Evidence for Shape or Quasimolecular Resonances in the $^{16}O + {}^{16}O$ Interaction*

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(Received 24 April 1972)

Differential cross sections have been measured for the reaction $^{16}O(^{16}O, {}^{12}C)^{20}Ne$ leading to the first three states of ^{20}Ne at c.m. energies from 17.5 to 30 MeV and c.m. angles of approximately 62°, 76°, and 90°. The yield curves are characterized by (1) gross structures and narrow structures, and (2) strong angular and cross correlations. It is suggested that these results present direct evidence for shape or quasimolecular resonances in the $^{16}O + {}^{16}O$ system.

The striking gross structures observed[1] in the excitation functions for elastic scattering of ^{16}O from ^{16}O have since been observed[2,3] for many different heavy-ion systems. The prominent result of systematic optical-model analyses[2-5] of these data is that the scattering is dominated by surface partial waves which are weakly absorbed. The weak absorption can lead to shape resonances of surface partial waves. Because of the difficulties in obtaining unique phase shifts in a partial-wave analysis, there is only indirect evidence for such resonances from optical-model[6] and Regge-pole[7] analyses. If the weak absorption is due to the availability of only very few exit channels which can carry away the incoming angular momenta of the surface partial waves,[4,8] then such resonances might also show up in those exit channels. The reaction $^{16}O(^{16}O, {}^{12}C)^{20}Ne$ is a good candidate for investigating this phenomenon, and this report describes the results of such a study[9] in which we find strong evidence for the existence of shape resonances.

The ^{16}O beam from the Argonne National Laboratory tandem Van de Graaff accelerator was used to bombard self-supporting Al_2O_3 targets approximately 100 $\mu g/cm^2$ thick. The detection of the two associated product particles in kinematic coincidence served to identify the specific reaction. Three pairs of large-area, solid-state detectors with acceptance angles of ±0.25° were used in a 180-cm scattering chamber and positioned at the kinematically correct angles under computer control. Excitation functions were obtained for the reactions leading to (a) the 0^+ ground state of ^{20}Ne, (b) the 1.63-MeV 2^+ state of ^{20}Ne, and (c) the 4.25-MeV 4^+ state of ^{20}Ne and/or the 4.43-MeV 2^+ state of ^{12}C (hereafter referred to simply as the 4.3-MeV state[10]). The measurements were made from 17.5 to 30 MeV c.m. energy in 125-keV steps at fixed laboratory angles (indicated in Fig. 1) corresponding to c.m. angles of approximately 62°, 76°, and 90°. For each transition studied, angular distributions were measured at eleven selected energies at c.m. angles from 50° to 90° in 2° intervals (several of these are shown in Fig. 2).

The excitation functions for the reactions $^{16}O(^{16}O, {}^{12}C)^{20}Ne$ shown in Fig. 1 are characterized by narrow structures (~300 keV wide) and gross structures (~1.5 MeV wide). Although the narrow width is only slightly larger than the target thickness (250 keV) and could hence be due to energy averaging introduced by the target, preliminary measurements with a thinner target (100 keV) extending over 25 to 27.5 MeV c.m. energy in 62.5-keV steps did not show narrower structures. Of particular interest is the gross structure in the 4.3-MeV excitation curve [Fig. 1(c)]. A strong resonancelike peak is observed around 26.5 MeV, which has a width of 1.5 MeV. There are indications of a similar structure just beyond 30 MeV,[11] and to a lesser extent near 22.5 MeV. For the other two states [Figs. 1(a), 1(b)] there are also indications of gross structure near 22.5 and 26.5 MeV, especially when the cross sections are averaged in energy (Fig. 1, dashed curves).

A very striking feature of our data is the strong angular correlations in the excitation functions, especially for the 4.3- and 1.63-MeV states; each peak or shoulder in the yield curve for one angle is present as a peak or shoulder in those for the other angles. In order to obtain a quantitative measure of these correlations, a statistical an-

