Resonances in $^{16}O + ^{16}O$

M. Gai, E. C. Schloemer, J. E. Freedman, A. C. Hayes, S. K. Korotky,[a] J. M. Manoyan, B. Shivakumar, S. M. Sterbenz, H. Voit,[b] S. J. Willett, and D. A. Bromley
A. W. Wright Nuclear Structure Laboratory, Yale University, New Haven, Connecticut 06511
(Received 24 August 1981)

Unambiguous S matrix elements (resonant *and* background contributions) have been extracted from data on the reaction ^{16}O, $(^{16}O, \alpha_0)^{28}Si$. Assignments of $J^\pi = 10^+$, 8^+, and 8^+ have been made to resonances at $E_{c.m.} = 15.8$, 15.9, and 16.1 MeV, respectively: Nonresonant amplitudes result from a narrow angular momentum window about the $l = 10$ grazing partial wave; at 90° these dominate the reaction. Systematic behavior of the 8^+ resonances in this and other heavy-ion systems suggest that they may not be of binary character and that α-particle substructure may play a role.

PACS numbers: 25.70.-z, 24.30.-v

In the earliest measurements[1] on resonant phenomena in heavy-ion interactions it was already clear that the $^{12}C + ^{12}C$ and $^{16}O + ^{16}O$ systems displayed strikingly different behavior. Subsequent studies have delineated some 38 resonances in and above the barrier region in $^{12}C + ^{12}C$, while none have been reported for the $^{16}O + ^{16}O$ system. Recently reported[2] systematics of a number of heavy-ion systems involving $A = 4n$ nuclei have suggested the possibility that two quite distinct resonant structures are involved in the interactions of these light nuclei: Those in which the interacting nuclei retain their identity to yield a binary molecular complex, and those which are more complex and in which the underlying α-particle components of one or both of the interacting nuclei play an essential role.

We have been stimulated to undertake a more detailed examination of the $^{16}O + ^{16}O$ system via the channel $^{16}O(^{16}O, \alpha_0)^{28}Si$, and have located resonant phenomena at $E_{c.m.} \cong 15.8$, 15.9, and 16.1 MeV. In order to establish the parameters of these resonances we have carried out detailed angular distribution measurements in the resonance energy region, and have measured the $^{16}O + ^{16}O$ elastic scattering excitation function, as well as the $^{16}O(^{16}O, \alpha_1)^{28}Si^*$ total cross section.

Detailed analysis of all these data has yielded unambiguous S-matrix elements for the reaction $^{16}O(^{16}O, \alpha_0)^{28}Si$ in the resonance region. We have been able to disentangle the resonant and background amplitudes as well as examine the energy dependence of the background. From this analysis we have made the assignments $J^\pi = 10^+$, 8^+, and 8^+ to the new resonances; we have also demonstrated that the background comes from a narrow angular momentum window centered on the $l = 10$ grazing partial wave.[3]

Finally, we note that these resonances extend the systematic behavior that we have previously reported[2] for certain resonances in interaction between $A = 4n$ nuclei.

Figure 1 shows excitation function data in the range $15.5 \leq E_{c.m.} \leq 17.0$ MeV; all were measured in this laboratory. In addition to such data, fifteen angular distributions were measured in the angular range $17° \leq \theta_{c.m.} \leq 93°$, at 50-keV intervals over the energy range $15.5 \leq E_{c.m.} \leq 16.4$ MeV. Obviously the excitation functions of Fig. 1 show correlated structure suggestive of resonances. It bears emphasis, however, that such correlations are neither necessary, nor do they

