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HEAVY-ION REACTIONS AT ENERGIES NEAR THE COULOMB BARRIER*

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1. INTRODUCTION

The title covers a very broad area of both experimental and theoretical studies. The common characteristic of heavy-ion collisions at these energies, compared to what is usually seen at higher energies, is the important interplay between different reaction channels or internal degrees of freedom. The couplings between the various channels can result in important multistep contributions to a given channel. These often have to be treated explicitly, for example by solving the appropriate set of coupled equations. In contrast, at higher energies the effects of these couplings frequently can be represented in a simple, average way, as is done when one introduces an imaginary part to the optical potential for elastic scattering.

At first, it might be thought that the possible importance of multistep transitions would be a strong disadvantage of working at these energies. However, although the analysis of the data becomes more complicated, the study of these terms and their interferences can be a rich source of information. In particular, it can tell us, indirectly, something about transitions between two excited states.

Overviews of some of these phenomena have been presented elsewhere[1,2]; here I have selected two topics as representative. Even then I cannot go into much detail, so perhaps this paper is best regarded as providing some references as the starting point for a literature search!

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2. MULTISTEP EFFECTS IN SOME NUCLEAR REACTIONS

At high energies, when there is a good overlap between the entrance and exit channels, a reaction such as inelastic scattering or nucleon transfer can be described as a one-step process; i.e. it is a direct reaction [3]. The other open channels primarily result in some absorption of the flux, which can be described in an average way by allowing optical and transition potentials to have imaginary parts.

However, these interchannel couplings may become very important as the bombarding energy approaches the top of the Coulomb barrier and the scattering becomes more adiabatic. One aspect of this to which much attention has been paid recently is the so-called "threshold anomaly"[2] observed for elastic scattering and also, in at least one case, for inelastic scattering. (The enhancement of sub-barrier fusion[1,2] is another aspect of the same phenomenon.) Here we can think of the two ions polarizing each other as they approach, and we have been able to make considerable progress with a simple description in terms of the optical model, provided one allows a strong energy dependence for the parameters. An important constraint can be imposed on this energy dependence by invoking a dispersion relation between the real and imaginary parts of the interaction[2,5]. Even here, however, a deeper (or, at least, different!) understanding may be obtained by a coupled-channels analysis[6] which treats the various channels explicitly.

The $^{17}O + ^{208}Pb$ provides an interesting example, in which the 0.87 MeV, $1/2^+$ excited state of the valence neutron in ^{17}O plays an important role[7] (Figs. 1 and 2). Transfer of this neutron to the ^{208}Pb target is greatly facilitated by first exciting it from the $0d_{5/2}$ orbit it occupies in the ground state into the weakly bound $1s_{1/2}$ orbit, which may then provide a better overlap with the final ^{209}Pb orbitals. The strong effects seen (Fig. 1) at the barrier top persist in weakened form at higher energies (Fig. 2), where they are mainly characterized by a shift to smaller angles of the angular distribution peaks for the neutron transfer. Similar shifts have been observed in a number of heavy-ion transfer reactions, both neutron and proton.

Another "anomaly" that has been observed recently in some experiments at São Paulo,[8] occurs in the excitation of the 2_1^+ state of ^{92}Zr by ^{16}O. Figure 3 shows the angular distribution at 56 MeV, with a pronounced Coulomb-nuclear interference pattern that could not be reproduced by using the standard collective model interaction[3]. Even large deviations from the standard model did not provide a satisfactory fit, until a two-step amplitude was introduced by giving the 2^+ state a quadrupole moment and thus allowing it to be reoriented after it had been excited. While the direct (one-step) nuclear

