Heavy ion resonances in mismatched channels

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Recently measured cross sections for inelastic 0_2^+ and 3^- excitations in $^{16}O + {}^{16}O$ are analyzed in the framework of coupled channel calculations. The correlation between the peaks in both channels is explained in terms of a strongly mixed resonant state of the nucleus-nucleus system. The equivalent local potentials including the channel couplings are calculated for each channel. The resonances are seen to arise in all channels simultaneously at the barrier tops of these effective potentials.

[NUCLEAR REACTIONS $^{16}O(^{16}O,{}^{16}O)$, $E = 20$–40 MeV; calculated $\sigma(E)$; inelastic excitations. Coupled channels method, strong coupling.]

Freeman *et al.* have recently reported measurements of the $^{12}C + {}^{16}O^*$ and $^{16}O + {}^{16}O^*$ total inelastic cross sections leaving the ^{16}O nucleus in the 6.05 MeV excited 0^+ state.[1] In both reactions the observed gross structure is correlated with that in the $^{16}O(3^-)$ channel.[2] Similar excitation functions at some angles have also been obtained for $^{12}C + {}^{12}C$ where—among other channels—the 3^- and 0_2^+ excitations show resonant structures similar to those in the inelastic 2^+ channels.[3]

The gross structures in these as well as the elastic and other inelastic reaction channels have often been taken as evidence for molecular resonances of the nucleus-nucleus system.[4] A particularly simple and successful description in this framework has been given by the band crossing model.[5] In this model the inelastic band in which the intrinsic spin and the orbital angular momentum are aligned crosses the elastic band. In the crossing region both configurations are expected to mix strongly and this mixing provides the coupling mechanism between the two channels. Recently, however, it has been demonstrated that also a nonresonant diffraction model can account for the $^{12}C + {}^{12}C(2^+)$ and $^{16}O + {}^{16}O(3^-)$ cross sections.[6]

The results obtained by Freeman *et al.*[1] and Fulton *et al.*[3] for the strongly mismatched 0_2^+ channel are important because they may allow one to distinguish between these different competing explanations. Freeman *et al.* have concluded that a simple Austern-Blair calculation,[7] based on a strong absorption model, is unlikely to be able to describe simultaneously both the 0_2^+ and the 3^- cross sections with their correlated structures. On the other hand, the band crossing model can definitely not account for this correlation because the inelastic band corresponding to the 0_2^+ excitation does not cross the elastic band. Instead it is far away (6.05 MeV) from the latter as well as from the aligned 3^- band.

In this report we demonstrate that a consistent coupled channel description of the data for both the 3^- and the 0_2^+ channel in the $^{16}O + {}^{16}O$ reaction is possible if the coupling between all channels is strong as provided by the folding model. Using the coupled channel wave functions we then calculate in a second step the equivalent local potentials for each channel separately. We demonstrate that these potentials allow a physically very transparent explanation of the observed correlation between the gross structures in the two different channels.

The coupled channel calculations performed follow the lines of Ref. 8. The interaction used is that of a phenomenological potential, being the same for every channel, plus a folded coupling interaction:

$$U_{ij} = \delta_{ij}(V(\vec{r}) + V_{\text{Coul}}(\vec{r}) + iW(\vec{r})) + (1-\delta_{ij})\langle i|\int\int d^3r_1\, d^3r_2\, \rho_1(\vec{r}_1)\rho_2(\vec{r}_2)v(|\vec{r}-\vec{r}_1+\vec{r}_2|)|j\rangle \quad . \tag{1}$$

The diagonal term is that used by Maher *et al.*[9] except for the slight modification of the real part of the Woods-

Saxon form, i.e., $V_0 = -10.0$ MeV, $r_0 = 1.4$ fm, and $a = 0.35$ fm, and the imaginary potential which is modified by a J-dependent cutoff factor:

$$W(\vec{r}) = W_M(\vec{r}) \frac{1}{1+\exp\{[0.054J(J+1)+8-E_{\text{c.m.}}]/0.75\}} \quad . \tag{2}$$

Here W_M is the imaginary potential used by Maher *et al.* The J-dependent cutoff is chosen such that the absorption contains a "molecular window" around the elastic band.[10,11]

The effective potential $\mathcal{U}$ used in the nondiagonal couplings is the force $M3Y$ used extensively by Satchler and Love.[12] It is known to give excellent fits to elastic scattering data when used in a folding calculation.

