Characterization of Gross-Structure Resonances in Angular-Momentum-Mismatched Channels in Heavy-Ion Collisions

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Gross-structure resonances previously observed only in inclusive measurements have been studied in both single and mutual inelastic scattering involving the 0_2^+ state of ^{16}O. Analysis of the excitation functions in the single-excitation channel at the zeros of Legendre polynomials permits the dominant L values to be determined for most of the resonances. The measured spins disagree with the predictions of a recently published microscopic model of the inelastic-scattering process.

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The presence of resonancelike behavior in peripheral scattering and reaction processes involving p- and sd-shell nuclei has been well established experimentally for many years. Pronounced oscillations have been observed in both scattering and reaction cross sections as a function of energy in many systems. The simplest of these have widths and spacings of a few megaelectronvolts, similar to those found in potential scattering, and have been called gross structure in the literature. These gross structures are often accompanied by narrower structures which are believed to result from a coupling to more complex degrees of freedom.

There have been numerous theoretical attempts to explain these phenomena; most have involved coupled-channels treatments in which the coupling of a few inelastic channels to the entrance channel is treated explicitly. Some of the earliest attempts, the so-called band-crossing models, assumed weak coupling between elastic and inelastic channels. In these models[1] the predicted resonances satisfy an angular-momentum-matching condition in which the smaller available energy in an exit channel with a negative Q value is compensated for by a lower allowed value of the orbital angular momentum. These models cannot explain the occurrence of resonances in angular-momentum-mismatched channels (e.g., $0^+ \rightarrow 0^+$ transitions with large negative Q values). Strong evidence for the existence of just such resonances was reported recently by Freeman *et al.*,[2] who observed gross structures in the total production cross section for the ^{16}O 0_2^+ state in ^{16}O + ^{16}O collisions by measuring internal pair decays in singles. These structures were found to be correlated with resonances seen in well-matched channels. Shortly thereafter it was shown that if the resonances in Ref. 2 are *assumed* to result primarily from the single excitation of the 0_2^+ state, they can be explained[3] by an increase in the strength of the channel coupling in a phenomenological way. Physically, the strong off-diagonal coupling results in equivalent local potentials which are nearly the same in the well-matched and poorly matched channels, thereby permitting a size resonance in a particular partial wave to occur at the same energy in both cases. Whether this strong coupling is required by the data, as opposed to being consistent with them, is not known. For example, a more sophisticated weak-coupling picture has recently been proposed by Laganke, Friedrich, and Koonin, who use a microscopically derived ion-ion potential including the effects of reduced Pauli blocking in excited-state channels.[4] These potentials typically have more than one rotational band for each channel, thereby making band crossing possible even in mismatched cases.

Other previous work involving mismatched channels has included observation of a strong anomaly in the ^{12}C + ^{12}C (0_2^+) exit channel in ^{12}C + ^{12}C scattering which is *not* well correlated with structures seen in the well-matched 2_1^+ and $2_1^+2_1^+$ channels[5] and which has been interpreted through a direct reaction picture, and a measurement[6] of the yield to the $E_x = 8.87$ MeV $J^\pi = 2^-$ state in the ^{16}O + ^{16}O system. This last case involves an exit channel with nonzero spin; it is well known that the additional complication of M degeneracy and nonunique orbital angular momentum (even for an isolated resonance of definite J) usually precludes definitive spectroscopic studies in such cases, even for strong well-matched channels.[7]

The foregoing suggests that detailed experimental investigation of a mismatched channel with channel spin zero may permit definitive L-value assignments to be made and may help to resolve the question of strong versus weak coupling discussed above. We have chosen to focus on the ^{16}O + ^{16}O system, and in particular to determine which specific reaction channels (e.g., single excitation, mutual excitation, and/or fusion and evaporation) are responsible for the gross structure seen in Ref. 2. In addition, for the channel-spin-zero single-excitation channel we have performed a model-independent investigation of the orbital angular momenta responsible for the gross structure observed.

Differential cross sections for the reaction ^{16}O + ^{16}O $\rightarrow$ ^{16}O(0_2^+) + ^{16}O$_{(\mathrm{g.s.})}$ have been measured at 65 energies between $E_{\mathrm{c.m.}}=17$ and 41 MeV in 375-keV steps. The data span an angular range between 55° and 90° in the c.m. system with a step size of approximately 0.7°. The angular acceptance of each datum point is also approximately 0.7°. Both particles in the final state were detected with solid-state position-sensitive detectors. Mass identification of the reaction products was accomplished by use of standard kinematic coincidence techniques. Reactions leading to $^{16}\mathrm{O}(0_2^+)$ were selected by our requiring a coincidence with an electron or positron from the internal pair decay of the 0_2^+ level.[8] Mutual inelastic excitation involving the 0_2^+ state was also observed for angles between 65° and 90° in the c.m. system. These events have Q values near -12.1 MeV, and represent the unresolved sum of the 0_2^+-0_2^+ and 0_2^+-3_1^- channels. The latter would be expected to dominate on kinematic grounds, and in fact the observed angular distributions are relatively featureless, which suggests that this is the case.

