Heavy-Ion Resonances in Angular-Momentum-Unfavored Channels

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The systems $^{16}O+^{12}C$ and $^{16}O+^{16}O$ have been studied in the inelastic channel leaving ^{16}O in the 6.05-MeV excited 0^+ state. This channel has a grazing angular momentum ~2.5 units less than the elastic channel. Surprisingly, the excitation functions show pronounced peaks which are closely correlated with the well-matched $^{16}O(3^-$, 6.13 MeV) channel. This correlation demonstrates the importance of the wave reflected from the interior of the ion-ion potential.

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The discovery of regular resonancelike structure even above the Coulomb barrier in the excitation functions of many light-ion reactions has stimulated a large amount of theoretical and experimental work. The excitement comes from a possibility that these structures arise either from eigenstates of the nuclear ion-ion potential (gross structure) or from slightly more complicated excitations (intermediate structure) of a very deformed composite system. A prime case has been inelastic scattering to the $^{16}O(3^-$, 6.13 MeV) state in the $^{16}O+^{16}O$ and $^{16}O+^{12}C$ system.[1-4] But even in these much studied reactions, both of which show clear and regular structure, the dynamical mechanism responsible for this structure is still undetermined. Proposed explanations include coupling of elastic and inelastic bands,[5] resonant α-particle transfer,[6] or purely nonresonant phenomena arising from strong absorption and good angular momentum matching between the entrance and exit channels.[7] Some of these models may be tested by investigating these systems in exit channels that are poorly matched to the entrance channel. Excitation of the emerging ^{16}O to the 0_2^+ state at 6.05 MeV is of particular interest, not only because of its large (ΔL_{gr}~2.5) mismatch, but also because of the very different nuclear structure of the 0_2^+ (4p-4h) and the (well-matched) 3^- (1p-1h) states. We report in this Letter total $^{16}O(0_2^+)$ cross-section excitation functions for the $^{16}O+^{16}O$ and $^{16}O+^{12}C$ systems.

A unique signature of 0_2^+ population is provided by detecting the $0_2^+\to0^+$(g.s.) e^+-e^- pair transition. The pair yield is directly proportional to the total 0_2^+ cross section since feeding from higher-lying states in ^{16}O and contributions from external or internal pair conversion of the $3^-\to0^+$(g.s.) γ transition are negligible. A large solid-angle (annular) detector constructed of plastic scintillators was used in these experiments.[8] It operated as a ΔE-E telescope, identifying minimum-ionizing pairs on the basis of energy loss. Additionally a fast triple coincidence was demanded between the ΔE detector and each of two optically isolated halves of scintillator that surrounded it and comprised the total-energy detector. Data were recorded in a two-dimensional ΔE versus summed E array. Because of the large multiplicity of γ rays stemming from fusion evaporation, a significant nonpair background was present. This was removed by performing two runs at each energy, one with an Al absorber inserted between the ΔE and E detectors to stop the pairs. The detector was calibrated by observing the pair transition in the reaction $^{19}F(p,\alpha)^{16}O(0_2^+)$.[8]

The $^{16}O+^{16}O$ excitation function was measured in 750-keV steps from $E_{lab}=50$ to 80 MeV using a Ta_2O_5 target of 670-$\mu g/cm^2$ thickness ($\Delta E_{c.m.}$ ~700 keV). The $^{16}O+^{12}C$ data were taken in 500-keV steps from $E_{lab}=39$ to 65 MeV, and in 1-MeV steps from 65 to 110 MeV with a 50-$\mu g/cm^2$ self-supporting C-foil target. Both experiments utilized ^{16}O beams from the Stony Brook and Brookhaven National Laboratory tandem accelerators.

The $^{16}O+^{16}O$ pair data are shown in Fig. 1. The regular gross structure ($\Gamma_{c.m.}$~1.5 MeV) in the 0_2^+ excitation function is strikingly similar to that observed in the well-matched 3^- channel. For comparison, we show the $3^-\to0^+$(g.s.) γ-decay data of Kolata *et al.*[1] The smaller 0_2^+ average cross section (~2 mb) at least partially reflects the poor matching of this exit channel versus the 3^- channel. In both curves, the peak energies are near the entrance channel shape resonances for successive even grazing partial waves in the Gobbi optical potential.[9]

Figure 2 displays our results for the reaction $^{12}C[^{16}O,^{16}O(0_2^+)]^{12}C$. The 0_2^+ data are characterized by many peaks of intermediate width ($\Gamma_{c.m.}$ $\approx$400 keV), most of which are correlated with those seen in the 3^- data,[2-4] shown in the same figure. Previously reported correlated peaks