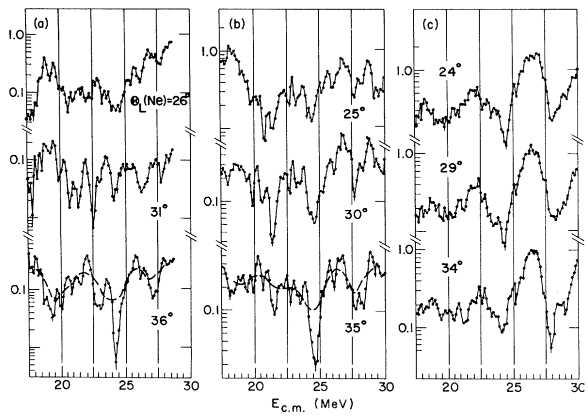

FIG. 1. Excitation functions for the reactions $^{16}O(^{16}O, {}^{12}C)^{20}Ne$ leading to (a) the ground state, (b) 1.63-MeV state, and (c) 4.3-MeV state. The solid circles are data points. Representative error bars are shown in some cases. The dashed curves are the averaged cross section, smoothed with a rectangular function of total width 1.5 MeV. The angles indicated are the lab angles of the observed ^{20}Ne recoil and correspond to approximately 62°, 76°, and 90° in the c.m. system.

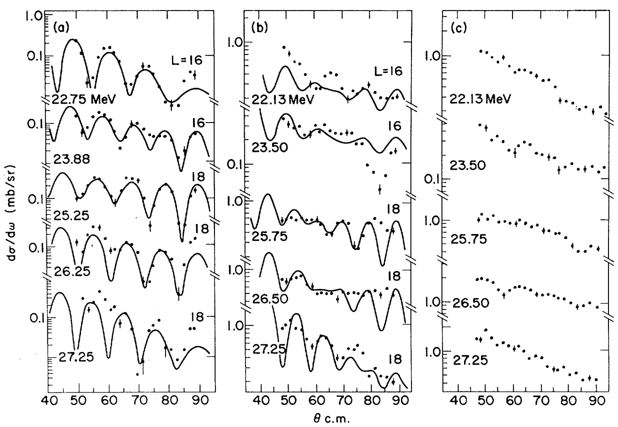

FIG. 2. Angular distributions at the c.m. energies indicated for the reactions $^{16}O(^{16}O, {}^{12}C)^{20}Ne$ to (a) the ground state, (b) 1.63-MeV state, and (c) 4.3-MeV state. The solid lines represent fits to the data with a partial-wave expression (Ref. 17) for values of L indicated next to each curve.

alysis was performed using an average cross section computed on a running interval of 3 MeV. These calculations gave angular correlations for the ground state of the order of 40%, but values of 80–90% for the 1.63- and 4.3-MeV states. Strong cross correlations at 90° were found between the 4.3- and 1.63-MeV states (~60%) and between the 1.63-MeV and ground states (~50%). The extracted coherence widths for the ground and 1.63-MeV states are in the range of 250–300 keV.

These extensive angular correlations over a wide energy range are suggestive of a reaction mechanism in which only a few partial waves contribute. This selectivity is expected because at any given energy the surface partial waves in the $^{16}O + {}^{16}O$ channel can only be absorbed[8] into a few channels, including the $^{12}C + {}^{20}Ne$ channel, whereas the lower partial waves may be absorbed into many more channels. Although it may be possible to understand angular correlations in terms of a purely statistical process if only one partial wave dominates, the strong angular and cross correlations over a large energy range are unlikely to be a random statistical phenomenon. The narrow structures in the excitation functions and the angular correlations are obviously not a direct interaction effect. The lack of structure in the angular distributions for the 1.63- and 4.3-MeV states rules out a diffraction phenomenon as the cause of the pronounced gross structure at 26.5 MeV. Finally, the gross structures found in Hauser-Feshbach calculations[12] of the $^{16}O + {}^{16}O$ elastic scattering are too shallow (peak-to-valley ratios of 2:1) to account for the observed gross structures in the present data (peak-to-valley ratios up to 15:1).

We propose that the gross structures in these data represent shape resonances of a particular surface partial wave. The strength of a shape resonance is shared among the states of the $^{16}O + {}^{16}O$ compound system, just as in the case of a doorway state.[13] The underlying states give rise to narrow structures seen in the excitation functions. The existence of the shape resonances is made particularly visible in this system because (1) only even partial waves contribute (because of the identity of particles in the entrance channel) and the energies at which the shape resonances occur are well separated, and (2) since the surface partial waves are only weakly absorbed, their strength neither spreads[14] over a large energy range nor is shared among many channels. Though there may be many, even overlapping, resonances of the $^{16}O + {}^{16}O$ system in the vicinity of the shape resonance, the coherence introduced by the latter keeps the former from interfering with one another in a random fashion resulting in statistical fluctuations. Rather, collectively these resonances act as if there was only one resonance. The same effect is found for analog resonances[15] and for giant dipole resonances[16] in

(p, γ) studies. In the latter case, as a result of the dominance of a specific configuration, the angular distributions show little variation in the energy region of the giant resonance even though the excitation functions show large gross and narrow structures.