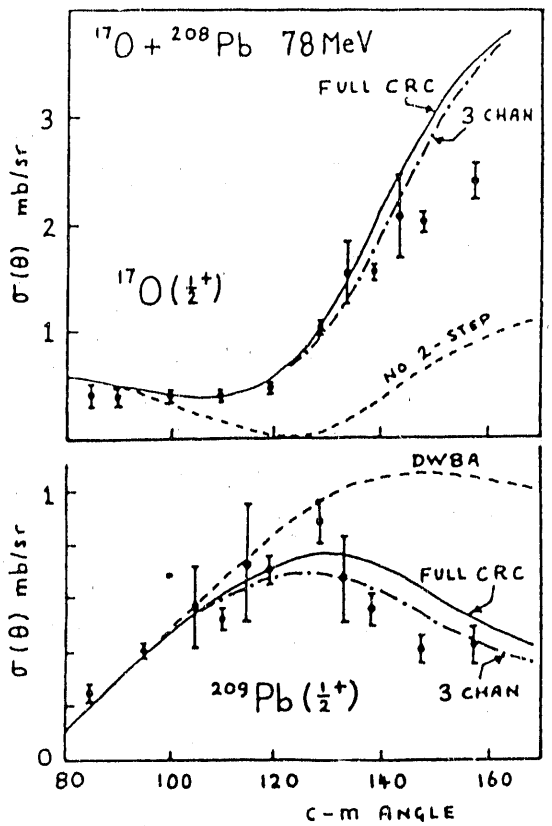

Fig. 1. Two-step effects on inelastic (above) and transfer (below) reactions. (From Ref. 7.)

and Coulomb amplitudes are comparable in magnitude, the reorientation is due primarily to the nuclear interaction, so that including it alters the balance (and especially the phase) between nuclear and Coulomb contributions. Although a remarkably good fit to the data (Fig. 3) is now obtained, a disturbing feature is that a very strong reorientation coupling is required (implying a quadrupole moment for this state about four times as large as would be obtained if ^{92}Zr were a rotor!). We are led to believe that this coupling does not correspond to an intrinsic property of this state of ^{92}Zr, but is simply an "effective" way of representing the results of couplings to other channels, such as transfer. This view is reinforced by analysis of the excitation function (Fig. 4), where the interference structure near the top of the Coulomb barrier (about 47 MeV here) can only be reproduced by increasing the reorientation strength even further.

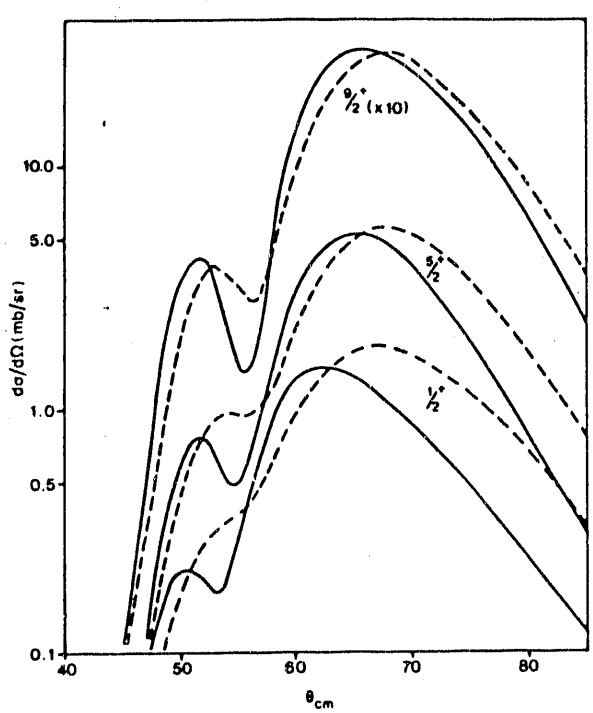

Fig. 2. Predicted two-step effects (solid) on $^{208}Pb(^{17}O,^{16}O)^{209}Pb$ transfer compared to one-step alone (dashed) at 102 MeV. (From Ref. 7.)

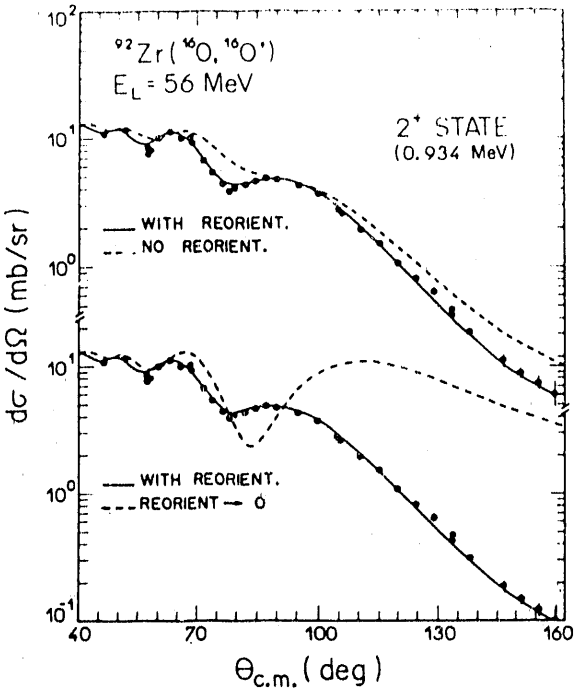

Fig. 3. Comparison of fits with and without reorientation of the 2^+ state.