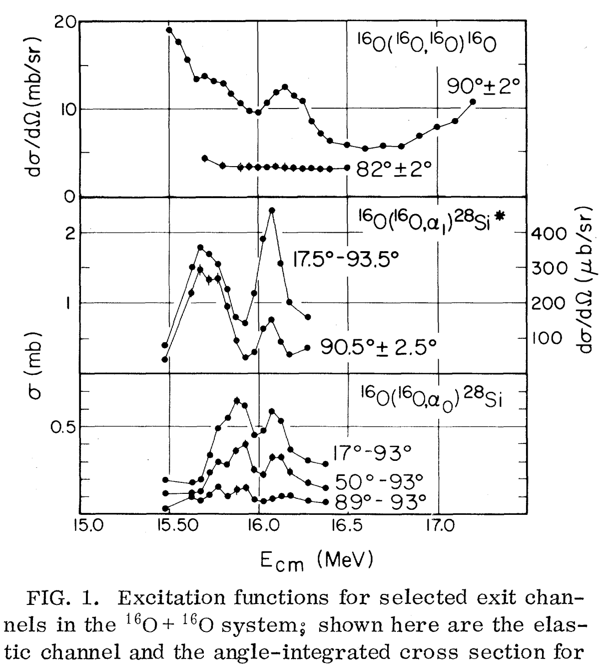

FIG. 1. Excitation functions for selected exit channels in the $^{16}O + ^{16}O$ system; shown here are the elastic channel and the angle-integrated cross section for α-particle groups corresponding to population of the ground and first excited states of ^{28}Si. The integration interval is given.

prove the existence of resonances as such.

We focus initially on the excitation function corresponding to population of the ^{28}Si ground state (α_0), here shown following angle integration over an interval $\Delta\theta \geq 40°$, which is substantially larger than the coherence angle[4] as we shall discuss below. It is important to note first, however, that the absence of structure in the elastic excitation function measured at $82° \pm 2°$ [very close to a zero of P_8, P_{10}, and $P_{12}(\cos\theta)$] suggests that $l = 8$, 10, and 12 partial waves are those of importance to the structure; $l = 10$ is the grazing partial wave in this energy region.[3]

To gain further insight into the structure, we have fitted our angular distribution data in the usual fashion, i.e.,

$$\frac{d\sigma}{d\Omega}(\theta_{\text{c.m.}})$$

$$= \frac{1}{2k^2}\left|\sum_{l=0}^{14} (2l+1)\exp[2i(\sigma_i + \sigma_0 + \delta_l)]S_l P_l(\theta_{\text{c.m.}})\right|^2$$

$$= |\textstyle\sum A_l P_l|^2,$$

where σ_i and σ_0 are the incident- and exit-channel Coulomb phase shifts and δ_l and S_l are the nuclear phase shift and the S-matrix element, respectively. In the least-squares fitting of this expression to our data it was found that the fits were sensitive only to variation in the $l = 8$, 10, and 12 terms, and in the final fits we limited the $l = 0$, 2, 4, 6, and 14 parameters and freely adjusted only the $l = 8$, 10, and 12 ones. This yielded a well-behaved curvature matrix in the fitting procedure and a single, deep, well-defined χ^2 minimum (at $\chi^2 \lesssim 3$).

Turning then to the angle-integrated cross sections, as shown in Fig. 1, we require an additional fit of the form $\sum|A_l|^2$ searching for a set of S_l parameters that provide the best fit to all the data. We have carried through this procedure and have obtained the results shown in Fig. 2, where we plot both the extracted S-matrix elements and the calculated angle-integrated cross section. It is clear that the S_l other than S_8 and S_{10} show behavior characteristic of statistical nonresonant processes; S_8 and δ_8 show two well-defined structures while S_{10} and δ_{10} show only one.

