New $J^{\pi}=10^{+}$ resonance in $^{16}O+^{16}O$

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Small angle cross sections for $^{16}O(^{16}O,\alpha_0)$ and $^{16}O(^{16}O,\alpha_1)$ reactions have been measured from $E_{c.m.}\sim 12$ to 20 MeV in 50 keV steps and angular distributions are measured at selected energies. A well-isolated resonance with $J^{\pi}=10^{+}$ and $\Gamma\simeq 100$ keV is found at $E_{c.m.}\simeq 15.2$ MeV. The high density of narrow structure over the entire energy range studied indicates no significant influence of dinucleus resonant states of ^{32}S in these reactions.

Resonantlike structures in the scattering and reaction cross sections for heavy-ion collisions have been observed most commonly for $A=4n$ nuclei. Reactions from the $^{12}C+^{12}C$ and $^{12}C+^{16}O$ systems in particular have been found to exhibit an abundance of resonances of intermediate width ($\sim$100–500 keV). The interaction of $^{16}O+^{16}O$, which very clearly had shown gross structure and intermediate structure in the elastic scattering cross section,[1] has not been investigated in great detail in the reaction channels. Only very recently have narrow resonances been reported in $^{16}O+^{16}O$ reaction channels, and they seem to appear both in the Coulomb barrier region[3] and also well above the barrier.[4,5] The status and recent history of heavy ion resonance reactions has been reviewed very well by Cormier.[2] It is clear that the narrower resonances must involve more degrees of freedom and a more complex structure than what is most usually referred to as molecular states.

The work of Gai *et al.* has clearly demonstrated resonances with $\Gamma<100$ keV near $E_{c.m.}=16$ MeV for $^{16}O+^{16}O$. Their analysis has also allowed them to determine J^{π} values for these resonances, although assumptions are required in order to remove the inherent ambiguities in the coherent Legendre fitting of angular distribution data. The only disturbing feature of their analysis is the necessity of an $l=10$ background amplitude which has a resonantlike energy dependence with a 500 keV width, not very different from some structures referred to as resonances. The energy dependent effects of l-dependent potentials should yield structure widths of not less than 1 MeV.

The present work performed at the Florida State University Tandem Accelerator Laboratory is a broad energy range study of the $^{16}O(^{16}O,\alpha)$ cross section at small angles, $\theta_{lab}\sim 4°$, to see if the narrow resonances observed by Gai *et al.* persist at other energies, and of detailed angular distributions over the range $\theta_{c.m.}\sim 6°\rightarrow 93°$ in the energy region studied by Gai *et al.*, as well as slightly lower energy where a well-isolated resonance appears at $E_{c.m.}\simeq 15.2$ MeV. The small angle detector used was a lithium drifted silicon annular detector which spanned the angular range $\theta_{lab}\sim 2°$–$6°$ with $\Delta\Omega\sim 32$ msr. For angular distribution measurements an array of eight rectangular Si(Li) detectors was used with 5° separations and with $\Delta\Omega\sim 9$ msr for each detector. In all cases, the beam energy loss in targets of SiO_2 vacuum deposited on thin carbon backings was <100 keV. The silicon and oxygen content of the targets was determined by observing the elastic scattering of a 20 MeV oxygen beam at angles $\leq 20°$ where the cross section was assumed to be due to Coulomb scattering only.

The small angle excitation functions for the reactions $^{16}O(^{16}O,\alpha_0)$ and $^{16}O(^{16}O,\alpha_1)$, measured from $E_{c.m.}\sim 12$ to 20 MeV in 50 keV steps, are shown in Fig. 1. The structure observed is extremely complex. The resonances reported by Gai *et al.* at $E_{c.m.}\simeq 15.8$, 15.9, and 16.1 MeV appear as only two peaks near 15.8 and 16.0 MeV in both the α_0 and α_1 cross sections of Fig. 1. Our actual resonance energies are extracted from a linear Legendre analysis which will follow. The most isolated structure of the 20 to 30 appearing in this energy region is at $E_{c.m.}\simeq 15.2$ MeV. It is clear, however, that the high density of narrow structures initially observed persists over this entire energy range. There are many correlated maxima in the α_0 and α_1 cross sections (13.7, 13.8, 14.4, 14.7, 15.1, 15.5, . . . , MeV), but the high density of structures

