A COUPLED CHANNEL APPROACH TO THE BACKWARD ANGLE SCATTERING OF $^{16}O + ^{28}Si$ AT LOW ENERGIES

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The long-standing theoretical problem associated with backward hemisphere scattering between heavy ions is approached, for the particular case of $^{16}O + ^{28}Si$, in a multichannel formalism involving the coupling of elastic waves to the rotational band of ^{28}Si. The strong coupling description obtained exploits a volatility of the excited 2^+, 4^+, 6^+ states at backward angles. This molecular-like description, although achieved for energies near the Coulomb barrier, is clearly universal, extendable to higher energies and to other systems including lighter ones such as $^{12}C + ^{16}O$.

Considerable interest has been attached in recent years to the experimental observation of a backward rise in the elastic cross section of some heavy-ion collisions. While for most ions the differential cross section drops exponentially to large angles one has found, notably for low energy scattering of ^{16}O and ^{12}C on several nuclei such as ^{28}Si [1,2], that the angular distribution at backward angles exhibits strong oscillations and rises sharply at 180° to an appreciable fraction of the Rutherford cross section. An equally striking resonance-like structure is seen in the backward elastic excitation function [3]. To date, attempts to explain this behavior have generally been based on an optical model description of the scattering [2–5], using surface transparent or weakly absorbing potentials. A recent investigation of interest [5], deliberately concentrating on low energy data a few MeV above the Coulomb barrier for $^{16}O + ^{28}Si$, used a real potential departing markedly from folding in the nuclear surface, suggesting the necessity for including polarization effects.

In this note we show that at least for the case of $^{28}Si + ^{16}O$ the above phenomenon is a straightforward consequence of the weak long range absorption at the relevant bombarding energies and of the deformed nature of ^{28}Si. In the process we demonstrate that the use of coupled channels is essential for the description of the dynamics of the two ions at small separation. We do this most dramatically by presenting a case where oscillatory behavior is clearly absent before the coupling to excited states of ^{28}Si is switched on. At the heart of our treatment moreover is the recognition that strongly coupled states whose residual scattering energy $E(J) = E_{CM} - E_{excitation}(J)$ leaves them near the Coulomb barrier are profoundly important in the backward angular distribution.

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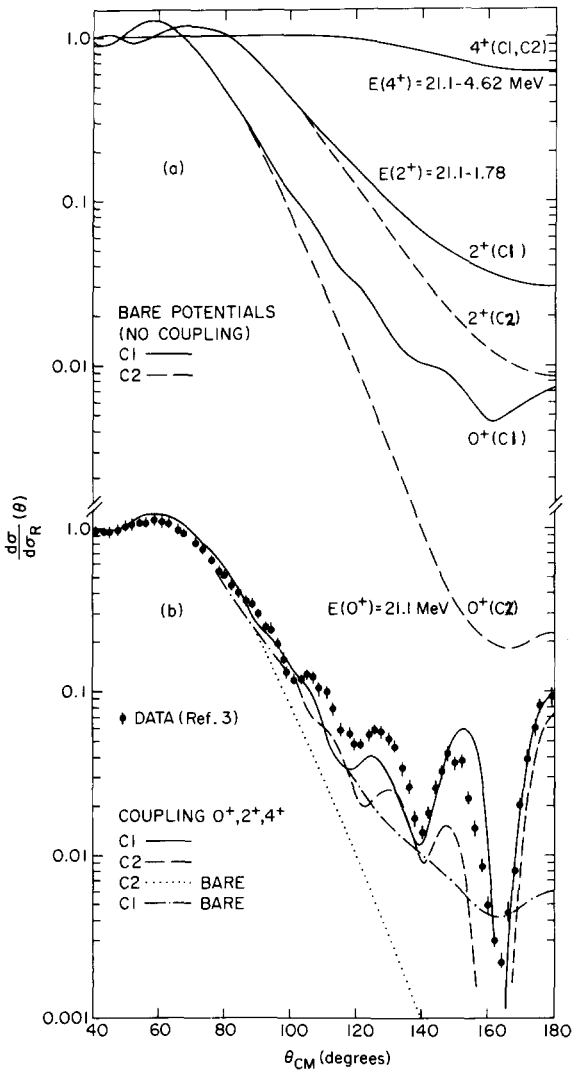