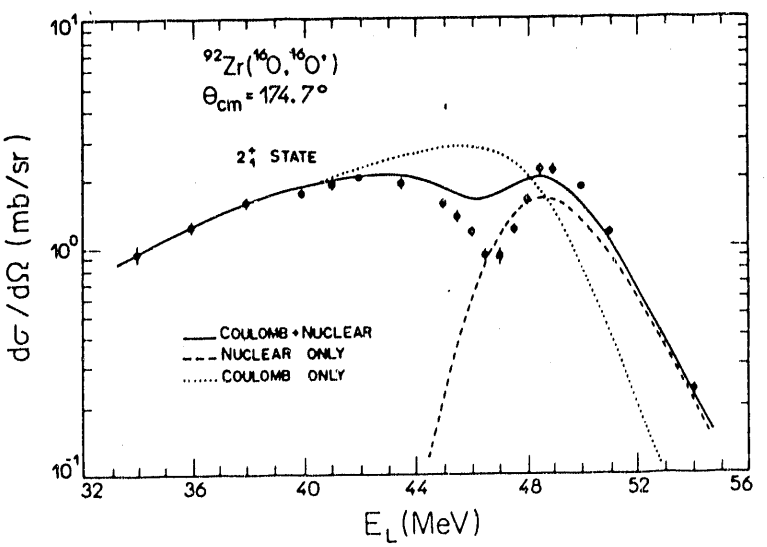

Fig. 4. Comparison of excitation function with model that fits (Fig. 3) the data at 56 MeV. (From Ref. 8.)

It is hoped that a particle-γ angular correlation measurement on this reaction, planned at Oak Ridge, will throw more light on the reaction mechanism by telling us the populations of the various magnetic substates[9]. In addition, some preliminary coupled-channels calculations[10] indicate that the couplings to various nucleon transfer channels do have the same kinds of effects as the introduction of reorientation, but much work remains to be done. It is also noteworthy that, although neutron transfer data could not be extracted from these $^{16}O + ^{92}Zr$ measurements, they were obtained from similar studies of $^{18}O + ^{92}Zr$ at 54.7 MeV, and the angular distributions all show marked shifts in angle, compared to the one-step theory, analogous to those shown in Fig. 2. There is also a long history of "anomalous" angular distributions being observed for the inelastic excitation of the 2_1^+ state of ^{18}O (see [11] for a recent example and other references). Although it was suggested long ago[12] that these anomalies were due to couplings to neutron transfer channels, a fully satisfactory account of these data has not yet been given.

3. LOW-ENERGY SHAPE RESONANCES AND AMBIGUITIES IN THE ION-ION POTENTIAL

What kind of optical potential is appropriate for the interaction of two nuclei? Crudely, is the real potential "deep" or "shallow"? Strong absorption usually obscures (or renders irrelevant) the answer to this question for heavy systems, when the scattering is sensitive only to the potential at large distances in the vicinity of some strong absorption radius (typically $\sim 1.5\left(A_1^{1/3} + A_2^{1/3}\right)$ fm). However, optical model analysis of the scattering of lighter systems, such as $^{12}C + ^{16}O$, has implied some sensitivity to the real potential at small radii[13]. Residual rainbow phenomena are observed in their elastic scattering angular distributions at higher energies (e.g. $^{16}O + ^{16}O$ at 350 MeV[14]: see Fig. 5). These data require deep real potentials (e.g. of order 200 MeV deep for $^{12}C + ^{12}C$, 300 MeV for $^{16}O + ^{16}O$, at small radii). In favourable circumstances, these observations can determine the potential unambiguously, just as was found much earlier for alphas scattering from nuclei[15]. The deep real potentials that are needed are similar to those obtained by simply folding some reasonable effective nucleon-nucleon interaction over the density distributions of the two nuclei[16].

