Resonances and compound fluctuations in the reactions $^{16}O(^{16}O,\alpha)$ and $^{16}O(^{16}O,^{8}Be)$

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Small angle cross sections for the reactions $^{16}O(^{16}O,\alpha)^{28}Si$ and $^{16}O(^{16}O,^{8}Be)^{24}Mg$ leading to ground states and first excited states of residual nuclei are reported for $E_{c.m.}\sim 12$ to 20 MeV. Angular distributions are measured for all four exit channels at about forty energies in the neighborhood of resonancelike features. Resonant l values are inferred from both α_0 and $^{8}Be_0$ angular distribution and results are compared with other work. The distribution of maxima test shows that cross section maxima in the excitation functions are distributed randomly and that there is a low probability for any resonances in the energy range covered. Statistical model calculations with proper energy level densities and angular momentum conservation reproduce all the general features attributed to heavy-ion resonances.

I. INTRODUCTION

For many years considerable effort has been directed to the study of resonancelike structure in scattering and reaction cross sections from heavy-ion collisions. Many resonances of intermediate width, $\Gamma\sim 100$–500 keV, have been reported and reviewed[1] for a variety of interacting nuclei, most frequently for reactions involving the $^{12}C+^{12}C$ and $^{12}C+^{16}O$ systems. Despite the numerous investigations, no model has emerged with sufficient predictive power to describe the intermediate structure observed at energies above the Coulomb barrier. This is due in part to the fact that essentially all of the investigated reactions exhibit some statistical features. None of the intermediate structures above the Coulomb barrier are characterized by the strong cross-channel correlations which distinguish the sub-Coulomb resonances in $^{12}C+^{12}C$ (Ref. 2) and more recently in $^{16}O+^{16}O$ (Ref. 3). Whether the resonancelike structures of intermediate width observed in heavy-ion reactions are due to the population and decay of resonances of the compound system or result from the interference of many closely spaced resonances[4] is a question that is still open.

Siemssen *et al.*[5] extended the earliest[6] $^{16}O+^{16}O$ elastic scattering measurements to well above the Coulomb barrier and found nearly periodic gross structure in the excitation functions in the energy range from $E_{c.m.}\sim 20$ to 33 MeV with structure widths of 2 to 3 MeV. An intermediate substructure superposed on the gross structure has been interpreted as possibly being a statistical fluctuation phenomenon,[5] while the gross structure has been successfully described as a potential scattering phenomenon using optical-model potentials with weak absorption near the surfaces of the interacting ^{16}O nuclei.[7] Fragmented gross structures have also been observed in the same energy region in several $^{16}O(^{16}O,^{12}C)^{20}Ne^{*}$ reaction channels.[8] A fluctuation analysis of intermediate structure in the $^{16}O+^{16}O$ elastic and alpha-particle cross sections for $E_{c.m.}=17.5$ to 19.5 MeV by Shaw *et al.*[9] gives some indication of nonstatistical correlation in the alpha-particle channels, but reliable conclusions are hampered by the limited energy range of their data.

Resonances have been identified above the Coulomb barrier at $E_{c.m.}\sim 15.2$, 15.8, 15.9, and 16.1 MeV by the combined works of Liendo *et al.*[10] and Gai *et al.*[11] in studies of the $^{16}O(^{16}O,\alpha_{0,1})$ reactions. They have made spin assignments for these resonance energies of 10^+, 10^+, 8^+, and 8^+, respectively, based on a partial wave analysis[11] or Legendre analysis[10] of their α_0 angular distribution data. In both cases the appropriate amplitudes are shown to exhibit a resonant behavior versus energy over the structures.

The combination of all previous studies of the energy dependence in $^{16}O+^{16}O$ interactions does not present a consistent picture of the intermediate width structure observed in scattering and reaction cross sections at energies above the Coulomb barrier. Studies involving the α_0 and α_1 exit channels are especially confusing. Shaw *et al.*[9] report structure that is mainly accounted for by statistical-model predictions; Pocanic *et al.*[12] find resonancelike anomalies that cannot be identified as isolated resonances; yet Gai *et al.*[11] and Liendo *et al.*[10] identify resonances for which they make consistent spin assignments using totally different analysis methods. These very different observations illustrate the difficulties encountered in attempts to distinguish isolated resonances from statistical fluctuations. An investigation more comprehensive and detailed than those described above is required to determine whether clear evidence of isolated resonances is discernible in $^{16}O+^{16}O$ reaction cross sections at energies above the Coulomb barrier.

The present work is an investigation of the resonance and statistical characteristics of the intermediate width structure in the reactions $^{16}O(^{16}O,\alpha)^{28}Si^{*}$ and $^{16}O(^{16}O,^{8}Be)^{24}Mg^{*}$ leading to the 0^+ ground states and 2^+ first excited states of the residual nuclei. We have measured the cross sections at small angles in ~ 50 keV steps over a broad energy range, $E_{c.m.}=12$ to 20 MeV, to facilitate the application of statistical tests and to permit a quantitative search for nonstatistical cross-channel correlations between the many resonancelike structures in the excitation functions. Angular distributions have been measured at energies over selected structures for a broad angular range. The energy dependences in angle-summed cross sections are examined to identify structures which satisfy conventional resonance criteria adopted from previous investigations. Resonant J^{π} values are inferred based on the energy dependence of coefficients in either linear Legendre expansions or interfering angular momentum pair parametrizations of the angular distributions for the spin-zero exit channels, α_0 and $^8Be_0$. The work is an extension of an earlier investigation by Liendo *et al.*[10] Much of that work has been repeated, but only portions of the repetitions are specifically presented here. The density of observed cross section maxima in four reaction channels is tested for an indication of significant nonstatistical behavior. In addition, statistical model calculations of excitation functions and angular distributions are generated to determine whether statistical fluctuations can produce resonancelike structure similar to that observed in the data. The results are discussed in light of previous works.

II. EXPERIMENTAL PROCEDURES

This work was performed at the Florida State University S-FN Tandem Van de Graaff Laboratory. Beam currents of 200 to 500 nA of ^{16}O were used to bombard SiO_2 targets vacuum deposited on self-supporting carbon foils. Target thicknesses were measured by use of the known small angle elastic scattering cross sections for ^{16}O bombardment at $E_{lab}=20$ MeV and $\theta_l \leq 20°$. In the energy range employed in this work, $E_{lab}=24$—40 MeV, the energy loss of the beam in SiO_2 was always in the range of ~ 90—200 keV. All energies reported for excitation functions and angular distributions have been corrected to the center of the ^{16}O thickness. Carbon and oxygen buildup on the target were also accounted for in the energies and cross sections quoted. The total systematic error associated with the extraction of cross sections is estimated to be less than 10%. Relative cross section errors, which usually result from finite counting statistics, were often less than 5%.