It is clear, however, that the S_{10} sharp structure appears to be superposed upon an energy-dependent background. We have therefore parametrized the S_8 and S_{10} elements as $S_l = S_l^{\text{BG}} = S_l^{\text{BW}}$, where the background component S_8^{BG} has been taken to be a complex constant consistent with the data of Fig. 2, and S_{10}^{BG}, reflecting the

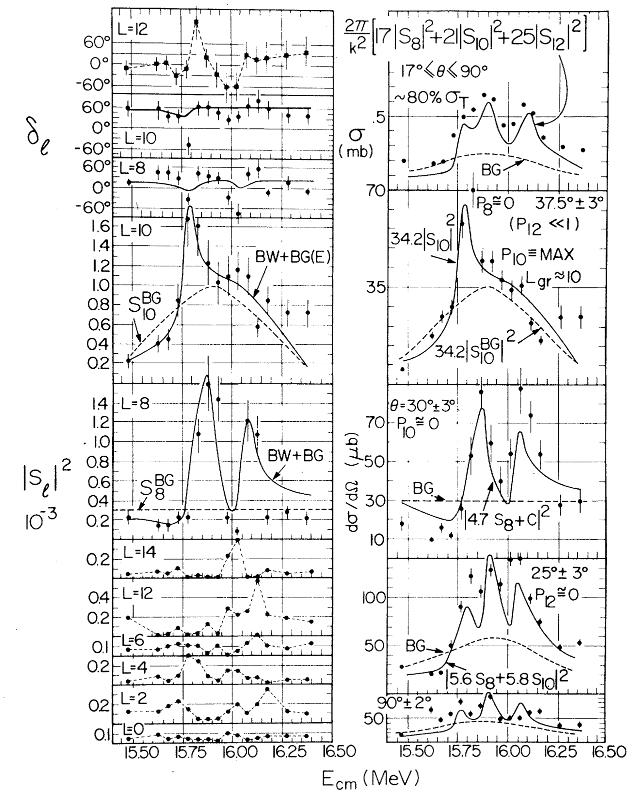

FIG. 2. Extracted S matrices and measured cross sections for the α_0 exit channel; the dashed lines are simply drawn through the data. The full line is the result of a Breit-Wigner plus background parametrization of the total S matrix as explained in the text. The measured total cross section, and the differential cross sections measured at zeros of appropriate Legendre polynomials, are reproduced by the contributions from one, two, or three partial waves ($l = 8, 10$, 12) solely, as shown by the full line. In particular, at $\theta_{\text{c.m.}} \cong 37.5°$, the cross section is entirely given by the $l = 10$ grazing partial wave, and it shows a narrow resonance superimposed on an energy-dependent background. It should be noted that the resonance mixing phase results in minima in the experimental values for δ_8 and δ_{10} which are more enhanced than the predicted one, reflecting additional fluctuations of the background phases.

fact that $l = 10$ is the grazing partial wave, has been taken as

$$S_{10}^{\text{BG}}(E) \propto \exp\left(\frac{E - E_0}{\Delta}\right)\left[1 + \exp\left(\frac{E - E_0}{\Delta}\right)\right]^{-2},$$

with $E_0 = 15.9$ MeV and $\Delta = 0.25$ MeV. We have assumed a standard Breit-Wigner form for the resonant component S_l^{BW}. This yields a width $\Gamma \sim 80$ keV for all three resonances. As shown in Fig. 2, a quite acceptable reproduction of the energy dependence of the extracted S_8 and S_{10} matrix elements is obtained with this procedure, including the background energy dependence of S_{10}.

We note, too, that at 15.75, 15.90, and 16.10 MeV (on resonance), the angular distributions, which we shall publish shortly in a more complete report on this work, in the angular range $17° \leq \theta_{c.m.} \leq 55°$ are well reproduced by P_{10}^2, P_8^2, and P_8^2, respectively. Several angular distributions measured off resonance show the oscillatory pattern characteristic of P_{10}^2, but the envelope of that oscillatory pattern is maximized at 90°, unlike that of a single Legendre polynomial. At 90° the envelope of all angular distribution oscillations remains maximized, consistent with a cross section derived from several partial waves centering upon the $l = 10$ grazing one. In the angular range $70° \leq \theta_{c.m.} \leq 90°$ the oscillatory pattern changes very little with energy over the entire region studied. Thus, it appears that the behavior of the angular distribution can be understood as reflecting the superposition of two coherent amplitudes, one a background amplitude which arises from the sharp l window around the $l = 10$ grazing partial wave and which dominates the cross section in the vicinity of $\theta_{c.m.} = 90°$, and the other the resonance amplitude that dominates the cross section in the range $17° \leq \theta_{c.m.} \leq 55°$, where the background amplitude is small. Energy-dependent interference of these two amplitudes is observed in the angular range $55° \leq \theta_{c.m.} \leq 70°$.