The calculations include the elastic channel and the single excitations to the 0_2^+ and 3^- states in ^{16}O at 6.05 and 6.13 MeV, respectively. The transition density operator is taken to be

$$\rho(\vec{r}) = \rho_0(r) + R_0 \frac{d\rho_0(r)}{dR_0} \sum_\mu \alpha_{3\mu} Y_{3\mu}(\hat{r}) - \frac{\alpha_0}{r^2}\frac{d}{dr}(r^3\rho_0(r)) \quad , \tag{3}$$

with

$$\rho_0(r) = \frac{\rho_0(1-cr^2)}{1+\exp[(r-R_0)/a]} \tag{4}$$

and

$$\alpha_{3\mu} = \frac{S_3}{\sqrt{7}}[a_{3\mu} + (-)^\mu a_{3-\mu}^\dagger] \quad , \qquad \alpha_0 = S_0(a_{00} + a_{00}^\dagger) \quad . \tag{5}$$

The parameters c, R_0, and a are obtained from charge-density measurements.[13] Their values are $c = 0.051$ fm^{-2}, $R_0 = 2.608$ fm, $a = 0.513$ fm. All couplings are taken into account only in first order. This is justified because of the large excitation energies of the two phonon states in ^{16}O. The transition density for the octupole excitation is normalized to the measured $B(E3)$ value.[14] This gives the coupling strength $S_3 = 0.65$. For the 0_2^+ state in ^{16}O, however, no reliable transition densities do exist.[14] We have, therefore, used the transition density proposed by Satchler for the breathing monopole[15] although the 0_2^+ state in ^{16}O is generally believed to be a deformed 4p4h excitation.[16] Lacking any better prescription we hope to compensate for any possible deficiencies of this description by leaving the 0_2^+ coupling strength as a free parameter.

Figure 1 shows the comparison of the experimental and the calculated cross sections both for the 3^- and the 0_2^+ inelastic excitation. The solid and dashed curves shown in Fig. 2 are calculated with the values $S_0 = 0.1$ and $S_0 = 0.03$, respectively. As mentioned earlier the octupole coupling strength ($S_3 = 0.65$) was adjusted to yield the measured $B(E3)$ value. The coupled channel calculation obviously reproduces the 3^- excitation both in its gross structure and in its absolute cross section. For the 0_2^+ excitation the gross

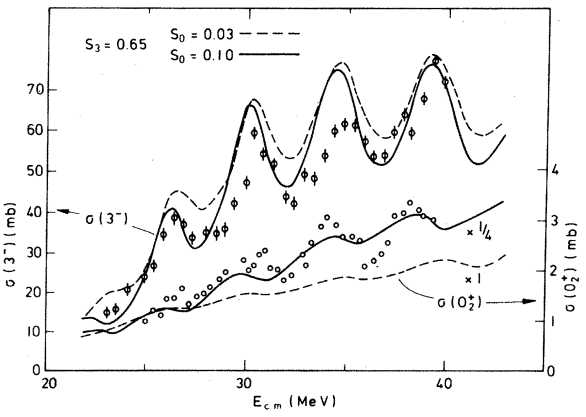

FIG. 1. Experimental (Refs. 1 and 2) and calculated cross sections for the inelastic excitations in ^{16}O + ^{16}O. The cross sections for the 3^- and 0_2^+ channels belong to the left and right scale, respectively. The solid curves have been obtained with a 0_2^+ coupling strength of $S_0 = 0.1$, the dashed ones with $S_0 = 0.03$. The 0_2^+ cross section with $S_0 = 0.1$ (solid curve) has been reduced by a factor of 4.

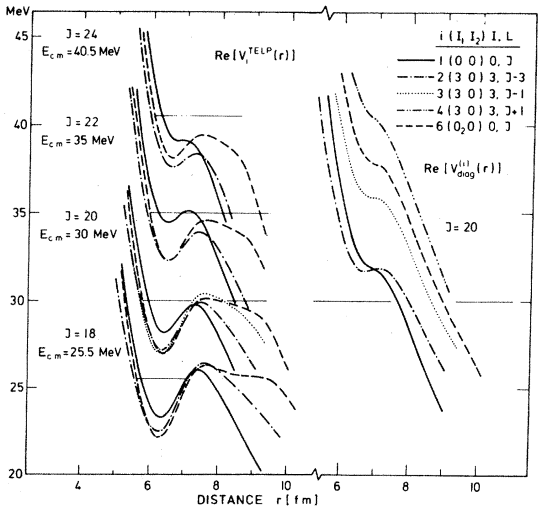

FIG. 2. Trivially equivalent local potentials, V_i^{TELP} for the resonating partial waves (left part) and the total diagonal potentials for $J = 20\hbar$ (right part). The channels are specified in the upper-right corner. The potentials V_i^{TELP} generate for each channel exactly the coupled channel wave functions. The thin horizontal bars give the locations of the coupled channel resonances and correspond to the measured enhancements in both the 3^- and 0_2^+ channels.

structure and in particular its correlation with that in the 3^- channel is correctly reproduced in the calculation with $S_0=0.1$ (solid curve).

The calculation is able to reproduce the observation of a large difference in cross section for the two channels although the calculated 0_2^+ cross section ($S_0=0.1$) is on the average about four times larger than the experimental one. On the other hand the calculation with the smaller 0_2^+ coupling strength of $S_0=0.03$ gives a cross section that is only slightly worse for the 3^- channel, somewhat underestimates that for the 0_2^+ excitation and exhibits practically no structure.