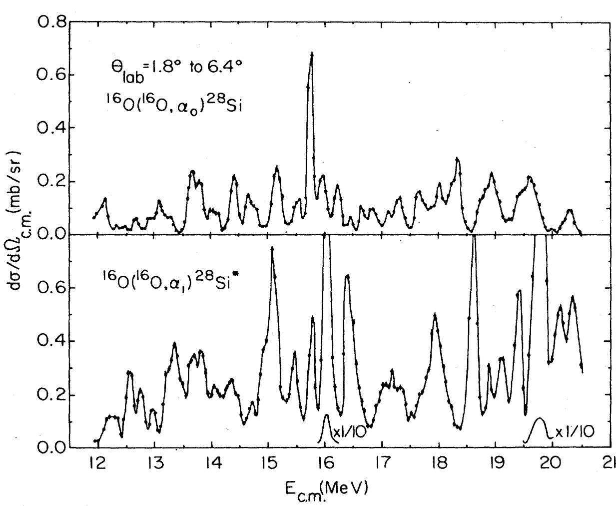

FIG. 1. Small angle cross section for the α_0 and α_1 reaction channels of $^{16}O+^{16}O$ and $E_{c.m.}=12$ to 20.5 MeV.

degrades the energy correlation as good evidence for resonances.

Angular distributions were measured in energy increments of 50 keV over the energy regions of the identified resonances already cited. In Fig. 2 we see that the cross section exhibits a very well-behaved $l=10$ periodicity near the approximate resonance energy of 15.2 MeV, whereas off resonance, the yield is less and obviously not dominated by single l values. Similar measurements over the three resonances reported by Gai *et al.* do not show results so easily interpretable (see Fig. 3). From the angular distribution measurements, we have simulated the total cross section by use of the equation

$$\sigma_{\text{sum}}=\sum \sigma(\theta_i)\sin(\theta_i) ,$$

and the result is shown in Fig. 4. We see that the summed cross section maximizes in both the α_0 and α_1 channels for the energies of 15.2 and 16.1 MeV, and somewhat for 15.8 MeV. A resonance at 15.9 MeV reported by Gai *et al.* appears only in α_0 as a broadening of the σ_{sum} curve or when different angular regions are summed, in particular, all three of their resonances appear as small maxima in σ_{sum} for $\theta_{\text{c.m.}} \sim 75°–90°$ (see open circles in Fig. 4), whereas only the one near 15.8 MeV appears in the forward angles summation data, $\theta_{\text{c.m.}} \sim 6°–25°$ (open squares).

The angular distributions have also been expressed as linear Legendre expansions by least square evaluation of coefficients in the expression

$$\sigma(\theta,E)=\sum_{k=0}^{2L} a_k(E)P_k(\cos\theta) .$$

The energy dependence of coefficients, $a_K(E)$, is used to determine resonant J^π values as described earlier[6] for symmetric entrance channels and spin zero particles. The coefficient a_{2l} will maximize on a resonance of $J=l$ in addition to smaller effects on all other coefficients $a_{2l'}$, $l'<l$. A resonance can also sometimes be observed

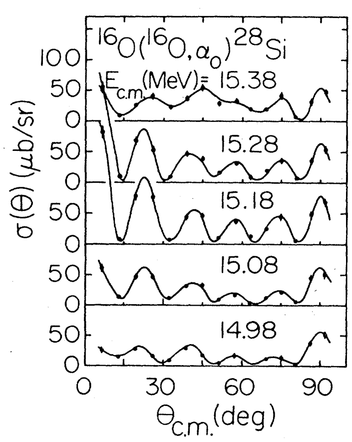

FIG. 2. Angular distributions measured over the $J^\pi=10^+$ resonance at 15.20 MeV. Maxima in the $|P_{10}(\cos\theta)|^2$ function occur at $\theta=21°$, 38°, 56°, and 73°, in addition to 0° and 90°. Curves have been drawn through the data to guide the eye.