Energy spectra of ^8Be ground state reaction products are formed by adding the energies of the coincident alpha particles from ^8Be decay. The geometry of ^8Be decay at the energies encountered require, for high ^8Be detection efficiency, closely spaced active detector areas with center separations $\sim 5°$. The detectors can be used simultaneously in singles mode to record alpha-particle energy spectra from the $^{16}O(^{16}O,\alpha)^{28}Si^*$ reactions. For angular distributions an array of eight detectors with 5° separations was used. The circuitry and efficiency calculations for ^8Be detection by this array has been discussed in detail previously.[13] Energy resolution of ~ 200 keV is typical at forward angles, but the kinematic broadening became a prohibitive factor in ^8Be angular distribution data for $\theta_{c.m.} \geq 75°$.

Excitation functions were measured at small angles simultaneously for $^{16}O(^{16}O,\alpha)^{28}Si^*$ and $^{16}O(^{16}O,^8Be)^{24}Mg$ reactions by use of an annular quadrifid detector. The lithium drifted silicon detector has an active thickness of ~ 900 μm and each separate detector quadrant has an angular range of $\theta_{lab} \sim 2°$—6° and spans a solid angle of ~ 8 msr. ^8Be events are identified by gating two-dimensional energy spectra of alpha-alpha coincidences formed from all possible quadrant pairs. The effective solid angle for ^8Be detection has been calculated as a function of ^8Be energy and the projected radial position of the ^8Be on the detector for both adjacent and opposite quadrant pairs. These calculations indicate an angular full width at half maximum in detection angle of $\sim 2.6°$ for adjacent pairs, which is nearly constant for $E_{^8Be}=10$ to 50 MeV, while the mean detection angle varies from $\theta_l \cong 2.9°$ to 3.5° in that energy range. For opposite pair ^8Be identification, $\Delta\theta_l$(FWHM) $\cong 1.7°$ to 1.0° and $\theta_l \cong 1.3°$ to 0.6° in the energy range $E_{^8Be}=10$—50 MeV. The angular efficiencies have been numerically integrated to give effective solid angles for different quadrant combinations vs $E_{^8Be}$. These curves are shown in Fig. 1 along with the detector geometry as collimated. The total effective solid angle, curve c in Fig. 1, exceeds 8 msr over a broad energy range resulting in a ^8Be detection efficiency of $>25\%$.

The energy signals from detector quadrants are delayed, gated, and routed[14] such that all events from opposite quadrant pair coincidences and adjacent quadrant pair coincidences appear in only two two-dimensional energy spectra. The two-dimensional spectra are gated to eliminate most of the $(^{16}O,\alpha\alpha)$ events, then addition of the two alpha-particle energy coordinates produces representative ^8Be energy spectra from which events corresponding to $^{16}O(^{16}O,^8Be_0)^{24}Mg$ and $^{16}O(^{16}O,^8Be_1)^{24}Mg^*(2^+)$ are easily extracted.

III. EXPERIMENTAL RESULTS

To study the possible resonant and statistical characteristics of heavy ion reactions, one would ideally include measurement of cross sections over a broad energy range,

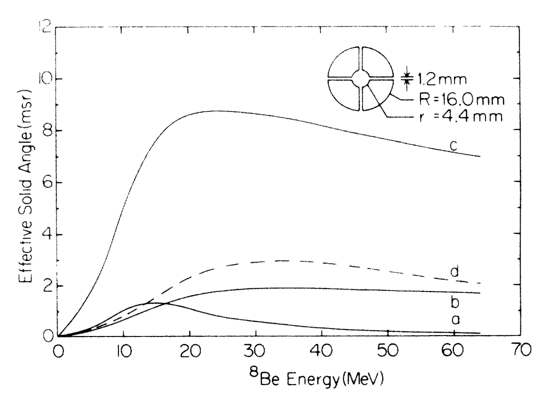

FIG. 1. Geometry of the annular quadrifid detector and effective solid angle for the detection of ^8Be(g.s.) in the following detector configurations: (a) one opposite detector pair of the quadrifid small-angle system; (b) one adjacent detector pair of the quadrifid small-angle system; (c) the sum of four adjacent and two opposite detector pairs of the quadrifid small-angle system; (d) one adjacent detector pair of the eight-detector array.

at a number of angles sufficient for an unambiguous Legendre analysis, and at energy intervals considerably less than the compound fluctuation coherence width, Γ. Investigations of that scope have been used to establish resonance energies and J^{π} values in the ^{8}Be exit channels of the $^{12}C + ^{12}C$ and $^{12}C + ^{16}O$ systems.[15,16] For ^{32}S, however, empirically derived coherence widths as small as 76 keV have been reported[9] compared with 200 to 600 keV for the above mass 24 and 28 systems. In addition, the cross sections reported[9,17] for ^{8}Be and alpha-particle production from $^{16}O + ^{16}O$ are more than a factor of 10 smaller than for the previous detailed studies.[15,16] The combination of small cross sections and narrow widths makes the ideal investigation scope quite impractical. Instead we measure excitation functions at small angles where cross sections are enhanced and all l-value contributions are present. Detailed angular distributions are then measured only in the neighborhood of possible resonance structure which has appeared in two or more reaction channels.

The annular quadrifid detector set at zero degrees was used for small angle measurements as described earlier. Small-angle excitation functions for the reactions $^{16}O(^{16}O,\alpha_0)^{28}Si(0^+,g.s.)$, $^{16}O(^{16}O,\alpha_1)^{28}Si(2^+,1.78$ MeV), $^{16}O(^{16}O,^{8}Be_0)^{24}Mg(0^+,g.s.)$, and $^{16}O(^{16}O,^{8}Be_1)^{24}Mg(2^+,$ 1.37 MeV) measured from $E_{c.m.} = 11.95$ to 19.98 MeV in ~ 50 keV steps are shown in Fig. 2. The ^{8}Be cross sections at $\theta_{c.m.} \sim 1.5°$ and $\theta_{c.m.} \sim 5.7°$ correspond to ^{8}Be events registered, respectively, in opposite and adjacent quadrant pairs of the quadrifid detector.

All of the excitation functions shown in Fig. 2 display complex structure with average structure widths and spacings which do not show systematic dependence on center of mass energy or reaction channel. The widths ranging from $\Gamma < 100$ keV to ~ 200 keV are a factor of 2 or 3 narrower than for the $^{12}C + ^{12}C$ system and the structure density, $\rho \sim 3$/MeV, is approximately twice that for $^{12}C + ^{12}C$ at similar compound excitation energies. The narrow structure appears to be superimposed on a background cross section which varies much less rapidly with energy. Typical peak to background ratios are approximately 5:1 for the alpha-particle channels and more nearly 2:1 for the ^{8}Be channels.

Excitation functions for total cross sections are approximated for each channel by forming a summed cross section in regions of interest where a broad angular range of differential cross section has been measured. The results, using the expression

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

for the energy ranges investigated are shown in Fig. 3. The region near $E_{c.m.} = 16$ MeV, detailed earlier,[10] is omitted here. The sums include differential cross section measurement for the alpha-particle channels at 28 angles from $\theta_{c.m.} \sim 6°$ to 91° and for the ^{8}Be channels at 16 angles from $\theta_{c.m.} \sim 12°$ to 61°. Measurements from the quadrifid detector are not included in σ_{sum}.

