EVIDENCE FOR THE ENERGY DEPENDENCE OF EFFECTIVE HEAVY-ION INTERACTIONS ☆

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By analyzing the Coulomb-nuclear interference in the excitation of ^{208}Pb by ^{16}O at sub-barrier energies, nuclear coupling strength is extracted which is about twice as large as its value at energies above the barrier.

A number of recent analyses of heavy-ion elastic scattering measurements at low bombarding energies have inferred a marked increase in the strength of the real part of the optical potential [1–3]. This polarization effect originates from the virtual excitation of inelastic and transfer reaction channels which occurs during the relatively long collision times at lower energies. Because of the general nature of this process one would also expect to see its consequences for observables other than elastic scattering cross section. Indeed the formal theory of effective interactions makes no fundamental distinction between the diagonal part of the effective interaction represented by the optical potential and the off-diagonal parts represented by nuclear coupling form factors [4]. Moreover, a specific examination of this problem using semiclassical perturbation approximations to the microscopic theory has shown that sizeable renormalizations of inelastic excitation form factors are to be expected in heavy-ion collisions [5].

The inelastic cross section at very low energies where the first deviations from Coulomb excitation occur provides a unique opportunity for observing these effects. This is because at such low energies the cross section depends directly on the interference between the nuclear excitation amplitude and the known Coulomb excitation amplitude. The nuclear distortion of the relative motion wave functions can be neglected so that the nuclear coupling is the only unkown quantity. Therefore it can be extracted rather unambiguously by analyzing such data [6].

Some of the most precise measurements of the onset of nuclear effects in heavy-ion inelastic collisions have been made in connection with "safe distance" determinations for Coulomb excitation studies. Such data are shown in fig. 1 for the collision of ^{16}O + ^{208}Pb, exciting the ^{208}Pb(3^-, 2.62 MeV) state [7]. The measurements determine the ratio of the inelastic to elastic cross section at a fixed backward angle as a function of bombarding energy. It should be noted that the energy range here is considerably lower than for the set of elastic scattering ^{16}O + ^{208}Pb data which were used to extract the energy dependence of the optical potential [2].

We have used the conventional distorted wave Born approximation and collective model to analyze these data. In this model the nuclear coupling interaction is proportional to the derivative of the optical potential. We start with a set of Woods–Saxon potential parameters and Coulomb and nuclear deformation parameters which give a reasonably good description of the ^{16}O + ^{208}Pb inelastic angular distribution at $E_{\text{lab}} = 104$ MeV ($V_0 = -68.4$ MeV, $W_0 = -39$ MeV, $r_0 = r_w = 1.178$ fm, $a_0 = 0.658$ fm, $a_w = 0.565$ fm, $\beta_c = \beta_n = 0.1227$; see ref. [8]). For energies below 104 MeV we allow the strength of

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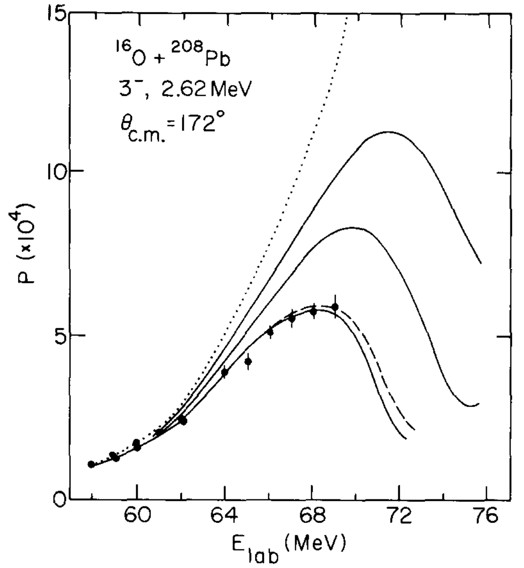