Fig. 1. (a) Effective scattering in 0^+, 2^+, 4^+ states for the bare potentials C1 (V_{0R} = −26.7 MeV, a_R = 0.753 fm, r_{0R} = 1.160 fm, V_{0I} = −26.5 MeV, a_I = 0.2 fm, r_{0I} = 1.00 fm) and C2 (V_{0R} = −36.3 MeV, a_R = 0.66 fm, r_{0R} = 1.164 fm, V_{0I} = −35 MeV, a_I = 0.2 fm, r_{0I} = 1.00 fm). A small exterior absorption a_I = 0.52 fm, r_{0I} = 1.074 fm, with strength changing gradually with energy from 0 to 1.6 MeV has been added to represent flux lost to transfer. To represent an expected reduction in absorption with $E(J)$ the radius r_{0I} and the depth V_I were cut by 10% and 50% respectively in the 2^+, 4^+ states for the potential C1; however slight alterations in, say, V_{0R} would have compensated for these changes. The rapid increase of $\sigma(180^\circ)$ with J overcomes a decreasing probability of excitation to produce a coherent sum of comparable amplitudes for the overall ground state scattering. (b) Angular distributions at E_{CM} = 21.1 MeV. The data from ref. [3] is compared to results of C1 and C2. At back angles the magnification and structure introduced by coupling is striking.

This point is made most simply by reference to fig. 1 where the effective elastic scattering in the 0^+, 2^+, 4^+, 6^+ states of ^{28}Si is shown to increase steeply with decreasing $E(J)$. Thus we expect the 0^+, 2^+, 4^+ states of ^{28}Si to permit us to describe the silicon + oxygen system up to perhaps 24 MeV in the center of mass and the addition of the 6^+ to extend this region of validity somewhat further. The failure of earlier coupled channel calculations to generate the backward rise at higher energies is also understood in this context. The more rigid ^{16}O nucleus plays a more passive role in the dynamics.

In situations of surface transparency we always expect to see the signature of the grazing angular momentum in the angular distribution and excitation function at backward angles. It is the partial waves for $l < l_g$ which are above their respective Coulomb and centrifugal barriers and, at least classically, can penetrate deeper into the real potential. Some disturbance produced directly by the potential, or indirectly by coupling, is likely to create an angular distribution given approximately by $P_{l_g}(\cos\theta)$. It is obviously the details of this angular distribution near 180° which carry information about interactions inside the barrier. To extract this information it is necessary to realize the importance of coupling of grazing elastic waves to nuclear surface modes; for ^{28}Si this coupling is clearly to the deformed band.

Our largest area of ignorance is evidently in the interior bare potential and especially the interior absorption. The tails of the optical real potential can be calculated from folding or similar procedures while an extension of earlier results [6] on absorption, to the lower bombarding energies relevant here, yields almost vanishing imaginary tails due to one- or two-particle transfer. For non α-like nuclei one expects this source of absorption to severely damp the observed phenomenon near θ = 180° CM. The residual interior imaginary potential then presumably arises entirely from massive particle transfer leading eventually to fusion. From known α-particle binding energies one deduces the absorption possesses a diffusivity $\leqslant$ 0.28 fm. The "absorption" due to inelastic excitation is of course automatically included. This is of vital importance in the extension of this model to high energies since treatment of this strong process as a "potential" absorption would completely eliminate the desired resonances.

We have in the present note considered two some-

what different extrapolations of the real potential from outer regions, one C1 employing a shallow real potential approximately −26 MeV in depth, and the other C2 possessing similar geometry but with a somewhat deeper potential $V_0 \approx -36$ MeV. In both cases one uses imaginary potentials very nearly equal to the real in depth. The choice C2 is a more straightforward extrapolation of the known tails of the real potential while C1 was derived from scattering and transfer investigations in neighboring nuclei [7].

