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Nature of Molecular Resonances and Background in the $^{16}O+^{12}C$ System

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High-resolution total reaction excitation functions for $^{16}O+^{12}C$ and detailed angular distributions for the reaction $^{12}C(^{16}O,\alpha)^{24}Mg$ have been measured. The interplay between (fifteen) resonance amplitudes and l-window (background) amplitudes is emphasized. Spin assignments, obtained from the α_0 data, are dominated by values of $8\hbar$ and $9\hbar$ while the grazing partial wave varies from $l=5$ to $l=10$ over the energy range studied. Elastic widths for the low-energy resonances indicate a dinuclear molecular nature; higher-energy resonances appear to originate from a more complex nuclear configuration.

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Recent experimental investigations[1] reveal that resonance phenomena are ubiquitous in light heavy-ion collisions. As part of our ongoing systematic study of molecular phenomena in nuclei, and because we wished to test further the apparent validity of the U(4) model[2] of binary nuclear molecular systems[3] that had been applied with considerable success to the $^{12}C+^{12}C$ system,[4] we have undertaken a detailed study of the $^{16}O+^{12}C$ system.

Measurement of the total reaction cross section via gamma-ray yields indicates the presence of fifteen resonances in the energy region from 7 to 15 MeV (c.m.). Angular momentum assignments were made to the structures from 10.3 to 14.0 MeV from measurements on detailed alpha-particle angular distributions from the reaction $^{12}C(^{16}O,\alpha_0)^{24}Mg$. Resonance spins in this region were found to be dominated by values of $8\hbar$ and $9\hbar$ despite a change of the grazing partial wave from $l=5$ to 10 over the same region. Elastic partial widths have been extracted and a comparison of the corresponding reduced widths with the Wigner limit indicates an apparent bifurcation in the nature of the observed resonance states. Those at energies below the Coulomb barrier show large fractions of the Wigner limit suggesting that they can be understood as dinuclear molecular states of the compound system strongly coupled to the entrance channel. Such binary systems are the ones to which the U(4) model[2] would be expected to be applicable. Above the barrier, the reduced widths exhaust a much smaller fraction of the Wigner limit suggesting that these resonances correspond to other, more complex nuclear configurations, not of the binary (dinuclear) character.

The total reaction cross section was measured in ~ 50-keV steps from 7 to 15 MeV (c.m.) via gamma-ray yields from residual reaction products. Thin 5–10 $\mu g/cm^2$ ^{12}C targets on thick Au backings (~ 3 mg/cm^2) were used. The data were normalized with use of Rutherford scattering.

The total reaction cross section, thus determined, is shown in Fig. 1, together with that extracted from the elastic scattering of $^{16}O+^{12}C$ by use of the sum of differences method[5] as well as the total fusion cross section.[6] Our data cannot include any exit channels leaving both reaction products in their ground states (e.g., states in ^{20}Ne that predominantly decay to $\alpha+^{16}O$). Thus they are of smaller absolute normalization than the true total reaction cross section measured from the sum-of-differences method,[5] but larger than the fusion data.[6] All three measurements of total cross section show excellent agreement as

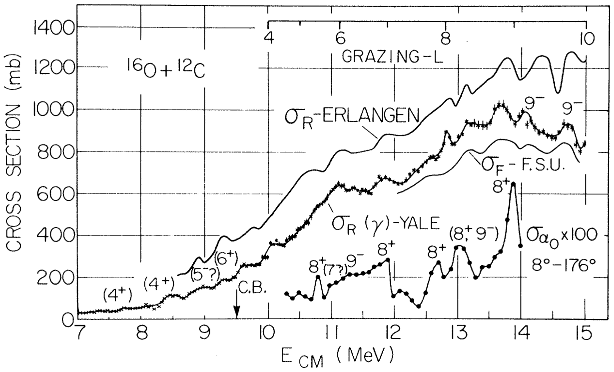

FIG. 1. Total reaction cross section for $^{16}O+^{12}C$, and angle-integrated α_0 exit-channel cross section. Our total reaction cross section, deduced from gamma-ray yields, lies between the sum-of-differences cross section (Ref. 5) and the fusion (Ref. 6) cross section, as expected.