These observations suggest that we are dealing with resonances having $J^\pi = 10^+$, 8^+, and 8^+ at $E_{c.m.} = 15.75$, 15.90, and 16.10 MeV, respectively. The fits to the angle-integrated cross section in Fig. 2 indicate that the cross section comes almost entirely from the $l = 8$, 10, and 12 partial waves with resonances in the first two. Here we also show that at $\theta_{c.m.} \cong 37.5°$, which is a zero of P_8, a near zero of P_{12}, and a maximum of P_{10}, only the $l = 10$ partial wave is required to reproduce the experimentally measured excitation function. It bears emphasis that the angular momentum limitations imposed by the surface nature of the interaction have permitted us to choose an observation angle at which the experimentally observed cross section, and the S-matrix element derived from it, can be attributed to a single partial wave. Conversely, this places unusually stringent limitations on our extraction of these S-matrix elements, and thus, unambiguous extraction of the S matrix is made possible. At $\theta \cong 30°$, a zero of P_{10}, only the $l = 8$ partial wave and a constant background, which reflects the small contribution from all other partial waves, are required. At $\theta \cong 25°$, a zero of P_{12}, the $l = 8$ and $l = 10$ partial waves both contribute and reproduce the observed structure.

In the energy region of interest here, there are significant contributions from the $l = 8$, 10, and 12 partial waves; as shown in Ref. 4, this would correspond to a coherence angle of $\sim 20°$.

We recognize, of course, that statistical fluctuations can give rise to resonantlike structures in heavy-ion excitation functions. In the $^{12}C + ^{12}C$ system it has been shown[5] that the higher-energy structure was entirely consistent with a statistical origin, although the analysis did not *require* such an origin; at lower energies it is now well established that the structure is *not* statistical but, rather, of molecular character. Similarly, in the $^{16}O + ^{16}O$ system, it has been shown that at higher energies[6] the observed structure is consistent with a statistical origin. However, we believe that our data at lower energies, presented herein, as in the carbon case support a nonstatistical interpretation, although statistical components are also clearly evident, as in the behavior of the resonant phase shifts.

Clearly, the surface localization of the interaction here to the region of the grazing partial wave greatly simplifies the situation and has made possible an unambiguous detailed partial-wave analysis. This has enabled us to isolate and identify both $l = 8$ and $l = 10$ intermediate-width ($\Gamma \sim 80$ keV) phenomena within a gross-structure potential-scattering maximum normally attributed to the $l = 10$ grazing partial wave.

The pronounced 8^+ resonances located here further extend the empirical systematics that we have previously reported in which 8^+ resonances appear to occur at $E_{c.m.} = (4 \times 2.8) + (N \times 2.4)$ MeV, where N is integral, in moving from system to system involving $A = 4n$ nuclei.[2] As we have suggested earlier, this family of 8^+ resonances may well be those in which the underlying α-particle substructure of the interacting nuclei plays an essential role in distinguishing these resonances from the simpler binary type characteristic of the $^{12}C + ^{12}C$ barrier region.[7,8]

We are continuing our study of these resonances in $^{16}O + ^{16}O$, in particular, the extent to which they quantitatively satisfy the Bohr criterion,[9,10] and are continuing our study of what appears to be a qualitatively new family of heavy-ion interaction resonances related structurally among many heavy-ion systems.[2]

This work was supported in part by the U. S. Department of Energy under Contract No. DE-

AC02-76ER0374.