Pronounced gross structure was observed in both the single- and mutual-excitation channels. Figure 1 shows excitation curves integrated over the full angular range for which data are available in each channel. To focus on the gross structure, these data have been energy averaged with a square averaging interval of 1.5 MeV. Prominent resonances occur in the single-excitation channel at $E_{\mathrm{c.m.}}=25.6$, 29.3, 33.6, and 38.2 MeV. There is also a weak structure at $E_{\mathrm{c.m.}}\approx 20$ MeV. Some uncertainty (about 0.5–1 MeV) should be assigned to these energies purely from the fact that they are determined from angular distributions integrated only over part of a sphere. (Shifts of up to this magnitude are seen if the data are examined at individual angles; these presumably result from interference with background amplitudes and/or underlying intermediate-width structure.) All of the resonances observed above $E_{\mathrm{c.m.}}=25$ MeV are present in the inclusive data of Ref. 2, although with a considerably worse peak-to-valley ratio. The resonances at $E_{\mathrm{c.m.}}=33.6$ and 38.2 MeV are also prominent in the mutual-excitation channel, although the first of these is shifted toward lower energies by about 1 MeV. The highest-energy anomaly is somewhat stronger in the mutual-excitation channel, at least in the angular range shown in Fig. 1.

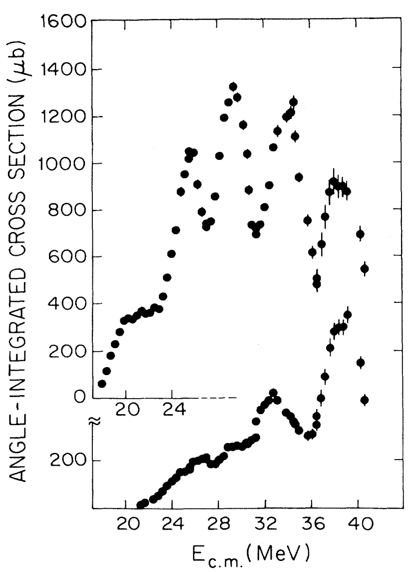

FIG. 1. Excitation curves for single (top) and mutual (bottom) inelastic scattering to the 0_2^+ state in $^{16}\mathrm{O}$. The single- and mutual-excitation data have been integrated over the angular range 55° to 90° and 75° to 90°, respectively, and energy averaged over 1.5 MeV.

Angular distributions in the single-excitation channel from $\theta_{\mathrm{c.m.}}=55°$ to 90° averaged over the gross-structure bumps (not shown) have the pronounced angular oscillations characteristic of a 0^+ final state, and represent good evidence of adequate rejection of inelastic events involving the neighboring 3_1^- level. The frequency of the oscillations in the angular distributions increases monotonically with energy, and shows that these resonances are dominated by near-grazing partial waves, as would be expected from models in which the gross structures are connected to size resonances in elastic scattering.

We now turn to the question of determining the particular partial-wave amplitudes which are responsible for the pronounced gross structure observed. For any scattering process involving spinless particles the differential cross section can be written

$$d\sigma/d\Omega=|\textstyle\sum_l A_l P_l(\cos\theta)|^2, \qquad (1)$$

where $P_l(\cos\theta)$ is a Legendre polynomial of degree l and the coefficients A_l are energy-dependent complex numbers which are proportional to the corresponding S-matrix elements. In an idealized picture of gross structure, a single S-matrix element resonates with energy while all others remain essentially constant in the region of interest. In the real many-body system this simple picture is modified by the presence of both intermediate-width structure and statistical fluctuations. Nevertheless, if the energy variation of a single S-matrix element dominates a given gross-structure anomaly, there should be no energy-dependent gross structure present at any of the zeros of the corresponding Legendre polynomial P_l. Note that this is true independent of whether the energy-dependent structures result from resonances or from other (e.g., kinematic) causes. In the present work it is assumed that the gross structures result from resonances because it is known[2] that the gross structure both persists in the total cross section and is correlated with structures seen in other channels. We thus calculate the quantities

$$Z_J(E)=2\pi\sum_{i=1}^{N_J}\int_{\theta_i-\Delta\theta/2}^{\theta_i+\Delta\theta/2}\frac{d\bar{\sigma}}{d\Omega}(\theta')\sin\theta'\,d\theta', \qquad (2)$$