All features of the data can be readily understood in terms of the picture presented above. The strong angular correlations are characteristic of cross sections which are dominated by resonances of the same spin. The extent of the cross correlations among the various channels, and the relative magnitudes of the gross and narrow structure, is governed by the partial widths of the underlying resonances for each of the channels. These partial widths are appreciable for the 4.3-MeV state producing, collectively, the observed gross structures. Slightly smaller partial widths for the 1.63-MeV state can explain why the narrow structure is somewhat more pronounced than the gross structure. Relatively small angular and cross correlations for the ground state imply that the underlying resonances have small partial widths for this channel. The progessively decreasing structure in the angular distributions for the 1.63-MeV 2^+ state and the 4.3-MeV 4^+ state is understood to result from coherent contributions of many outgoing L values (three for 2^+ and five for 4^+ final states).

Attempts to determine the dominant partial waves were made by fitting the observed angular distributions for the ground-state transition with a simple partial-wave expression.[17] Good fits (solid curves in Fig. 2) were obtained with $L = 16$ and 18 in the vicinity of 23 and 26.5 MeV, respectively, confirming the expected dominance of grazing partial waves in this reaction. For the 1.63-MeV state acceptable fits [solid lines in Fig. 2(b)] were obtained with the same L values as found for the ground state at the respective energies. Lack of structure in the 4.3-MeV angular distributions precluded any definitive analysis, but we expect the dominant partial waves to be the same in all channels since the yield curves are highly correlated. Thus the shape or quasimolecular resonances represented by the gross structures, as well as the underlying states responsible for the narrow structures, have probable spin of 16 near 23 MeV and 18 near 26.5 MeV. It is interesting to note that the optical model[2] predicts resonances with the same spins in the vicinity of the above energies,[18] whereas the molecular-type potential[5] predicts spins of 14 and 16 near 23 and 26.5 MeV.

In summary, the salient features of the $^{16}O(^{16}O, ^{12}C)^{20}Ne$ data are consistent with and indeed provide a confirmation of the idea that the elastic scattering of these heavy ions is dominated by surface partial waves which are weakly absorbed. The observed gross structures present direct evidence for the existence of the shape resonances in the $^{16}O + ^{16}O$ system. The narrow structures represent the high-spin states of the $^{16}O + ^{16}O$ compound system which are sharing the strength of the shape resonance just as in the case of doorway states. It is worth pointing out that the width of the narrow structures (~300 keV) seen in this study are considerably larger than those seen in the $^{16}O + ^{16}O$ elastic data (~85 keV).[19] Therefore these narrow structures may well be the intermediate states[20] of the $^{16}O + ^{16}O$ compound system.

The authors from Indiana University are indebted to the Argonne National Laboratory for the use of the experimental facilities.

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*Work partially supported by the National Science Foundation.

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‡Work performed under the auspices of the U. S. Atomic Energy Commission.

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[2]A recent and excellent account of most heavy-ion elastic scattering measurements and their analyses in terms of various models can be found in the Proceedings of the Symposium on Heavy-Ion Scattering, Argonne National Laboratory Report No. ANL-7837, March 1971 (to be published).

[3]R. H. Siemssen, H. T. Fortune, R. Malmin, A. Richter, J. W. Tippie, and P. P. Singh, Phys. Rev. Lett. 25, 536 (1970).

[4]R. A. Chatwin, J. S. Eck, D. Robson, and A. Richter, Phys. Rev. C 1, 795 (1970).

[5]Microscopic theories for heavy-ion interactions have been proposed, e.g., by W. Scheid, W. Greiner, and R. Lemmer, Phys. Rev. Lett. 25, 176 (1970), and ANL Report No. ANL-7837. See also K. A. Brueckner, J. R. Buchler, S. Jorna, and R. J. Lombar, Phys. Rev. 171, 1188 (1968). These theories have had some success in explaining the qualitative features of the data and agree with the optical-model analyses in predicting very shallow real potentials.