The usual constraints to be imposed on the coupling strengths result from known BE(2) values [8] for the ^{28}Si $0^+ \to 2^+, 2^+ \to 4^+, 4^+ \to 6^+$ transitions and the 2^+ quadrupole moment [8]. We employ the code CHUCK [9] in a deformed option and have modified it to include a "reduced radius" effect. The results are exhibited in figs. 1, 2 and 3, containing angular distributions and scattering matrices for the reference energy of $E_{CM} = 21.1$ MeV as well as the 180° excitation function at low energy, $E_{CM} < 24$ MeV.

The procedure followed in obtaining these results involved a moderate but not exhaustive tuning of the bare potentials to fit the angular distribution in fig. 1 at $E_{CM} \approx 21.1$ MeV. All other results for $18 \leqslant E_{CM} \leqslant 24$ MeV with slight modification, flow from this initial determination. It is immediately evident from fig. 1 that the character of the backward hemisphere scattering results entirely from channel coupling. At 21.1 MeV the calculation with C1 is unaffected by the addition of the 6^+ state, i.e. it is self-truncated or convergent. The 6^+ state plays a somewhat more quantitative role for the deeper potentials in C2.

The theoretical excitation functions in fig. 2 are in good qualitative agreement with the data. The structure of this function may be understood as reflecting the more or less smooth progression of the grazing wave length with energy. Evidently in fig. 2 this progression is modified significantly by the detailed coupled channel dynamics, since some peaks are suppressed relative to neighbors. For the choice C2 we have not altered the potential determined at $E_{CM} \approx 21$ MeV while for C1 we have introduced an expected gradual reduction in the imaginary depth with decreasing energy. The present calculations were stopped near $E_{CM} = 25$ MeV, just at the point where the 6^+ state begins to contribute significantly. Considerably higher energies should be accurately described with the addition of a few more states, though