There is a large number of energy correlated cross section maxima in the forward angle excitation function data. Many of the energy correlations extend to three of the four channels studied. As pointed out earlier,[10] how-

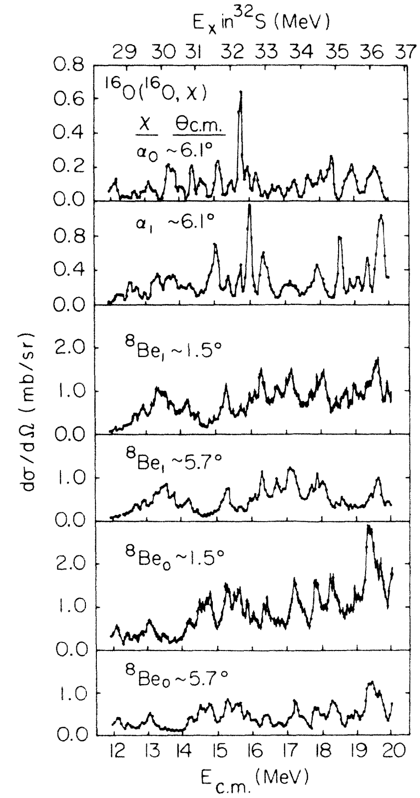

FIG. 2. Excitation functions measured with the quadrifid small-angle detector system for the reactions $^{16}O(^{16}O,\alpha_{0,1})^{28}Si^*$ and $^{16}O(^{16}O,^{8}Be_{0,1})^{24}Mg^*$ from $E_{c.m.} = 11.95$ to 19.98 MeV.

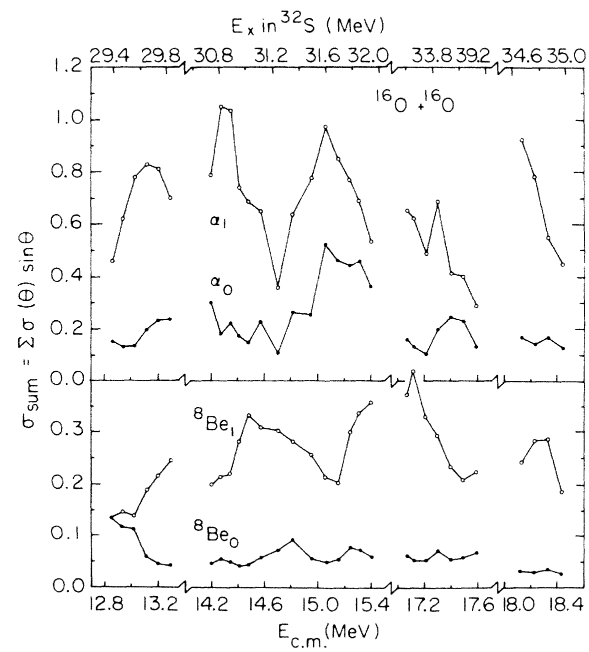

FIG. 3. Cross sections of the reactions $^{16}O(^{16}O,\alpha_{0,1})^{28}Si^*$ summed over the center-of-mass angular range of $\theta_{c.m.} \sim 6°$ to 91° and for the reactions $^{16}O(^{16}O,^{8}Be_{0,1})^{24}Mg^*$ summed over the range from $\theta_{c.m.} \sim 12°$ to 61°. These angular ranges do not include data from the quadrifid small-angle detector.

ever, the high density of structure would lead one to expect some accidental correlations even in the absence of resonances. Figure 3 shows that cross section enhancements still persist even after the data are summed over many angles. The energy correlation of maxima in σ_{sum} between the different channels is also still present to some extent, although it is not nearly so striking as in the small angle data. This is to be expected when different partial waves contribute with differing strengths in separate reaction channels even when resonances are present. Similarly, enhancements and reduced correlations would result from fluctuations in which only a few partial waves are important.

The excitation functions of Fig. 2 present considerable structure of interest for a resonance interpretation for which angular distribution information is needed. Several energy regions were selected for such measurements, as illustrated in Fig. 3. The energy region of the narrow resonances reported by Gai *et al.*[11] at $E_{\mathrm{c.m.}} \cong 15.8$, 15.9, and 16.1 MeV is not included here, although their results have been tested by measuring angular distributions for the α_0 and α_1 reaction channels at 12 energies from $E_{\mathrm{c.m.}} = 15.63$ to 16.18 MeV. As previously reported,[10] this work supports the work of Gai *et al.*[11] At slightly lower energy where Liendo *et al.*[10] reported a $J^{\pi}=10^{+}$ resonance at 15.2 MeV, we have remeasured angular distributions since the small angle yields show cross section maxima for both $^{8}\mathrm{Be}_0$ and $^{8}\mathrm{Be}_1$ near 15.3 MeV, while for the α_0 and α_1 channels the maxima are at 15.1 MeV. Due to additional correlated maxima in the small angle yield for α_0 and α_1 found near $E_{\mathrm{c.m.}} = 14.40$ and 14.65 MeV, this particular series of angular distributions has been extended to 14 energies from $E_{\mathrm{c.m.}} \cong 14.2$ to 15.4 MeV. The measured cross sections for the α_0 and $^{8}\mathrm{Be}_0$ exit channels only are shown in Figs. 4 and 5 since it is the zero spin channels which are most useful in obtaining angular momentum information about the compound system. The curves in these figures will be discussed in the following section.

Angular distributions have also been measured in the energy regions from $E_{\mathrm{c.m.}} = 12.85$ to 13.29 MeV, 17.07 to 17.58 MeV, and 18.13 to 18.44 MeV. In each of these energy regions, the small angle excitation functions exhibit structure that appears correlated in the α_0 and $^{8}\mathrm{Be}_0$ channels, suggesting the possibility for resonances in these two zero-spin reaction channels for which independent, and complementary, determinations of resonant J^{π} values should be possible. The angular distributions near the cross section maximum in α_0 and $^{8}\mathrm{Be}_0$ observed at small angles at $E_{\mathrm{c.m.}} \sim 17.30$ MeV (see Fig. 2) are shown in Figs. 6 and 7. Several other energy regions appear interesting, but upon close scrutiny of all excitation functions in Fig. 2 are found to have structure which is too complex to expect informative resonance results.