In view of the uncertainties in the transition density for the 0_2^+ state we have not searched for an optimum between the two coupling strengths shown. In particular, one also has to be aware of the possibility that the 0_2^+ state is fed directly from the 3^- state. In our model that describes both states as collective excitations such a coupling would be possible only through a second order process.

Independent of these structural uncertainties, however, the calculations show that the mismatched 0_2^+ channel may have resonant structures that are strikingly correlated with those obtained in the well matched 3^- channel, in contradiction to the band crossing model. The Austern-Blair model, on the other hand, predicts the peaks for the 0_2^+ excitation in the middle between two successive maxima in the 3^- cross section.[1]

In order to clarify the physical origin of this coincidence we have calculated the exact trivially equivalent local potentials for each channel separately. These are obtained by inserting the coupled channel wave functions u_i into a local Schrödinger equation:

$$V_i^{\mathrm{TELP}}(r)=E_{\mathrm{c.m.}}+\frac{\hbar^2}{2\mu}\frac{d^2u_i}{dr^2}\Big/u_i \quad . \tag{6}$$

V_i^{TELP}'s are exactly equivalent to the polarization potentials obtained from Feshbach's projection formalism.[17] The real part of $V_i^{\mathrm{TELP}}(r)$ is shown in the left part of Fig. 2 for four energies corresponding to maxima in the experimental cross sections. For comparison we show the total diagonal potential $V_{\mathrm{diag}}^{(i)}(r)$, where $V_{\mathrm{diag}}^{(i)}(r)$ represents the sum of the diagonal nuclear, Coulomb and centrifugal potentials, and the intrinsic excitation energy, at $J=20$ in the right part of the figure. Obviously neither a resonant quasibound state nor a barrier-top resonance in these potentials will explain this structure in the cross section. This figure also illustrates the comment made in the introduction on the band crossing model: Whereas the elastic ($i=1$) and the inelastic aligned 3^- band ($i=2$) indeed are very close and even cross at $r=7$ fm the inelastic 0_2^+ excitation ($i=6$) lies 6.05 MeV above the elastic channel potential ($i=1$).

The V_i^{TELP} for the different channels are now all very close to each other. For example for $J=20$ and $E_{\mathrm{c.m.}}=30$ MeV the minima for all four channels shown lie at $r\approx 6.3$ fm at 27–28 MeV. $V_{\mathrm{diag}}^{(i)}(r)$, however, have values of ≈ 32–43 MeV at $r\approx 6.3$ fm. This remarkably large shift is due to the very strong polarization taking place during the time of overlap of the two nuclei.

In contrast to the real part, the imaginary parts of V_i^{TELP} for the elastic and inelastic channels were found to be negative and positive, respectively, reflecting the fact that the incident flux flows from elastic to inelastic channels, where the latter have outgoing wave boundary conditions only.

Most importantly, the barrier heights for all channels shown in V_i^{TELP} are the same within about 1 MeV and coincide in addition with the positions of the maxima in the inelastic cross sections. Inspection of the S matrix $S_J(E)$ shows clear irregularities at these energies. These observations lead us to conclude that the gross structures in inelastic scattering arise as a consequence of "barrier-top" resonances[18] that fall into the energy-dependent angular momentum window in the absorption [see Eq. (2)]. The detailed mechanism is, however, considerably more complicated than that of a shape resonance in the ion-ion potential or in the Austern-Blair model. What resonates in our calculations is a very strong mixture of all the different channels and thus a state of the combined ion-ion system. This strong mixture is in agreement with the reduced widths of these states.[1,3] It and the corresponding very large polarization effects cannot be treated in distorted-wave Born approximation (DWBA).

The large polarization effects on the potentials imply that the nuclear structure of the two nuclei gets significantly distorted once the nuclei come into contact. This distortion will also affect the wave functions and thus the transition densities. The effective transition densities may in the overlap region, therefore, be quite different from their asymptotic form for a single isolated nucleus as it is, e.g., tested in inelastic electron scattering. We note that these effects of polarization are similar to those proposed by Ascuitto *et al.*[19] for transfer reactions.

In summary, coupled channel calculations with strong channel interactions can reproduce the correlation in the gross structures of the well matched 3^- and the mismatched 0_2^+ channel in the $^{16}O+{}^{16}O$ reaction. The inelastic gross structures arise as a consequence of energy-dependent angular momentum windows in the strongly polarized $^{16}O+{}^{16}O$ system; the polarization potentials can reach up to 10 MeV. The DWBA and its derivatives like the Austern-Blair method cannot hold under such circumstances. Although our results do confirm the existence of a strongly mixed dinuclear system they do not support the classical notion of a nuclear molecule in which two nearly intact nuclei are bound together.

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