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[9]Preliminary results of this investigation were reported by P. P. Singh, D. A. Sink, P. Schwandt, R. F. Malmin, and R. H. Siemssen, ANL Report No. ANL-7837, p. 195.

[10]The predominent component is believed to be the 4^+ state of Ne^{20} since (1) the ^{12}C peaks in the energy spectrum did not show additional Doppler broadening due to γ decay, (2) the $2J+1$ factor would favor the reaction to the 4^+ state, and (3) in a recent measurement P. Glaessel, J. Hertel, and G. Trost, in the Annual Report of the Acceleratory Laboratory of the Technical University of Munich, 1971 (unpublished), p. 12, did not observe a significant yield of the 4.43-MeV γ rays in this reaction. Also, if the reaction proceeds through direct interaction, then the binding-energy arguments would favor the reaction to the 4^+ state.

[11]A pronounced gross structure around 31 MeV in the 4.3-MeV excitation curve has indeed been observed recently by K. A. Eberhard, G. Hindever, H. H. Rossner, and A. Weidinger, in the Annual Report of the Accelerator Laboratory of the Technical University of Munich, 1971 (unpublished), p. 20.

[12]R. W. Shaw, Jr., J. C. Norman, R. Vandenbosh, and C. J. Bishop, Phys. Rev. 184, 1040 (1967).

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[14]The spreading width of the shape resonances, as in doorway states, would be proportional to the absorption potential strength for the corresponding partial wave. See for example, A. M. Lane, in *Isospin In Nuclear Physics*, edited by D. H. Wilkinson (North-Holland, Amsterdam, 1969), p. 509.

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[16]P. P. Singh, R. E. Segel, L. Meyer-Schutzmeister, S. S. Hanna, and R. G. Allas, Nucl. Phys. 65, 577 (1965), and Phys. Rev. Lett. 13, 628 (1964).

[17]The expression used was of the form $\sigma(\theta)=\sigma_B+|\eta_L \times P_L(\cos\theta)+\eta_{L-2}e^{i\delta}P_{L-2}(\cos\theta)|^2$. The energy-independent background term σ_B represented only 5–10% of the cross section. The results showed no significant changes when the background was incorporated as a complex amplitude.

[18]The $^{16}O+^{16}O$ optical-potential phase shifts predict a $L=14$ resonance at 17.8 MeV (~1 MeV wide), a $L=16$ resonance at 22.3 MeV (~1.5 MeV wide), and a $L=18$ resonance at 26.7 MeV (~2.5 MeV wide).

[19]R. Vandenbosh, ANL Report No. ANL-7837, p. 103.

[20]There is increasing evidence for the existence of intermediate states in heavy ion interaction, e.g., see the Proceedings of the Symposium on Heavy Ion Reactions and Many-particle Excitations, Saclay, 1971, J. Phys. (Paris), Suppl. 32, C6 (1972).

Mixing of Two-Proton Bands with Two-Neutron Bands in ^{176}Hf

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(Received 18 May 1972)

We present evidence for the interaction of high-spin two-quasiproton bands with two-quasineutron bands in ^{176}Hf. The two $K^\pi=6^+$ bands at 1333.1 and 1761.5 keV are shown to be of highly mixed character. A $K^\pi=8^-$ band at 1559.4 keV, which is largely of two-proton character, is shown to be mixed with a predominantly two-neutron $K=8^-$ band at 1860.3 keV.

The observation in ^{178}Hf of the possible mixing of two $K^\pi=8^-$ bands[1,2] has stimulated an interest in the mixing of high-spin two-quasiproton and two-quasineutron states in other even-even nuclei. As a consequence of this mixing, one may expect to observe interband transitions between the rotational members of the two mixed states. The only example of this phenomenon which has been reported[1] is the transition between the band heads of the two $K=8$ bands in ^{178}Hf.

Very few high-K rotational bands have been observed in even-even nuclei. It is rarely possible to populate them in radioactive decay studies because of the paucity of high-spin sources. Moreover, (heavy ion, xn) reaction studies which do excite states of high angular momentum have, until the present, been largely unsuccessful in studies of high-K bands because these bands are not part of the strongly populated yrast line. Furthermore, the number of high-K bands which can be populated by single-nucleon transfer reactions is limited because the only two-quasiparticle states which can be formed are those for which one of the particles exists as the odd nucleon in the target ground state.

The ^{176}Hf nucleus is an ideal candidate for a search for mixed high-K states because it is expected that the level scheme should contain two