IV. RESONANCE INTERPRETATION

A. Current results

The criteria for establishing resonances in heavy ion reactions have been discussed extensively in the literature. Many proposed criteria have been shown to be neither

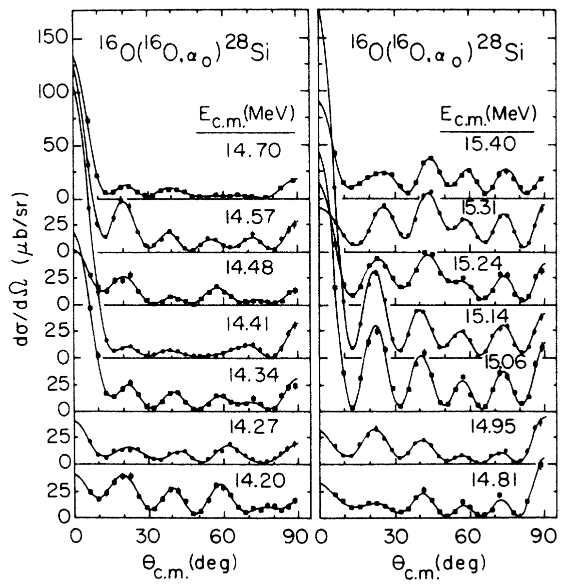

FIG. 4. Angular distributions of the $^{16}\mathrm{O}(^{16}\mathrm{O},\alpha_0)^{28}\mathrm{Si}$ reaction obtained between $E_{\mathrm{c.m.}} = 14.20$ and 15.40 MeV. The solid curves are generated in least-squares fits to the α_0 angular distributions of the linear sum of Legendre polynomials given by

$$\sigma(\theta)=\sum_{l=0}^{L} B_{2l}P_{2l}(\cos\theta) ,$$

with $L=12$.

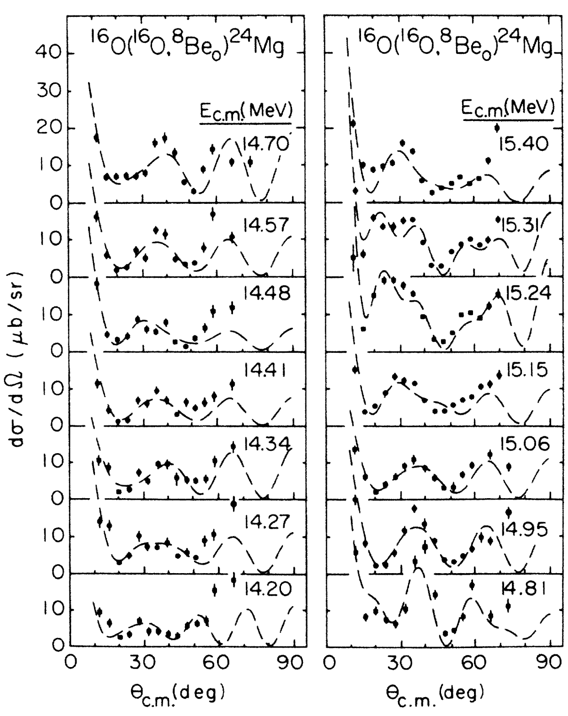

FIG. 5. Angular distributions of the $^{16}\mathrm{O}(^{16}\mathrm{O},^{8}\mathrm{Be}_0)^{24}\mathrm{Mg}$ reaction measured between $E_{\mathrm{c.m.}} = 14.20$ and 15.40 MeV. The broken curves are generated in least-squares fits to the data of a coherent pair of angular momentum components given by

$$\sigma(\theta,E)=\left|\sum_{l=l_1,l_2} A_l(E)\exp(i\delta_l)P_l(\cos\theta)\right|^2 .$$

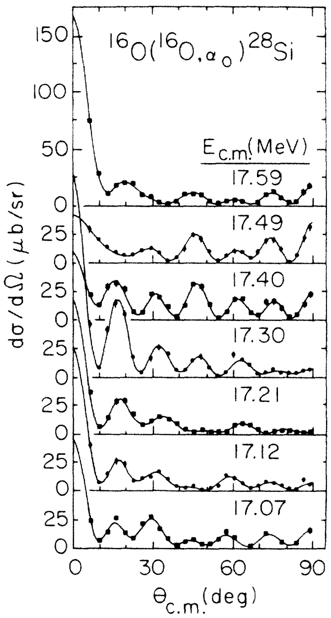

FIG. 6. Angular distributions of the $^{16}O(^{16}O,\alpha_0)^{28}Si$ reaction obtained between $E_{c.m.}=17.07$ and 17.59 MeV. The solid curves are generated in least-squares fits to the α_0 angular distributions of the linear sum of Legendre polynomials given by

$$\sigma(\theta)=\sum_{l=0}^{L} B_{2l}P_{2l}(\cos\theta) ,$$

with $L=14$.

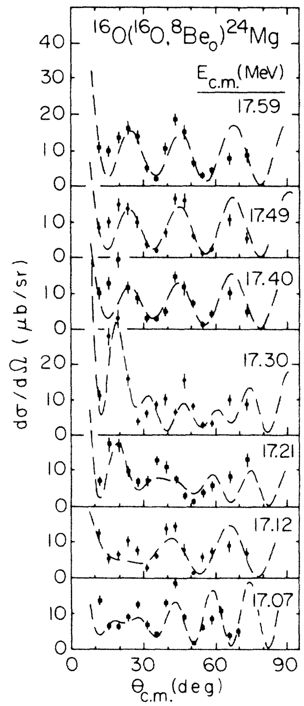

FIG. 7. Angular distributions of the $^{16}O(^{16}O,^{8}Be_0)^{24}Mg$ reaction measured between $E_{c.m.}=17.07$ and 17.59 MeV. The broken curves are generated in least-squares fits to the data of a coherent pair of angular momentum components given by

$$\sigma(\theta,E)=\left|\sum_{l=l_1,l_2} A_l(E)\exp(i\delta_l)P_l(\cos\theta)\right|^2 .$$

necessary nor sufficient.[18] Without attempting to be definitive we will adopt, for the purposes of discussing our observed cross section maxima in a resonance context, a rather limited criteria set which has been used previously[15,16] for the identification of resonance energies and participating reaction channels. First, the resonances should appear in the angle integrated cross section or at least in an angle-summed cross section. Second, the resonance should appear in more than one exit channel, but not necessarily in all exit channels.

Resonance structure as defined by these criteria is observed at several energies in the angle-summed cross sections shown in Fig. 3. The most easily discerned appears as prominent, correlated maxima in the α_0 and α_1 channels at 15.1 MeV. This structure corresponds to the $J^\pi=10^+$ resonance which is observed near 15.2 MeV in the earlier angular distribution data.[10] The shift in apparent resonance energies for the two data sets is largely due to corrections, which were applied to the present data and not to the earlier data, for beam energy losses resulting from carbon buildup on the target surface. The 15.1 MeV resonance is not evident in the summed cross sections for either the $^8Be_0$ or the $^8Be_1$ channel, both of which exhibit minima near the resonance energy.