where the θ_i are all zeros of $P_J(\cos\theta)$ which fall within the angular range of the data, and $d\bar{\sigma}/d\Omega$ is the energy-averaged differential cross section. The sum over zeros is intended to wash out the effects of a possible overlapping of intermediate-width structure not completely removed by energy averaging, which may confuse the results at a single angle. The interval $\Delta\theta$ was taken as 1° in the c.m. system. The results are shown in Fig. 2. Most of the gross-structure resonances observed display precisely the behavior predicted by the simple considerations noted above. Thus, the $E_{\text{c.m.}} = 25.6$ MeV resonance is absent in Z_{16}, but appears strongly everywhere else, requiring an $L = 16$ assignment. Similarly, $L = 18$, 22, and 24 are suggested for the $E_{\text{c.m.}} = 29.3$-, 33.6-, and 38.2-MeV resonances, respectively. In several cases small anomalies do show up where none should be present; these can probably be attributed to the effect of unresolved intermediate-width structure. Note in particular that the predominantly $L = 18$ and $L = 22$ structures both show small anomalies in Z_{18} and Z_{22}, respectively. This may be connected with the surprising fact that no structure which is predominantly $L = 20$ is observed. It is thus possible that the $L = 20$ strength is fragmented in the range $E_{\text{c.m.}} = 28$–35 MeV. An additional (weak) argument in favor of this suggestion is that the 90° excitation function for *elastic* scattering shows two bumps in this region, while an optical-model calculation shows a single gross-structure bump resulting from $L = 20$.[9] This same optical-model analysis, which uses the Gobbi potential, shows strong gross-structure anomalies at $E_{\text{c.m.}} = 24$ and 29 MeV which result from $L = 16$ and 18, respectively, the same values of L suggested by the present study for the 0_2^+ channel.

The L values observed in this work are in disagreement with the predictions of the microscopic model proposed in Ref. 4. Inspection of Fig. 2 of Ref. 4 shows that the gross-structure anomalies observed at $E_{\text{c.m.}} \sim 30$, 35, and 40 MeV are attributed to $L = 16$, 18, and 20, respectively, which are either two or four units of $\hbar$ less than the values observed here. In contrast, the fact that the $L = 16$ and $L = 18$ resonances occur near the same energies as the corresponding gross structures reported from optical-model fits to elastic scattering seems to be consistent with a picture in which strong channel-channel coupling results in simultaneous size resonances in the elastic- and inelastic-scattering channels. It must be noted, however, that while the present work supports the idea of strong coupling in a general way, the specific coupled-channels calculation of Ref. 3 is in relatively poor agreement with the present data. Neither the division of the flux between the single- and mutual-excitation channels nor the energies and spins of the observed resonances are correctly predicted. (A detailed comparison between the present data and these calculations, among others, will be given elsewhere.)

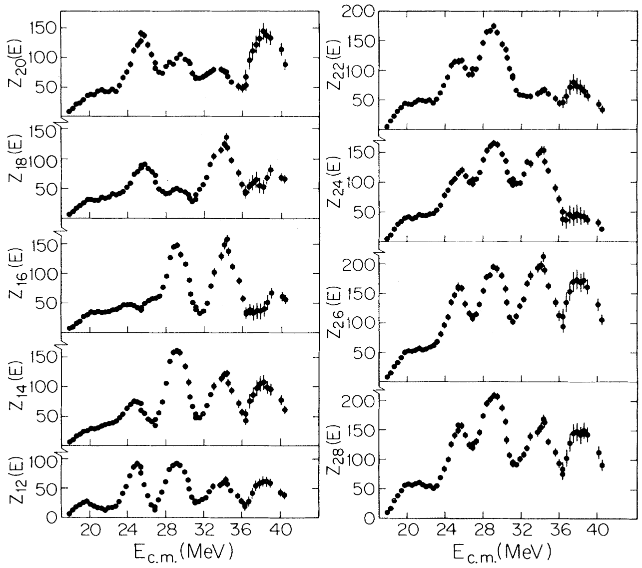

FIG. 2. Energy-averaged differential cross sections for single-excitation inelastic scattering. The function Z_J [Eq. (2)] is designed to represent data at all zeros, in the experimental angular range, of the Legendre functions P_J.

In conclusion, we have shown that the dominant partial wave responsible for a given gross-structure anomaly can be extracted in a model-independent way for heavy-ion inelastic-scattering data for a $0^+ \rightarrow 0^+$ transition. The present study suggests that coupled-channels effects are important in $^{16}O + ^{16}O$ scattering at energies a few times the Coulomb barrier, and are in disagreement with recently published explanations of these phenomena based on a version of the band-crossing model using microscopically derived ion-ion potentials.

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