It becomes much more difficult to obtain this kind of information unambiguously as the bombarding energy is reduced[17], but another source becomes available as the Coulomb barrier is approached. Here one observes individual partial-wave

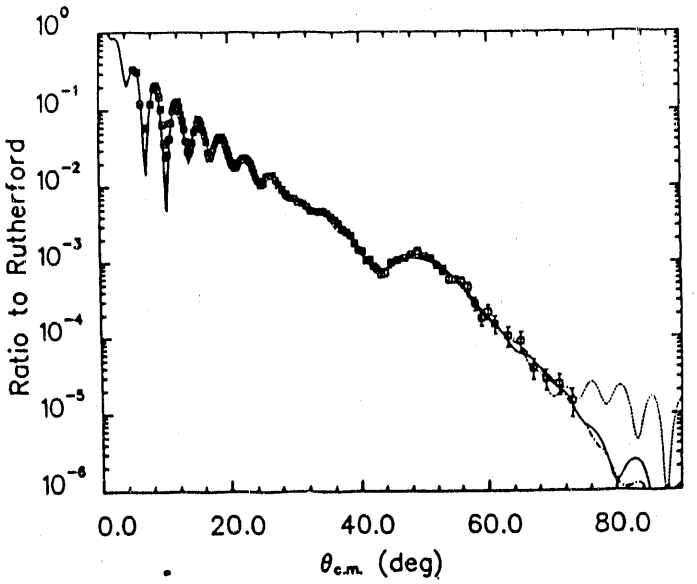

Fig. 5. Rainbow scattering in $^{16}O + ^{16}O$ at 350 MeV. The curves represent optical model fits. (From Ref. 16.)

resonances[18,19] which may be interpreted as shape (or quasi-molecular) resonances in the real potential. (In practice, such resonances are often fragmented into fine structure, so that shape resonances only provide the average behaviour.) This interpretation is an extension to the continuum of the cluster model that has often been applied successfully to describe the bound states of the combined system[18-20].

A critical constraint is that these quasi-molecular states, bound or resonant, should satisfy the Pauli principle under exchange of nucleons between the two constituent clusters. This requires that the wavefunction of relative motion of the two clusters should have more than a certain number n of radial nodes[20], sometimes called the Wildermuth condition[21]. The simple harmonic-oscillator shell model provides a first guess; for example, we must have $N = 2n + L \geq 20$ for those states in ^{32}S with spin L which are interpreted as having an $^{16}O + ^{16}O$ cluster structure, in order for them to be properly antisymmetrized. (More realistic models[22] indicate that we should require $N \geq 24$ for this system.) In turn, if these (n,L) relative motion states are to be generated by a potential well, the well must be deep enough to sustain this number of nodes (see Fig. 6). Indeed, the potential depths required do turn out to be "deep", and similar to those needed to explain the rainbow effects observed in the scattering of the same two cluster nuclei at much higher energies[23] (see Fig. 7).

The $^{16}O + ^{16}O$ system is a favourable one because of the relatively closed-shell nature of ^{16}O, and the results obtained so far[22,23] have established some general properties that a local, ion-ion potential must have in order to explain the scattering at both low and high energies. However, much work remains to be done, both for this

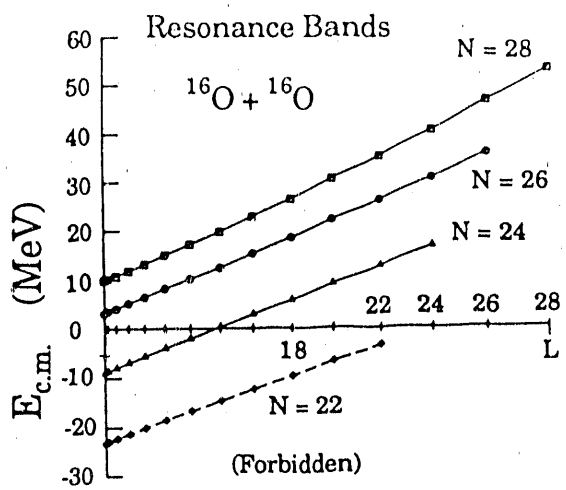

Fig. 6. Bands of bound and resonant quasi-molecular states characterized by N = 2n + L in one of the potentials that fits the 350 MeV scattering (Fig. 5). (From Ref. 23).

system and others, such as $^{12}C + ^{12}C$ for which high-energy scattering establishes[13] a residual "rainbow" phenomenon and for which extensive studies of the bound-state cluster structure have been made [24]. There is also much data for non-identical systems, such as $^{16}O + ^{12}C$, awaiting analysis in this way.

Description of the bound states in cluster terms often requires allowing one or both of the clusters also to be in excited states[24]. It is the coupling to these channels that can provide the fine structure of the quasi-molecular resonances seen in the elastic scattering, another example of the importance of channel couplings at low energies. (Of course, there is not a unique cluster structure for a given nucleus, and different states may require the assumption of different cluster pairs. These may also be coupled to each other, providing further fine structure, although I am not aware of any calculations taking this into account. At high energies, all these channels mainly contribute to absorption from the elastic channel which can be represented by an imaginary potential.)