Correlated structure is also present in the summed cross sections near $E_{c.m.}\sim 14.35$, 14.57, 14.79, and 17.30 MeV, although the evidence for resonances at these energies is not nearly so striking. A prominent peak is observed in the α_1 channel centered around ~ 14.30 MeV. Much smaller enhancements are seen in the summed cross sections for the α_0 channel at ~ 14.34 MeV and for the $^8Be_0$ channel at ~ 14.28 MeV. This structure seems to satisfy the two resonance requirements previously stated insofar as the maxima in α_0 and $^8Be_0$ summed cross sections are each correlated with the peak in the α_1 cross sections, even though the maximum in the $^8Be_0$ curve corresponds to a minimum in the α_0 curve. At 14.57 MeV, a structure that appears as a peak in the α_0 channel is discernible as a definite shoulder in the summed cross section curve for the α_1 channel. The third resonance is indicated by a somewhat similar signature. A broad ($\Gamma\sim 600$ keV) structure in the $^8Be_0$ summed cross section exhibits an anomalously sharp, asymmetrically placed maximum at $E_{c.m.}\sim 14.79$ MeV, which is correlated with a shoulder on a large peak in the α_0 channel. The remaining resonance structure apparent in Fig. 3 is observed at 17.30 MeV. At this energy, the summed cross sections maximize for both the $^8Be_0$ and α_1 channels. Although the α_0 cross section is significantly enhanced at 17.30 MeV, it certainly is not clear that the broader structure in α_0 is a resonance feature correlated with the $^8Be_0$ and α_1 exit channels.

In principle, it is possible to determine J^π values for the five structures which have satisfied our resonance criteria since each appears in the angle-summed cross section for at least one of the spin-zero exit channels. In practice the problem is complicated by the well-known fact that the strengths of all partial wave contributions to the cross sec-

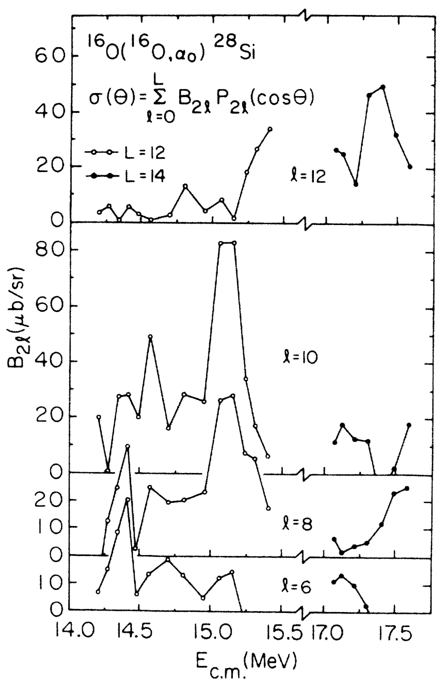

FIG. 8. Coefficients B_{2l} vs energy for $l=6$, 8, 10, and 12, as extracted in fits of the linear sum of Legendre polynomials to angular distributions of the reaction $^{16}O(^{16}O,\alpha_0)^{28}Si$.

tion cannot be uniquely extracted, so the resonating l value in the spin-zero channel is not determined. Instead we use the method of James *et al.*[16] in which the resonant l value is merely inferred from the energy dependence of coefficients in a linear Legendre expansion of angular distributions given by

$$\sigma(\theta,E)=\sum_{l=0}^{L} B_{2l}(E)P_{2l}(\cos\theta)\ .$$

Only even Legendre polynomials are included because of the initial state symmetry, and the summation is truncated at a maximum angular momentum $L \gtrsim l_{\text{grazing}}$. The unique $B_{2l}(E)$ coefficients are determined by a least squares fitting procedure.

Evaluation of the coefficients, $B_{2l}(E)$, has been carried out for the $^{16}O(^{16}O,\alpha_0)$ angular distribution data. The solid curves in Figs. 4 and 6 represent the best fit linear Legendre expansion. A maximum angular momentum value of $L=12$ is sufficient to fit the data in the energy range from 14.2 to 15.4 MeV, whereas $L=14$ is required to fit some of the angular distributions measured at energies above 17 MeV.

Spin assignments are inferred where possible from the Legendre coefficients $B_{2l}(E)$ for $l=6$, 8, 10, and 12, which are plotted as a function of energy in Fig. 8. Errors in the values of the $B_{2l}(E)$ coefficients are typically less than 10% for $B_{2l}(E)$ with absolute value greater than 10 μb/sr. Those $B_{2l}(E)$ with even l which are not plotted generally contribute little to the evaluated fits and thus include errors on the order of the magnitude of the coefficients. Odd-l coefficients represent interference between the allowed partial waves, do not facilitate the determination of resonant J^π values, and, therefore, are not plotted.

Resonant values of B_{2l} are clearly defined by structure seen in Fig. 8 at three out of the five resonance energies cited previously. The strong enhancement of the $l=10$ coefficient near $E_{c.m.} \sim 15.10$ MeV clearly supports the $J^\pi=10^+$ assignment reported earlier for this resonance.[10] This resonance also appears to a lesser degree in the $l=8$ and $l=6$ coefficients as expected. At 14.57 MeV, maxima are observed in the $l=8$ and $l=10$ coefficient curves with $l=10$ predominant, indicating a $J^\pi=10^+$ assignment. A value of $J^\pi=12^+$ for the resonance near 17.30 MeV is inferred from the resonant amplitude of the $l=12$ coefficient at this energy.

Possible spin assignments for resonances at $E_{c.m.}=14.79$ and 14.35 MeV are not nearly so obvious. At 14.79 MeV large coefficients for both $l=10$ and $l=12$ raise the possibility of a doublet. At 14.35 MeV the interpretation is even more difficult with $l=6$, 8, and 10 coefficients showing almost identical strengths. In view of the energy shift for the peaks in B_{2l} for $l=10$ to $l=6$, one possible interpretation is a $J^\pi=10^+$ resonance near 14.34 MeV and a $J^\pi=6^+$ resonance near 14.38 MeV from which interference could account for the large $l=8$ coefficient in this energy region.

The angular range of data from the $^8Be_0$ exit channel is not sufficient for determination of the coefficients, B_{2l}. A restricted version of the partial wave expression for the cross section is therefore used in which only two coherent angular momentum terms contribute. The coefficients A_{l_1} and A_{l_2} for all possible interfering pairs with l values of 6, 8, 10, and 12 have been determined by minimizing the reduced χ^2 for all angular distributions for both the α_0 and $^8Be_0$ exit channels. The coefficients A_{l_1} and A_{l_2} for the angular momentum pairs which show the least values of χ^2 over the energy regions of interest are shown vs $E_{c.m.}$ in Fig. 9. The $J^\pi=12^+$ assignment for the $E_{c.m.}=17.30$ MeV resonance is supported by this analysis in both the α_0 and $^8Be_0$ exit channels. Also supported in both channels is a $J^\pi=10^+$ assignment for the resonance at 14.79 MeV, whereas on the basis of the Legendre analysis there was ambiguity between 10^+ and 12^+. The situation near $E_{c.m.}=14.4$ MeV has clarified very little; however, this analysis still favors a $J^\pi=10^+$ assignment at $E_{c.m.}=14.35$ MeV with some slight evidence for a 6^+ resonance at slightly higher energy.

B. Comparison with previous results

The results of the foregoing analysis are presented in Table I for comparison with the results of other work.[11,12,19] The results of several investigations of the $^{16}O+{}^{16}O$ system show some agreement in reported resonance energies and J^π values, even though dissimilar experimental and analytic methods have been employed.