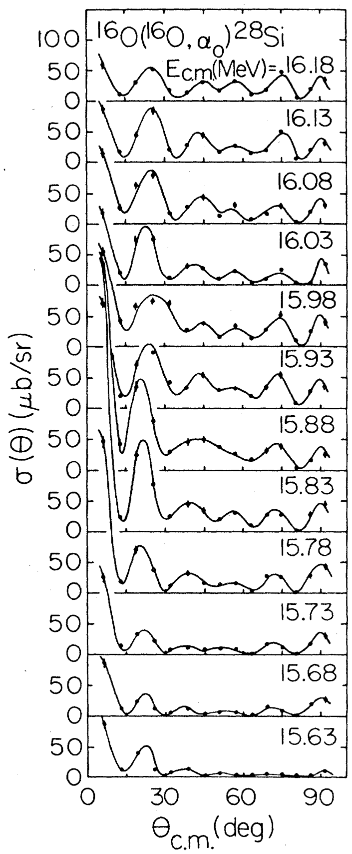

FIG. 3. Angular distribution measured in 50 keV steps over the region of the resonance triplet reported by Gai *et al.* (Ref. 4). Curves have been drawn through the data to guide the eye.

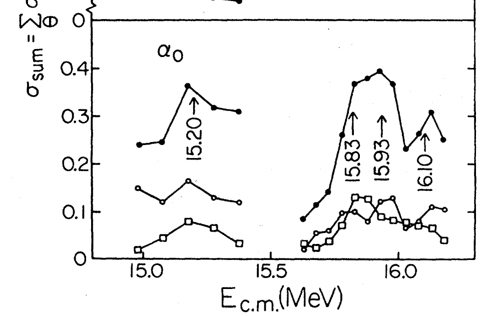

FIG. 4. Energy dependence of α_0 and α_1 cross sections in $\sigma_{\text{sum}}=\sum\sigma(\theta)\sin\theta$ in resonance regions. The angular ranges are $\theta_{\text{c.m.}}=6°–92°$ (closed circles), 6°–26° (open squares), and 75°–92° (open circles).

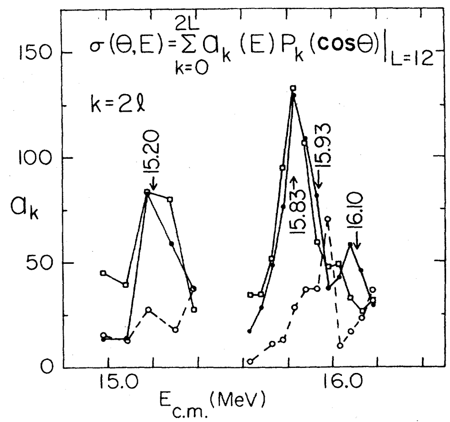

FIG. 5. Energy dependence of Legendre coefficients a_{2l} for $l=8$ (closed circles), $l=10$ (open squares), and $l=12$ (open circles). The full angular range, 6°–92°, was used in obtaining values of a_{2l} by least squares fitting.

to a lesser degree in the energy dependence of a coefficient with $l'>l$ through interference effects. For a maximum angular momentum in the expansion of $L=12$, the coefficients determined in the energy realm of these resonances are shown in Fig. 5. The $l=10$ values (open squares) show $J=10$ resonances near center of mass energies of 15.2 and 15.8 MeV, and the $l=8$ values (closed circles) show a $J=8$ resonance near 16.1 MeV. Near 15.9 MeV, where the evidence for a resonance is weaker both from the present data and the data of Gai *et al.*, the $l=8$ coefficient is much larger than the others, in agreement with the $J=8$ assignment by Gai *et al.*, who had identified this resonance primarily through its interference effect. The result here and in Fig. 4 is not compellingly in favor of resonance identification at $\sim$15.9 MeV. The irregular behavior of a_{2l} values between 15.9 and 16.1 MeV is difficult to interpret, but noting that the singular high yield at 15.98 MeV, $\sim$32° (see Fig. 3) causes the high $l=12$ coefficient at that energy, it is clear that thinner targets and a higher density of cross section measurements in both energy and angle would be necessary in order to accurately identify increased $l=12$ strength in this region. Plots of χ^2 per degree of freedom vs $2L$, the maximum k value in the linear Legendre expansion, are consistent with the l-value assignments especially for the resonances, $l_{res}=10$ at 15.2 and 15.8 MeV and $l_{res}=8$ at 16.1 MeV, in that there is a precipitous drop in $\chi^2(l)$ at $l=l_{res}$ with a tendency for $\chi^2(l)$ to level off for larger values of l.