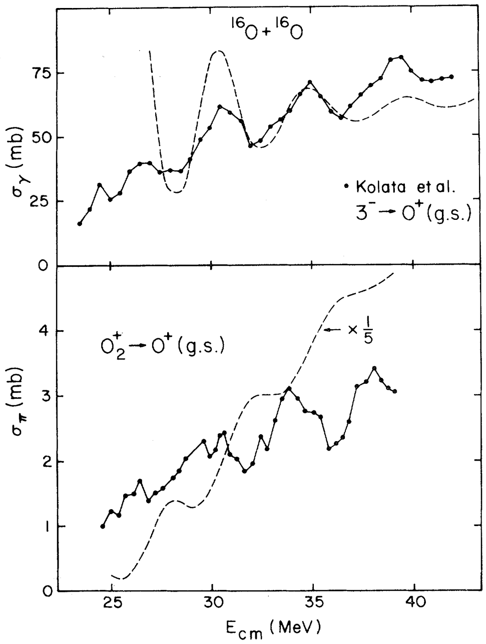

FIG. 1. Total cross section for the 6.05-MeV pair (π) transition (lower panel) in the $^{16}O + ^{16}O$ system. Statistical errors are smaller than the plotted data points; additional systematic (relative) errors may be as large as 8%. Also shown (upper panel) are the corresponding 3^-(6.13 MeV) γ-decay data of Kolata *et al.* (Ref. 1). The dashed curves are the result of a strong-absorption calculation (see text) with $\gamma = \pi/2$, $L_{gr} = 4.69 E_{c.m.}^{1/2} - 6.14$, $\Delta = 0.47 E_{c.m.}^{1/2} - 1.75$.

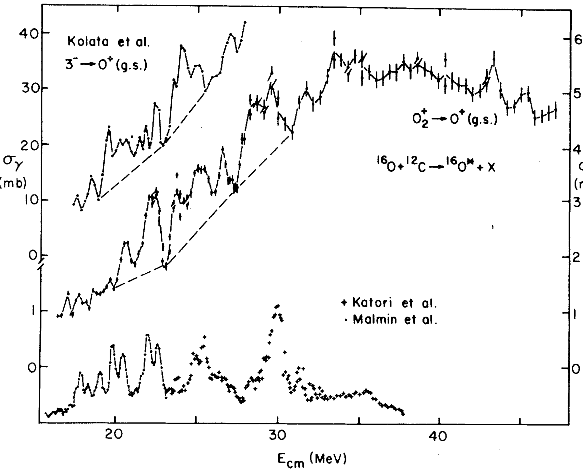

FIG. 2. Total cross section (middle curve) for the 6.05-MeV pair transition in the $^{16}O + ^{12}C$ system. The error bars reflect statistical uncertainties only. Also shown (top curve) are the corresponding 3^-(6.13 MeV) γ-decay data of Ref. 4, and (lower curve) the single-angle 3^- inelastic scattering data of Malmin, Harris, and Paul (Ref. 2) ($\theta_{c.m.} = 146.5°$) and Katori, Furuno, and Ooi (Ref. 3) ($\theta_{c.m.} \sim 15°$). The dashed lines represent the assumed nonresonant background. The vertical scales of the Malmin-Katori data are in arbitrary units.

near[10] 20.5, 22.0, and 22.6 MeV are confirmed by this experiment. The strong correlation persists above 23 MeV, contradicting the conclusions of Katori *et al.*, drawn from single-angle 0_2^+ and 3^- scattering measurements.[3]

The surprising correlation of structure in the 0_2^+ and 3^- excitation functions is at variance with several of the simple models that have been proposed. For the $^{16}O + ^{16}O$ system, involving only even partial waves in the entrance channel, Phillips *et al.*[7] have used a strong-absorption model to explain the gross structure in the $^{16}O(3^-)$ excitation function in terms of overlapping angular momentum windows for the external waves in the entrance and exit channels. We have performed a similar Austern-Blair calculation for both the 0_2^+ and 3^- exit channels, using the Ericson parametrization of the S matrix given by

$$S_L = \frac{1}{1 + \exp[-i\gamma + (L_{gr} - L)/\Delta(E)]}.$$

The parametrization of Ref. 7 has the feature that the width in angular momentum space $\Delta(E)$ is a decreasing function of energy, in contrast to what is expected semiclassically and found from optical-model calculations. We have therefore chosen an energy-dependent width parameter $\Delta(E)$ and grazing angular momentum L_{gr} to fit the optical-model dependence above $E_{lab} = 50$ MeV for the Gobbi potential.[9] The phase factor γ was set equal to $\pi/2$, precluding any potential resonances.