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to the location of narrow resonances and good agreement as to the general energy dependence. The suggested[7] fragmentation of the 13.7-MeV resonance is not supported by any of the data shown in Fig. 1. We have evidence, which we shall discuss in a more complete report on the relevant $^{16}O + ^{16}O$ work,[8] which suggests that the proposed fine-structure triplet (around $E_L = 32$ MeV) reflects oxygen contamination of the target used, with the result that both $^{16}O + ^{12}C$ and $^{16}O + ^{16}O$ reactions have contributed to the reported[7] reaction yield.

The existing resonance angular momentum assignments below 10 MeV[9] and above 14 MeV[6] are indicated in Fig. 1. New spin values between these energy limits, have been established on the basis of our present measurements of $^{12}C(^{16}O, \alpha_0)^{24}Mg$ angular distributions. Thirty-eight such angular distributions were measured for this reaction from 8° to 176° in $\sim 3°$ steps over the energy region from 10.3 to 14.0 MeV in 100-keV intervals. The backward angular region was measured with use of a 30-μg/cm^2 WO_3 target evaporated onto a 200-μg/cm^2 Au backing. The forward-angle cross section, reversing the reaction, was measured with an ^{16}O beam on a 10-μg/cm^2 ^{12}C target. The measured differential cross sections were parametrized as series expansions of Legendre polynomials ($\sum B_l P_l$) and it was found that good fits ($\chi^2 \leq 3$) could be attained by terminating the series summation at $16 \leq L_{\max} \leq 22$ over the measured energy range. This suggests that the largest partial wave contributing at 10.3 MeV is 8 and at 14 MeV is 11. This parametrization of the cross section was used to generate the cross-section surface plot of Fig. 2. This surface plot clearly shows a dramatic difference between the shapes of angular distributions at forward and backward angles. The backward-angle shapes evolve quite slowly in energy and appear to be dominated by the grazing l values while the forward-angle cross sections display a rapid shape evolution showing structures having widths comparable to those of the resonances. In Fig. 2 we also show the Legendre expansion ($\sum B_l P_l$) and one possible phase-shift analysis ($|\sum A_l P_l|^2$) for an angular distribution measured off resonance (10.7 MeV) and on resonance (10.8 MeV). The off-resonance distribution clearly arises from amplitudes concentrated in a narrow window[8, 10] around the grazing partial wave ($l = 5$ or 6). The on-resonance distribution shows an 8^+ resonance amplitude interfering with an l-window background amplitude. Again we observe that the l-window amplitude appears to dominate the cross section at backward angles [or forward angles for the $(^{12}C, \alpha)$ transfer-of-^{8}Be reaction], and the 8^+ resonance cross-section contribution is observed only over a fraction of the angular range, where it resembles a $P_8{}^2$.