Fig. 1. Ratio of inelastic cross sections at a fixed backward angle as a function of bombarding energy. The data are from ref. [7]. The dotted curve results from a pure Coulomb excitation calculation. The solid curves are obtained by increasing the strength of the nuclear interaction as explained in the text.

the real potential to increase and the imaginary potential strength to decrease according to the linear relations $V(E) = V_0+\alpha(E_{lab}-104)$, $W(E) = W_0-0.85(E_{lab}-104)$. The latter slope parameter was chosen to account for the type of energy dependence indicated by theoretical calculations of the imaginary potential reported in ref. [8]. It will be seen, however, that the imaginary potential strength is irrelevant for the analysis of the low-energy data in fig. 1. The key parameter α will be varied to fit these data.

It should be noted that such simple types of energy dependent strength parameters are taken for the sake of convenience. One might expect that the shape of the effective interaction in the surface region would reflect the energy dependence, rather than an overall strength. In this respect the formalism of ref. [5] is simplified since the approximations which are made lead to expressions for renormalized strength parameters. Also, there are theoretical reasons for expecting that the strength may eventually decrease again as the energy is further lowered [3].

A series of calculations are compared to the data in fig. 1. The dotted curve results from pure Coulomb excitation. It agrees with the data at the lowest energies and provides a reference for gauging the deviations due to nuclear excitation at the higher energies. The uppermost solid curve is obtained using the energy dependent potential given above (with $\alpha = 0.93$), but keeping the nuclear form factor fixed as at $E_{lab} = 104$ MeV. This clearly underpredicts the nuclear coupling. Allowing the coupling strength to increase with the slope $\alpha = 0.93$ is not sufficient, as shown by the middle solid curve. The lowest solid curve which fits the data is obtained by increasing the slope parameter for the real potential from 0.93 to 2.54. In this case the real nuclear form factors for the energies shown are about twice as strong as for 104 MeV.

To emphasize the fact that it is the nuclear coupling which is important, we have used the form factors from the last calculation but switched off the optical potentials so that the calculation involves pure Coulomb waves. The dashed curve in fig. 1 shows the result. It is seen from this comparison that the

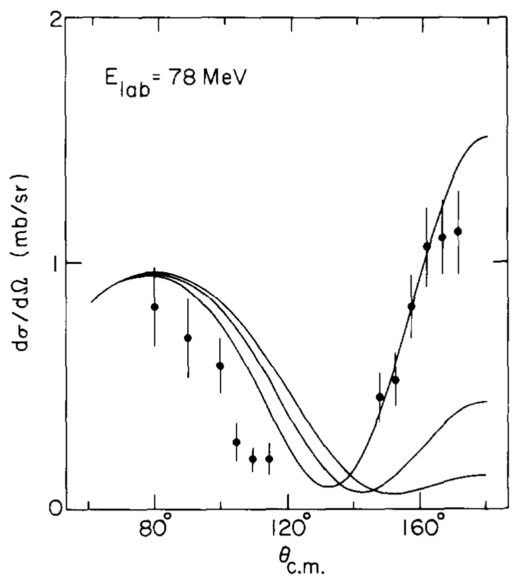

Fig. 2. Angular distribution for $^{208}Pb(^{16}O, ^{16}O')^{208}Pb$ (3^-, 2.62 MeV) at $E_{lab} = 78$ MeV. The data are from ref. [9]. The curves belong to the same family of calculations shown by the solid lines in fig. 1.

cross sections are independent of the nuclear potential at energies below 70 MeV.

As a further check we have performed the calculation at $E_{\text{lab}} = 78$ MeV in order to compare to a measured angular distribution [9]. The results are shown in fig. 2. The three solid curves correspond to those shown in fig. 1. The largest nuclear coupling also gives the best agreement with these data. The real potential depth at $r = 12.4$ fm for this calculation is 3.15 MeV, which may be compared to the value of 2.85 MeV obtained from analyzing the elastic scattering at this energy [2,3].

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