new coupling potential on the scattering has been probed through the total inverted potential, i.e., the dynamical polarization potential (DPP) plus the bare potential, obtained by inversion of the S-matrix. It is observed that for the standard coupling potential case, the added attraction is almost the same as the added absorption. On the other hand, for the new coupling potential case, the added attraction is much greater than the added absorption. Therefore, as shown in Fig. 5, the new coupling potential creates a deepening in the surface region

of the real potential, which can be related to the superdeformed structures of the compound nuclei [1].

To summarize, while these three systems show quite different properties and problems, a unique solution has come from a new coupling potential. This is very encouraging. However, it is not possible at present to provide a solid theoretical foundation where this term can be derived from first principles. Further work is needed and any insights that would lead to progress in this direction will be greatly welcome in the future.

Despite this limitation of which we are fully aware, the present work is still useful in that it may offer useful insight in any future theoretical study. The arguments in this Letter form part of a phenomenological study of these nuclear reactions. For such reactions, phenomenological potentials have been used for over 40 years now and continue to be used as they offer a useful contribution towards the understanding of the dynamics governing these systems. In such studies, a variety of form factors have been used ad hoc to explore these reactions. It is only later on that the formal justification of these has been developed. It is only required at first that these form factors do not lead to unrealistic physical effects and follow broadly some basic symmetries and relations (e.g., rotational symmetry). Furthermore, inverse scattering methods such as those developed by Mackintosh et al. (see, for example, the references in [14]) indicate that in most cases the form factors have features that depart markedly from the simple functional forms have been traditionally assumed. It is in this context and spirit that our postulating the use of such a coupling potential is presented. Within this phenomenological framework, the relative success of our approach in improving on the results and more importantly in tackling a variety of problems within the same framework, argues strongly in favor of this phenomenological adoption.

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