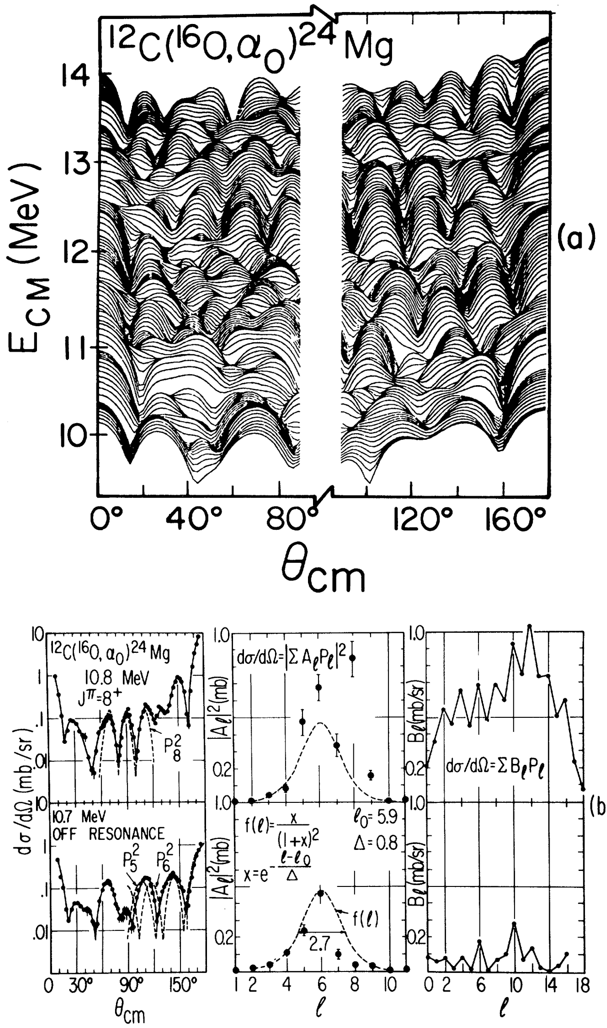

FIG. 2. Angular distributions of the α_0 exit channel for $^{16}O + ^{12}C$. (a) The surface plot and (b) the Legendre expansion ($\Sigma B_l P_l$) and one possible phase-shift analysis ($|\Sigma A_l P_l|^2$) suggest that the backward-angle region is dominated by slowly varying background l-window amplitudes centering around the grazing partial wave. The forward-angle region (first half) of the surface plot shows faster variations in the angular oscillatory pattern. At 10.8 MeV we clearly observe an 8^+ resonance amplitude interfering with a window around the l-grazing background amplitude. The resonant amplitude appears as a $P_8{}^2$ cross section over the limited angular range where the background contribution is too small to dominate it.

The spin assignments indicated on the angle-integrated cross section in Fig. 1 were deduced from the Legendre-expansion coefficients. These were then substantiated by data from excitation functions measured at the zeros of Legendre polynomials where resonances of relevant spin should not occur and by additional corraborative studies on this system.[11, 12]

The resonance total reaction cross section can be expressed as

$$\sigma^{\mathrm{Res}} = \frac{\pi}{k^2}(2J+1)\frac{\Gamma_C(\Gamma - \Gamma_C)}{(E - E_0)^2 + \frac{1}{4}\Gamma^2} \tag{1}$$

with the usual notation. From the total resonance reaction cross section we have deduced the two possible solutions of Γ_C/Γ for the observed resonances. The *physical* solution was then determined wherever possible, by examining the differential elastic scattering cross section and thus placing limits on the possible value of Γ_C/Γ.

A comparison of the elastic reduced widths to the corresponding Wigner limit provides a quantitative measure of the molecular nature of the states. A tabulation of this quantity labeled θ_C^2, for a particular radius parameter ($r_0 = 1.5$ fm), listed in Table I, shows a clear separation between the low- and high-energy resonances. Near the Coulomb barrier θ_C^2 is found to be a large fraction of the Wigner limit indicating that the resonances correspond to an $^{16}O + {}^{12}C$ dinuclear molecular configuration. The resonances above 10 MeV have values of θ_C^2 which are at least a factor of 4 less than those below the barrier suggesting that these resonances reflect different and more complex degrees of freedom.

TABLE I. Resonance parameters for $^{16}O + {}^{12}C$.

E_{cm} (MeV)	J^π	$\sigma_R^{\mathrm{Res}\,a}$ (mb)	Γ (keV)	Γ_C (keV)	$\theta_C^{2\,b}$
7.72	(4^+)	(12)	54		
8.45	(4^+)	44	179		
8.91	$(5^-?)$	26	234	220	0.81
9.26	(6^+)	24	101	96	0.41
9.58	···	49	108		
10.08	···	49	128		
10.75	8^+	27	103	(≤ 98)	(< 0.34)
11.09	$(7^-?)$	32	160	11	0.02
11.34	9^-	23	90	4	0.01
11.81	8^+	78	228	(≤ 189)	(< 0.29)
12.82	8^+	90	62	(≤ 48)	(< 0.05)
13.14	$(8^+, 9^-)$	59	109	14	0.01
13.67	8^+	107	260	(≤ 132)	(< 0.09)
14.06	9^-	74	133	23	0.02
14.72	9^-	96	177	46	0.03

[a] Estimated error ± 25%.

[b] Calculated for radius $R = 1.5\,(A_1^{1/3} + A_2^{1/3})$ fm.