Our results are indicated by the dashed lines in Fig. 1. Because of the increase of $\Delta(E)$, the 3^- oscillations are strongly damped with increasing energy and the 0_2^+ cross section increases too steeply. More importantly, the positions and amplitudes of the calculated 0_2^+ oscillations do not agree with the data. Thus, it is unlikely that a strong-absorption model can simultaneously account for the observed gross structure in the 0_2^+ and 3^- data. If, however, a wave reflected from the interior of the ion-ion potential is included, such peaks could be explained in several ways, either from interference between the waves reflected from the inner and outer barriers, or as true resonances in the interior.[11] One such explanation, in terms of the band-crossing model,[12] has deficiences which will be discussed in connection with the $^{16}O + ^{12}C$ system.

TABLE I. Total resonance cross sections observed in the $^{16}O(3^-)$ and $^{16}O(0_2^+)$ exit channels of the $^{12}C+^{16}O$ system and ratios of reduced widths evaluated at three radii for resonances with established spins. A radius of 7.0 fm corresponds to the top of the outer barrier for $L=14$.

$E_{c.m.}$ (MeV)	J^{π} [a]	$\sigma_R(0^+)$ (mb)	$\sigma_R(3^-)$ [b] (mb)	$\gamma^2(0^+)/\gamma^2(3^-)$ $R=7.0$ fm	$R=7.5$ fm	$R=8.0$ fm
19.7	14^+	<0.23	9.5	0.63	0.36	0.22
20.5	12^+	0.83	6.5	1.02	0.70	0.56
22.0	15^-	1.46	3.75	7.03	3.93	2.48
22.6	13^-	1.46	7.75	1.23	0.89	0.76
25.3	15^-	1.31	4.75[c]	1.92	1.34	1.12
29.6	16^+	1.42	5.0[c]	1.32	1.10	1.07

[a]Spin values are from Refs. 13 and 14.
[b]From Ref. 4 except as noted.
[c]From Ref. 14.

In the $^{16}O+^{12}C$ system the presence of both even and odd partial waves makes the appearance of gross structure less likely. Instead the intermediate width structure which is observed in well-matched inelastic channels suggests coupling to more complex excitations of the composite system. Such a coupling is provided by the band-crossing model in its various forms,[5] in which the elastic ion-ion band interacts with nearby excited bands. The almost total correlation between peaks in the 3^- and 0_2^+ excitation functions is difficult to explain with such a model since the mismatched 0_2^+ (molecular) band does not come close to the elastic or the aligned 3^- band. Further evidence against such a simple explanation comes from recent spin measurements.[13,14] For instance, the resonances at 20.5 and 22.6 MeV have spins two units lower than those at 19.7 and 22.0 MeV, respectively, whereas the band crossing picture would predict the same spin for closely spaced doublets.

In spite of these failures of the simple band-crossing model, the close correlation of peaks in two so dissimilar exit channels strongly suggests that these peaks are indeed resonances associated with eigenstates of the combined nuclear system. To obtain an estimate of the presence of these two channels in the eigenfunction we define a ratio of reduced widths through the usual relation

$$\gamma^2(0_2^+)/\gamma^2(3^-)=[\Gamma(0_2^+)/\Gamma(3^-)][\sum_{L'}P_{L'}(3^-)/P_L(0_2^+)],$$

where the ratio of partial widths $\Gamma(0_2^+)/\Gamma(3^-)=\sigma_R(0_2^+)/\sigma_R(3^-)$ and the P_L are the usual penetration factors evaluated at an appropriate radius. The resonant cross sections σ_R were obtained from the data by subtracting a smooth background. Reduced width ratios of resonances with known spins are listed in Table I. The fact that both channels appear with roughly equal strength indicates strong channel mixing. It is likely that a model involving α-particle exchange could explain these ratios since both the 0_2^+ and the 3^- states are strongly populated in α-particle transfer.[15]

To summarize, we have presented evidence for regular resonancelike structures in both the $^{16}O+^{12}C$ and the $^{16}O+^{16}O$ systems, in a channel which is very unfavored in angular momentum. Both the wide peaks observed in $^{16}O+^{16}O$ system and the narrow peaks observed in $^{16}O+^{12}C$ system are strongly correlated with peaks seen in a well-matched channel. The correlation in the gross structure demonstrates the importance of the wave reflected from the interior of the ion-ion potential. The correlation of peaks of intermediate width is further evidence for their resonance character. The relative strengths of these resonances in the well-matched and the mismatched channels indicates strong channel-channel mixing such as is provided by an α-particle exchange process.

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