The initial report by Gai *et al.*[11] of narrow ($\Gamma \sim 70$ keV) $J^\pi=10^+$, 8^+, and 8^+ resonances at $E_{c.m.}=15.8$, 15.9, and 16.1 MeV, respectively, has recently been followed by a more extensive presentation of their study of the $^{16}O(^{16}O,\alpha_{0,1})$ reactions in the energy range from 15.5 to 16.4 MeV.[11] They utilized a general partial wave decomposition of the α_0 angular distributions to extract

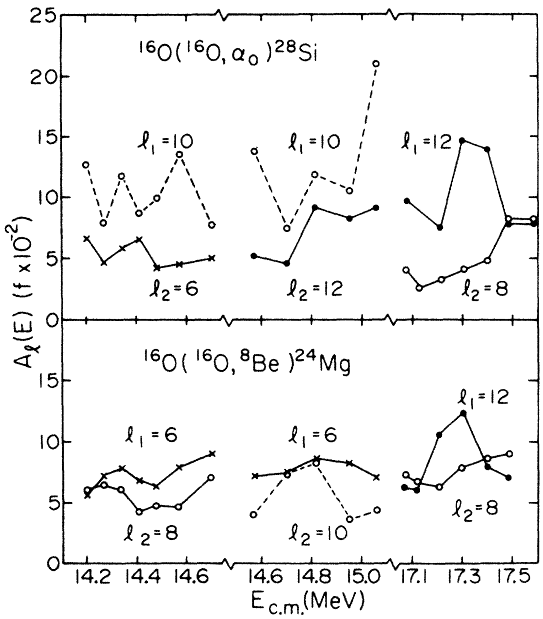

FIG. 9. Amplitudes A_{l_1} and A_{l_2} vs energy, as extracted in fitting the coherent angular momentum pair expression to angular distributions of the reactions $^{16}O(^{16}O,\alpha_0)^{28}Si$ and $^{16}O(^{16}O,^{8}Be_0)^{24}Mg$. The amplitudes are plotted for the particular angular momentum values, l_1 and l_2, which yield the minimum χ^2_ν near the resonant energies at 14.35, 14.57, 14.79, and 17.30 MeV.

resonance energies, J^π values, and widths which are in good agreement with the initial results reported for the present investigation.[10] In contrast to the linear Legendre expansion analysis employed in the present work, their method of fitting an angular distribution with a coherent sum of Legendre polynomials does not result in a unique set of coefficients. In order to provide constraints on the parameters in their fits, Gai *et al.*[11] have introduced several assumptions into their fitting procedure. These include a requirement that the extracted Legendre amplitudes fit the total angle integrated cross section. They also assume that only the $l=8$, 10, and 12 partial waves contribute significantly to the cross section and place an upper limit on the amplitudes of the other partial waves in the range from $l=0$ to 14, thereby reducing the fit to three partial waves plus a background. Finally, they require the extracted $l=10$ coefficient to fit the cross section measured at $\theta_{c.m.}=37.5°$, which is near zeros for P_8 and P_{12} and is near a maximum for P_{10}. Although this last constraint is to fully resolve the ambiguities in the extracted parameters, it is not entirely effective since the ratio of P_{12} to P_{10} at 37.5° is 0.43 and the resulting error in the value extracted for the $l=10$ coefficient may not be small enough to ensure a unique set of parameters. Their resonance energies, spins, and widths are deduced by fitting the coefficients extracted for the $l=8$ and 10 partial waves with a smooth background plus a Breit-Wigner resonance term. The background used for the $l=8$ partial wave is energy independent, whereas a resonancelike background with a width of 700 keV is required to fit the extracted $l=10$ coefficients. They attribute the energy dependent $l=10$ background to grazing partial wave effects. In the present work, a strong $l=10$ contribution to the α_0 cross section is observed over an energy interval in excess of 3 MeV, which is more consistent with the characteristic structure widths of potential shape resonances, in agreement with Liendo *et al.*[10] and Pocanic *et al.*[12] It is interesting to note that the distribution of

TABLE I. Energies[a] and J^π values[a] for $^{16}O+^{16}O$ resonances and cross section enhancements.

Present work[b]		Gai *et al.*[c]		Pocanic *et al.*[d]		Tiereth *et al.*[e]	
$E_{c.m.}$ (MeV)	J^π	$E_{c.m.}$ (MeV)	J^π	$E_{c.m.}$ (MeV)	J^π	$E_{c.m.}$ (MeV)	J^π
14.35	10^+						
(14.39)	(6^+)						
14.57	10^+						
14.79	10^+						
15.10	10^+			15.15	10^+		
15.83	10^+	15.8	10^+				
15.93	(8^+)	15.9	8^+	15.9	$(8^+,10^+,12^+)$	15.89	
16.10	8^+	16.1	8^+				
						16.32	$(12^+,8^+)$
				16.9	12^+		
17.30	12^+					17.31	12^+
						17.67	12^+
				17.9	12^+		
				19.8	14^+		

[a]Values in parentheses are not well established.
[b]Includes the results reported by Liendo *et al.* (Ref. 10).
[c]See Ref. 11.
[d]See Ref. 12. Energies are listed where angle-summed α_0 cross section exceeds Hauser-Feshbach cross section by a factor of 2 or more. Energies are listed as estimated from laboratory energies and target thicknesses given in Ref. 12.
[e]See Ref. 19.

partial cross sections for the background obtained by Gai *et al.* shows an angular momentum width $\Delta L \sim 2.3$ which is similar to the angular momentum width of partial cross sections obtained in the statistical model calculation to be mentioned later.

Four resonant structures have been observed by Tiereth *et al.*,[19] who utilized the sum-of-differences method to deduce the total $^{16}O + ^{16}O$ reaction cross section from elastic scattering data in the energy range from 15.5 to 18.0 MeV. They extracted total widths of ~ 150 keV and elastic partial widths of ~ 3 keV for the resonances at 16.32, 17.31, and 17.67 MeV, from which they conclude that the resonant states are not dinuclear. Their analysis employs several assumptions from which they imply a description of the total reaction cross section in terms of a resonance contribution and a noninterfering background contribution that varies smoothly with energy. They also assume $J=12$ spins for these resonances in their analysis, utilizing structure in elastic excitation functions measured at angles corresponding to maxima and minima of $|P_{12}(\cos\theta)|^2$ to support their choice of resonance spins. Their result for the resonance at 17.31 MeV is in agreement with the $J^\pi=12^+$ spin assigned to the resonance located at 17.30 MeV in the present work. The structure which they report at 15.89 MeV appears to correspond to the narrow resonances near 16 MeV in both the present investigation and that of Gai *et al.*[10,11]

Pocanic *et al.*[12] measured excitation functions for the α_0 and α_1 exit channels at eight angles in steps of 125 keV from ~ 11.5 to 21 MeV. They report nonstatistical cross section enhancements at the energies listed in Table I for which their angle-summed cross sections exceed by a factor of 2 calculated Hauser-Feshbach cross sections. They have inferred resonant spin values from fits of coherently summed pairs of Legendre polynomials to α_0 angular distributions measured at the resonance energies. Their report of a resonant enhancement of the $l=10$ angular momentum component at ~ 15.15 MeV supports the $J^\pi=10^+$ assignment for this resonance, which is observed at 15.10 MeV in the present work. They were unable to resolve the $J^\pi=10^+$, 8^+ resonance triplet near 16 MeV which appears in their data as a single resonant enhancement of the $l=10$ partial cross section with significant admixtures of the $l=8$ and $l=12$ components. The 125 keV energy interval in their excitation function data also severely limited their ability to observe narrow resonances such as those seen in the present work between 14.3 and 14.9 MeV.