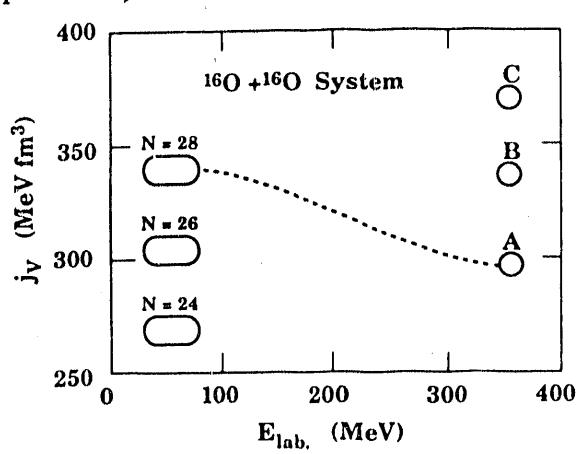

Fig. 7. Illustrating continuity argument between potentials that fit low- and high-energy data. (From Ref. 23.)

Another interesting question is, how heavy a system can these ideas be applied to? For example, resonant-like behaviour has been observed[25] for systems like $^{24}Mg + ^{24}Mg$ and $^{28}Si + ^{28}Si$. As the nuclei become heavier, the number of important internal degrees of freedom (and hence available channels) becomes larger. Then the many couplings between them tend to fragment the simple cluster states or resonances more and more, so that they become unrecognizable. (At the higher energies, this results in the scattering becoming more absorptive so that phenomena like residual rainbows are completely damped.) Even the addition of one or two neutrons, e.g. as in $^{30}Si + ^{28}Si$, can "loosen up" the system sufficiently for these features to go away[25] (see Fig. 8).

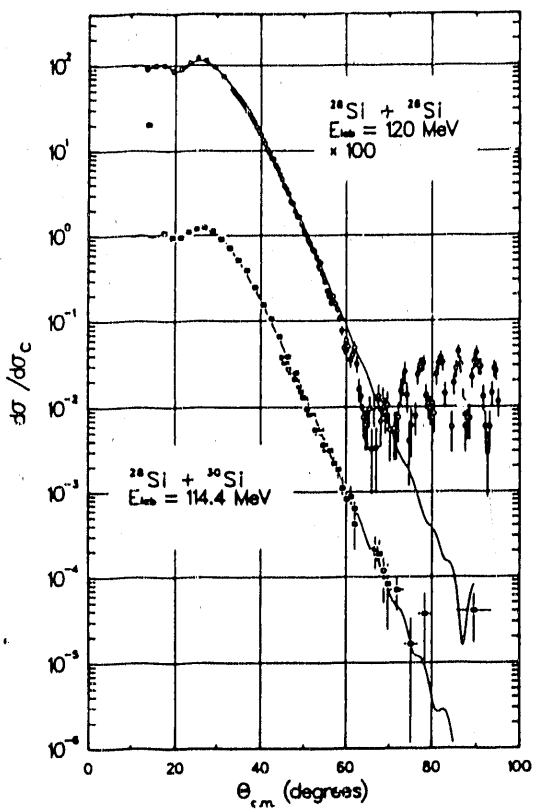

Fig. 8. Comparison of elastic data for similar identical and nonidentical systems. (From Ref. 25.)

Clearly these few remarks provide only a brief entree into the broad subject of low-energy "molecular" resonances[18,19]. My particular interest has been on what light their study may throw on the nature of the ion-ion potential. For this we need to concentrate on the gross (average) structure, which we may hope to interpret as the underlying potential shape (or "single particle") resonances, rather than the complicated fine structure which involves explicit consideration of couplings to various nonel... channels.

4. FINAL REMARKS

Clearly the study of heavy-ion interactions at low energies requires more than a one-shot measurement of, say, an angular distribution and the use of the DWBA[3] to immediately extract a deformation parameter or a spectroscopic factor. The variation of experimental results with bombarding energy is a critical feature (for example, in establishing a "threshold anomaly"[1,2], or in seeing continuity between low and higher

energy results[17,23]).

Furthermore, we need to correlate different kinds of data for a given system, for example, to reproduce simultaneously data for elastic scattering and sub-barrier fusion[26]. Explicit data for nonelastic channels (transfer, inelastic) are also needed in order to judge the relative importance of different processes[27].

All of this implies much more intensive work, both experimentally and theoretically, but this is a rich field, and I think the possible rewards make it worthwhile.

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