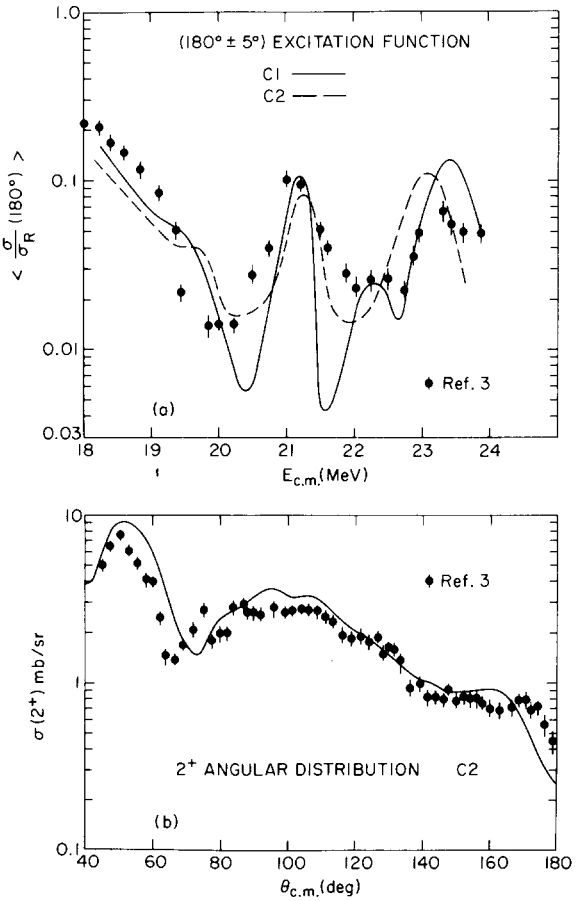

Fig. 2. (a) 180° excitation functions. The experimental data of ref. [3] were collected by averaging over the angular range 180° ± 5°. We have here multiplied the data for $E_{CM} > 18$ MeV by a theoretical averaging factor deduced from C1. This factor is close to unity for $E_{CM} \leqslant 20.5$ MeV. In addition the experimental data is averaged by virtue of target thickness [3] over an energy width of 300 to 400 keV, but no theoretical energy averaging is included. (b) Theoretical (C2) and experimental angular distributions for the excitation of the 2^+ state. The result for the potential C1 is similar with however a rise rather than a drop obtained in the angular distribution at 180°. This aspect of the 2^+ distribution at 180° is rapidly changing with energy. The 4^+ state is excited most strongly near 180°, in magnitude reaching perhaps 1/4 of the 2^+ but quite sensitive to the inclusion of the 6^+.

our predicted cross sections do contain oscillatory structure in both energy and angle for a broader range of energies. The longer range absorption from simple transfer channels is unimportant at 21.1 MeV but increasingly effective in damping the backward rise for

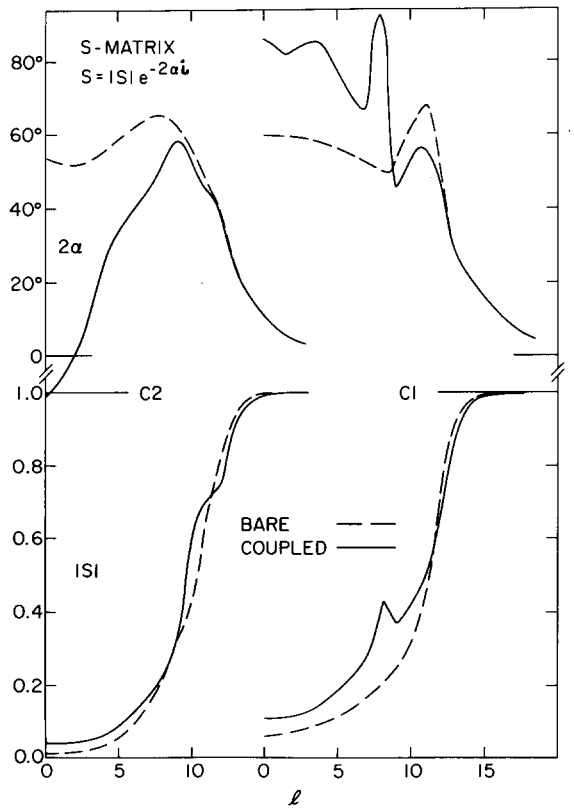

Fig. 3. Scattering amplitudes: magnitude and phase at E_{CM} = 21.1 MeV. Comparison is made between bare and full coupled channel S-matrices. The changes produced by coupling are an increase in reflectivity (low l magnitudes) and a localized "disturbance" near l_g. The increase in reflectivity is an expression of the information contained in fig. 1a. The disturbance in $S(l)$ is more evident for C1 but of equal importance for C2.

$E_{CM} > 24$ MeV. These must be carefully estimated for higher energies.

Some understanding of the process obtains from the S-matrix shown in fig. 3. Comparison of the amplitudes (and phases) with or without coupling indicates that there is an increase in reflectivity for small l and a disturbance is generated in a narrowly localized set of waves near grazing. The degree of localization is astonishing. Since the few waves in the disturbance are just below or just above their respective barriers it is likely the attractive coupling to nuclear surface modes has produced resonances, a point confirmed by examination of the Argand plot for a representative wave. One is tempted to refer to these as molecular states. Interestingly the center of the disturbance occurs at $l = 8$–9 for C1 and nearer $l = 12$ for C2, and indeed the character of the two S-matrices in fig. 3 differs, a point which will be pursued in further, more detailed work.

The theory outlined here is we believe universal, applicable to neighboring mass-asymmetric systems and to lighter systems as $^{12}C + ^{16}O$ [10]. The extension to much higher energies is straightforward but cumbersome in light of the possible importance of excitations up to the Coulomb barrier. In an ideal approach we would combine our present knowledge of the exterior regions of the heavy-ion potential with the coupled channel dynamics, to extract important clues about the interior regions. We believe this work represents a first step in that direction.

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