The areas of agreement in the results of Table I are not surprising, since the authors Liendo *et al.*,[10] Gai *et al.*,[11] and Pocanic *et al.*[12] and the current experiment all have studied the $^{16}O(^{16}O,\alpha_0)$ reaction. Where experiments are performed with the same energy resolution and angular range, such as in the neighborhood of $E_{c.m.}=16$ MeV,[10,11] the results agree, even with quite different analysis techniques. There is a considerable discrepancy, however, between the current work and that of Pocanic *et al.*[12] who have a lower density of data in the excitation functions and fewer angles in the summed cross sections. For example, the small but quite well isolated $J^\pi=12^+$ resonance at $E_{c.m.} \simeq 17.30$ MeV has gone unnoticed in their summed cross section. Similarly, our better energy resolution excitation functions show very complex overlapping structures at $E_{c.m.} \sim 19.4$, 19.6, 19.8, and 19.9 MeV, so the energies near the 19.8 MeV, 14^+, "resonance" of Pocanic was not a region chosen by us for detailed angular distributions. Perhaps the most significant agreement from a resonance point of view is that both the α_0 and $^8Be_0$ exit channels show a clearly resonating 12^+ strength (see Fig. 9) at 17.30 MeV. Whether or not any of the resonances discussed above are statistically significant is addressed in the next section.

V. STATISTICAL FLUCTUATION INTERPRETATION

There are many energy correlated maxima in the alpha-particle and ^8Be excitation functions of Fig. 2, which is not surprising considering the high density of structures. The ^8Be excitation functions at $\theta_{c.m.} \sim 1.5°$, however, should not be considered in any discussion of correlated maxima, since, being within the coherence angle ($\theta_c \sim 20°$) of the $\theta_{c.m.} \sim 5.7°$ data, the two sets of structures are not independent. A number of statistical tests have been devised for the purpose of distinguishing resonancelike features which are inconsistent with the fluctuations predicted by a statistical model for cross section behavior. In a critique of several statistical methods previously used to identify nonstatistical structure, Dennis *et al.*[20] indicated that the distribution of maxima method can be very sensitive to resonant features in heavy-ion reactions. The distribution of maxima method involves the comparison of a statistically predicted number of energy intervals, $N_s(\Delta E,M)$, of width ΔE, for which cross section maxima are to appear in M reaction channels, with the actual number observed, $N_0(\Delta E,M)$.

The nuclear statistical model predicts reaction cross sections at high excitation energy that fluctuate randomly with energy such that the density of maxima depends only slightly on the spins and final excitations of the residual nuclei, and the strength of any direct component in the cross section.[21] From these considerations, it is statistically expected that nearly the same number of maxima will be counted in each of the excitation functions provided the sample size, i.e., the number of data points, is large. The variation of the density of maxima with energy and exit channel should be sufficiently small that the probability, p, for finding a maximum within any energy interval of any of the excitation functions depends only on the size of the interval, ΔE.

By considering the four excitation functions ($m=4$) of Fig. 2 at $\theta_{c.m.} \sim 6°$, we find the density of cross-section maxima is indeed quite constant vs $E_{c.m.}$ and reaction channel. We adopt the trivial definition of a maximum as where the cross section is greater than at the adjacent energies and such that the cross section decreases sufficiently at higher and lower energies that the error bars do not overlap with the error at the maximum cross section. The total number of maxima found in the α_0, α_1, $^8Be_0$, and $^8Be_1$ exit channels is $\eta=85$ and is distributed as 22, 22, 19, and 22, respectively, clearly satisfying the requirement of approximately the same number of maxima per channel. The effect of statistical errors in the data on the number of maxima counted can be estimated by comparing the number of maxima counted for the ^{8}Be cross sections at $\theta_{c.m.}\sim 6°$ to the number counted in the $\theta_{c.m.}\sim 1.5°$ data. Although the percentage statistical error in the 1.5° data is twice that of the 6° data, the variation in the number of maxima counted is less than 4%.

For cross section maxima which are randomly distributed in energy, the probability $P(M)$ for observing a maximum within an energy interval ΔE in M channels out a total of m channels is given by the binomial distribution

$$P(M)=\frac{m!p^M(1-p)^{m-M}}{M!(m-M)!} ,$$

where p is the probability of finding a maximum in a randomly placed energy interval, ΔE, in any of the m excitation functions. In practice its value is approximated by letting $p=n_+/n$, where n_+ is the number of intervals exhibiting maxima and n is the total number of intervals in the data sample of m excitation functions. When the sampling energy interval, ΔE, is a multiple of the data point spacing, δE, and no more than one maximum appears within ΔE, then

$$n_+=\frac{\Delta E}{\delta E}\eta=\sum_{M=0}^{m} MN_0(M)$$

and

$$n=\frac{m}{\delta E}(E_{\max}-E_{\min}-\Delta E+2\delta E) .$$

The calculated number of intervals which show maxima in M channels is then given by

$$N_S(\Delta E,M)=\frac{n}{m}P(M) .$$

The statistical error in this number is found by using the statistical error in the estimated value for p given by

$$\Delta p=[p(1-p)/n]^{1/2} .$$

The statistically estimated distribution of maxima, $N_S(\Delta E,M)$ vs M, has been calculated for $\Delta E=100$ and 150 keV, and the results are compared with the observed distributions in Table II and Fig. 10. For both values of ΔE the number of observed correlations, histogrammed in Fig. 10, agrees very well with the number expected for a purely random distribution of maxima, points with associated errors in Fig. 10.

TABLE II. Distribution of maxima in the small angle excitation functions measured at $\theta_{c.m.}\sim 6°$ ($m=4$).