The results of this work are compared with those of Refs. 4, 5, and 7 in Table I. The simple Legendre expansion of our angular distributions leads to results in agreement with those obtained by Gai *et al.*,[4] who investigated a limited energy range, although the narrow widths cannot be as reliably extracted. A new well-isolated resonance with $J^{\pi}=10^{+}$ has been unambiguously located at $E_{c.m.}=15.20$ MeV. In addition, we have found correlated cross section enhancements at small angles in the α_0 and α_1 reaction channels at ten additional center of mass energies. Some of these agree with energies extracted from the work of VanBibber[5] whose cross sections summed over eight angles also show correlations between the α_0 and α_1 channels. The energy steps taken by VanBibber[5] do not allow observation of structures separated by less than 250 keV, and the small number of angles observed inhibits determination of l_{res}.

The elastic scattering investigation by Tiereth *et al.*,[7] from $E_{c.m.}=15.5$ to 18 MeV has revealed four resonances

TABLE I. Energies and J^{π} values of resonances[a] and correlated structures in $^{16}O(^{16}O,\alpha)$ and elastic scattering.

Present work $E_{c.m.}$ (MeV)	J^{π}	Gai *et al.* $E_{c.m.}$ (MeV)	J^{π}	VanBibber[b] $E_{c.m.}$ (MeV)	Tiereth[c] $E_{c.m.}$ (MeV)
13.7					
13.8				13.9	
14.4					
14.7					
15.20	10^{+}			15.25	
15.5					
15.83	10^{+}	15.8	10^{+}	(15.75)	15.89
(15.93)	(8^{+})	15.9	8^{+}		
16.10	8^{+}	16.1	8^{+}	16.05	
16.4					16.32
17.3				17.3	17.31
					17.67
18.0				18.0	
18.9					
20.3					

[a]For the ($^{16}O,\alpha$) reactions in the present work and that of Gai *et al.* (Ref. 4), resonances are fairly well established at those energies where J^{π} values are presented. Other energies listed are for correlated maxima measured for α_0 and α_1 channels.
[b]Energies of correlated structures in $^{16}O(^{16}O,\alpha)$ extracted from Ref. 2.
[c]Resonances in elastic scattering as reported in Ref. 7.

using an analysis containing assumptions which lead to no interference between resonance and scattering amplitudes. Three of their resonance energies are in fair agreement with those in the present work.

Whether or not a large number of resonantlike states would lead to a fragmented giant resonance structure, a clustering of resonances of the same J^{π} over a few MeV energy range, such as observed[2,6] in $^{12}C + ^{12}C$, remains to be seen. The preliminary indication (Table I) of two 10^+ resonances at lower energies than two possible 8^+ states is not particularly encouraging. It is unfortunate that a complete determination of a_{2l} ($E_{c.m.}$) cannot be so easily obtained as in the $^{12}C + ^{12}C$ case.[6] Compared to the $^{12}C + ^{12}C$ work, the resonant structures encountered in the present case are on the average a factor of 3 narrower with average spacing decreased at least a factor of 2, thus requiring a much higher density of data to produce similar results. These facts coupled with a factor of 10 smaller cross section and the complete exposé becomes formidable. Although the high density of narrow structures seems to rule out the influence of dinuclear states in these reactions, in agreement with Ref. 7, a fluctuation explanation for at least some of the structure cannot at present be ruled out.

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[5]K. VanBibber (unpublished), data appears in Refs. 2.

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[7]W. Tiereth *et al.*, Phys. Rev. C **28**, 735 (1983).