(a)Current address: Bell Laboratories, Holmdel, N. J. 07733.

(b)Permanent address: Physikalisches Institut der Universität Erlangen-Nürnberg, Erlangen, West Germany.

[1]D. A. Bromley, J. A. Kuehner, and E. Almqvist, Phys. Rev. Lett. 4, 365 (1960).

[2]M. Gai, Bull. Amer. Phys. Soc. 24, 843 (1979), and 25, 592 (1980), and in Proceedings of the International Conference on Nuclear Physics, Berkeley, California, 24–30 August 1980, LBL Report No. LBL-11118 (unpublished), pp. 424, 425; M. Gai and D. A. Bromley, to be published.

[3]A. Gobbi, R. Wieland, L. Chua, D. Shapira, and D. A. Bromley, Phys. Rev. C 7, 30 (1973).

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

[5]D. Shapira, R. G. Stokstad, and D. A. Bromley, Phys. Rev. C 10, 1063 (1974).

[6]R. E. Shaw, Jr., J. C. Norman, R. Vandenbosch, and J. C. Bishop, Phys. Rev. 185, 1040 (1969).

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

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

[9]N. Bohr, Nature 137, 344 (1936); N. Bohr and F. Kalckar, Mat.-Fys. Medd. Danske Vid. Selsk 14, No. 10 (1937).

[10]A. S. Rinat and J. Arvieux, Phys. Lett. 104B, 182 (1981); A. S. Rinat, private communication.

Limiting Angular Momenta for Light Heavy-Ion Fusion at High Energy

A. Szanto de Toledo

Laboratorio Pelletron, Instituto de Física da Universidade de São Paulo, São Paulo, Brazil, and Department of Physics, University of Rochester, Rochester, New York 14623

and

T. M. Cormier, M. Herman, B. Lin, and P. M. Stwertka

Department of Physics, University of Rochester, Rochester, New York 14623

and

M. M. Coimbra and N. Carlin Filho

Laboratorio Pelletron, Instituto de Física da Universidade de São Paulo, São Paulo, Brazil

(Received 12 August 1981)

The shapes of angular distributions in reactions $^{12}C(^{16}O, \alpha)$ to the $J^\pi = 0^+$ ^{24}Mg ground state are studied from $E(^{16}O) = 28.5$ to 100 MeV. The position of the first minimum (and maximum) of these oscillatory angular distributions is expected to be sensitive to the presence of a low–angular-momentum cutoff in the compound-nucleus formation cross section. No evidence for a low-L cutoff is found even at energies well beyond the predicted threshold.

PACS numbers: 25.70.Fg, 25.70.Bc

Time-dependent Hartree-Fock (TDHF) theory predicts the inhibition of low–impact-parameter fusion in nucleus-nucleus collisions at high energy.[1] This fact has provoked a number of experimental investigations attempting to isolate the effect.[2,3] An unambiguous result, however, has not been forthcoming chiefly because the low partial waves make an extremely small contribution to the fusion cross section. Recently, it has been shown by Szanto de Toledo and Hussein[4] that the presence of the low-L cutoff predicted by TDHF theory will strongly influence the shapes of zero-channel-spin angular distributions in statistical compound-nucleus decay. In the present Letter we report the results of applying this method to the fusion of $^{16}O + ^{12}C$ to search for the predicted inhibition of low-L fusion.

We have studied the ground-state transition (α_0) of the reaction $^{12}C(^{16}O, \alpha)^{24}Mg$ from $E(^{16}O) = 28.5$ to 100 MeV. The shapes of the α_0 angular distributions have been analyzed within the statistical-model framework. Our results show no significant deviation from compound-nucleus predictions using *no* low-L cutoff. Upper limits for the minimum angular momentum contributing to $^{16}O + ^{12}C$ fusion are established up to $E(^{16}O) = 100$