The angular distribution data were used to extract values for alpha-particle exit-channel widths, Γ_α, through the Legendre-expansion coefficients. The coefficients on resonance, with spin J, can be written as

$$B_{L=2J}{}^{\mathrm{Res}} = \frac{1}{k^2}(2J+1)^2(JJ00|2J,0)^2\frac{\Gamma_\alpha\Gamma_C}{\Gamma^2} \tag{2}$$

for all studied resonances $1 \leq \Gamma_\alpha \leq 5$ keV. The corresponding reduced alpha widths γ_α^2 exhaust a small fraction of the Wigner limit, $\theta_\alpha^2 < 10^{-3}$, indicating that the resonances at higher energies do *not* correspond to an $\alpha + {}^{24}Mg$ configuration. Since $^{16}O + {}^{12}C$ and $\alpha + {}^{24}Mg$ are the dominant channels in this energy region we conclude that the resonances at higher energies are not of binary (diatomic) character. However, a polynuclear configuration involving alpha particles[8] clearly cannot be excluded. These values of Γ_α are moderately large; a comparison to values for lower-energy resonances may yet give an indication of the relative importance of the underlying alpha particle structure of these states.

In conclusion, we have measured the total reaction cross section for the $^{16}O + {}^{12}C$ system spanning the Coulomb barrier region and have found a number of new resonances. These resonances appear superimposed on an energy-dependent background related to an l window centering on the grazing partial wave. The background amplitudes appear to dominate the cross section of the $^{12}C(^{16}O, \alpha_0)^{24}Mg$ channel measured at far backward angles. Spin assignments have been made from measurements of detailed angular distributions for the $^{12}C(^{16}O, \alpha_0)^{24}Mg$ reaction, and excitation function studies carried out at zeros of the appropriate Legendre polynomials. A dinuclear molecular character is evident at low energies, below and in the vicinity of the barrier, while at higher energies the elastic reduced widths drop dramatically. Dinuclear $^{16}O + {}^{12}C$ and $\alpha + {}^{24}Mg$ configurations have been shown to be unimportant for these high-energy resonances, but more complex polynuclear molecular configuration involving alpha clusters, as suggested by Gai *et al.*,[8] cannot be excluded as yet. As a consequence of these data, we find that the U(4) model which was used to correlate resonance data in the $^{12}C + {}^{12}C$ system[4] may apply to the $^{16}O + {}^{12}C$ system only below the barrier.

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[1] D. A. Bromley, in *Resonances in Heavy Ion Reactions*, edited by K. A. Eberhard, Lecture Notes in Physics Vol. 156 (Springer-Verlag, Berlin, 1982), p. 3.

[2] F. Iachello, Phys. Rev. C 23, 2778 (1981).

[3] M. Gai, M. Ruscev, A. C. Hayes, J. F. Ennis, R. Keddy, E. C. Schloemer, S. M. Sterbenz, and D. A. Bromley, Phys. Rev. Lett. 50, 239 (1983).

[4] K. A. Erb and D. A. Bromley, Phys. Rev. C 23, 2781 (1981).

[5] H. Frohlich, P. Duck, W. Treu, and H. Voit, Phys. Rev. C 27, 578 (1983).

[6] A. D. Frawley, N. R. Fletcher, and L. C. Dennis, Phys. Rev. C 25, 860 (1982).

[7] P. Taras, G. R. Rao, and G. Azuelos, Phys. Rev. Lett. 41, 840 (1978).

[8] M. Gai, E. C. Schloemer, J. E. Freedman, A. C. Hayes, S. K. Korotky, J. M. Manoyan, B. Shivakumar, S. M. Sterbenz, H. Voit, S. J. Willett, and D. A. Bromley, Phys. Rev. Lett. 47, 1878 (1981), and Yale University Report No. 3074–749 (to be published).

[9] W. Treu, W. Galster, H. Frolich, H. Voit, and P. Duck, Phys. Lett. 72B, 315 (1978).

[10] P. Braun Munzinger and J. Barrette, Phys. Rev. Lett. 44, 719 (1980).

[11] M. L. Halbert, F. E. Durham, and A. van der Woude, Phys. Rev. 162, 899, 919 (1967).

[12] J. R. Hurd *et al.*, Bull. Am. Phys. Soc. 25, 728 (1980); H. T. Fortune, private communication.