M	$\Delta E=100$ keV		$\Delta E=150$ keV	
	N_S	N_0	N_S	N_0
0	$46.5^{-4.2}_{+5.4}$	46	$20.5^{-2.5}_{+2.8}$	26
1	$67.6^{-1.4}_{+0.2}$	70	$54.8^{-2.8}_{+2.7}$	47
2	$36.5^{+3.0}_{-3.1}$	33	$55.0^{+1.6}_{-1.9}$	55
3	$8.8^{+1.6}_{-1.4}$	10	$24.6^{+2.8}_{-2.7}$	27
4	$1.0^{+0.3}_{-0.2}$	1	$4.1^{+0.9}_{-0.7}$	4

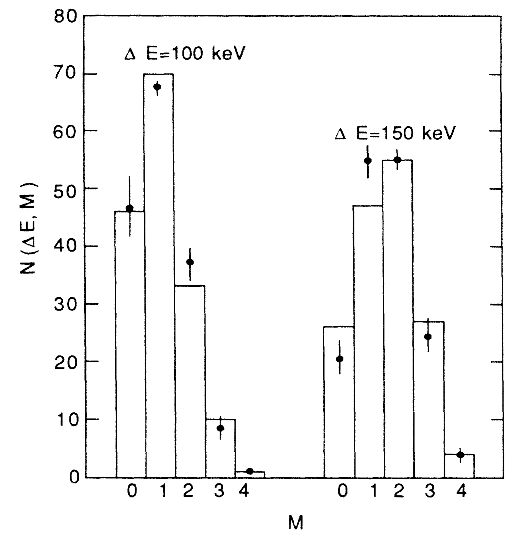

FIG. 10. Number of energy intervals, $N(\Delta E,M)$, of width ΔE which have cross section maxima in M number of reaction channels. The histograms represent the observed number, N_0, and the points are calculations based on a random occurrence of maxima, N_s, with associated statistical errors. Maxima are identified in the four excitation functions measured near $\theta_{c.m.}\sim 6°$ for ^{16}O(^{16}O,$\alpha_{0,1}$) and ^{16}O(^{16}O,^{8}Be$_{0,1}$); see Fig. 2.

Other values of ΔE were used in the distribution of maxima test with expected results. When $\Delta E=50$ keV, the number of observed correlations is reduced because the energy of cross section maxima may be expected to shift by half a coherence width, $\Gamma/2\simeq 70$ keV. When $\Delta E=200$ keV, the number of statistical correlations is reduced, since some of the energy intervals will contain more than one maximum, leading to an unnaturally small value of p. In all cases, with both correct and incorrect values of ΔE chosen, the small angle excitation functions are characterized by a statistical behavior.

It is interesting to compare the energies of structures correlated in all four channels with the energies of structures which have met the resonance criteria of Sec. IV. For $\Delta E=150$ keV, the maxima observed to be energy correlated in all four exit channels ($M=4$, $N_0=4$) are at average energies of $E_{c.m.}=15.73$, 15.97, 17.17, and 18.93 MeV. The structures at the lower two energies are likely those which have been reported[10,11] as $J^\pi=10^+$ and 8^+ resonances, respectively. The next one is very close in energy to the isolated $J^\pi=12^+$ resonance at 17.30 MeV and the last is at the energy where Pocanic *et al.*[12] find a strong enhancement in $\sigma_{\rm sum}$ and a dominant $J^\pi=14^+$. In spite of these resonance characteristics, the statistical analysis yields a probability for no resonances among these four energies equal to 78%. The probability that any specific pair of the four structures is nonstatistical is $\sim$1%.

Insofar as several structures in the ^{16}O(^{16}O,$\alpha_{0,1}$) and ^{16}O(^{16}O,^{8}Be$_{0,1}$) cross sections are found which satisfy criteria previously used to establish resonances, even though the distribution of maxima tests suggest a statistical origin for the narrow structure observed in the small-angle cross sections, the question naturally arises as to whether the resonant structure in these exit channels is consistent with statistical model predictions. In response, Hauser-Feshbach calculations[22] have been performed which are consistent with the energy-averaged cross sections of the small angle excitation functions for the α_0, α_1, $^8Be_0$, and $^8Be_1$ exit channels. In addition, synthetic small angle excitation functions and angular distributions are calculated using a compound nucleus decay model[23] which includes the effects of angular momentum conservation. The details of all these calculations are the subject of a future publication.[24] For completeness a few of the results will be discussed here. The distribution of Hauser-Feshbach partial cross section vs J shows the full width at half maximum to be $\lesssim 3$ units of angular momentum for the α_0 channel and <4 units of angular momentum for the $^8Be_0$ channel in the neighborhood of $E_{c.m.}=16$ MeV. One of a number of synthetic excitation functions generated for $^{16}O(^{16}O,\alpha_0)$ using a limited angular momentum space ($J_{max}-J_{min}=4$) is compared with our measurements in Fig. 11. The calculation shows an alarming similarity to the data. Angular distributions have also been generated versus energy and analyzed by the Legendre expansion method. The energy behavior of B_{2l} coefficients presents just as convincing a picture for resonant J^π assignments as does the analysis of actual data. All of these resonancelike features occur even when the average compound-nucleus level width is much greater than the average level separation, $\Gamma/D \gg 1$, and in some cases the "unique" angular momentum behavior of a structure can be determined by the coherent contributions of more than one hundred levels of that angular momentum.

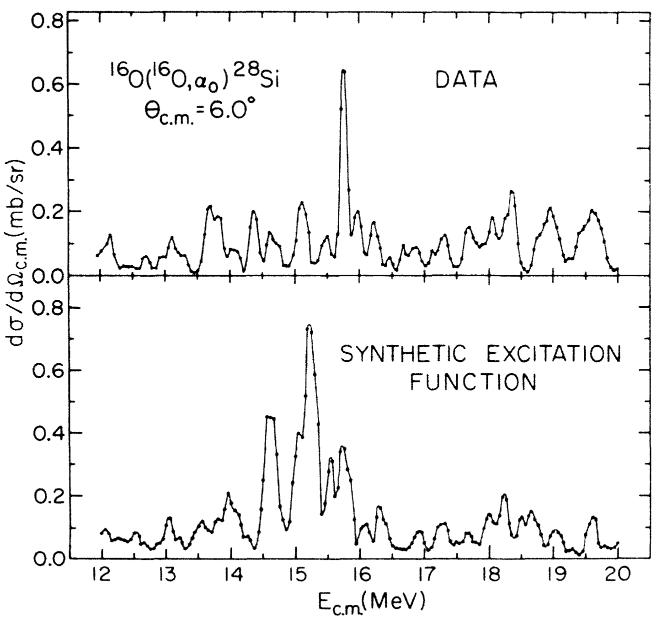

FIG. 11. A comparison of $^{16}O(^{16}O,\alpha_0)^{28}Si$ small-angle excitation functions: measured in this experiment and calculated using a statistical-model formalism (Ref. 23) which includes coherent contributions from compound-nucleus levels within a restricted range of angular momenta, $J_{max}-J_{min}=4$.

VI. SUMMARY AND CONCLUSIONS

We summarize as follows:

1. Angle summed cross sections do not resonate at quite the same energies as found in the small angle excitation functions, even for the strongest resonantlike maxima.

2. Based on angular distributions and a summed simulation of total cross sections vs $E_{c.m.}$, a number of resonancelike features have been identified along with resonant J^π values. In addition to the region near $E_{c.m.}=16$ MeV already discussed,[10] structures with $J^\pi=10^+$ are found at $E_{c.m.}=14.35$, 14.57, 14.79, and 15.10 MeV, and with $J^\pi=12^+$ at 17.30 MeV. In several of these the resonating character of the J value is very clear within the limitations of the analysis used.

3. At most of the energies where angular distributions have been measured, the angular momentum values contributing significantly to the $^8Be_0$ cross section appear to be two to four units less than for the α_0 cross section. The α_0 and $^8Be_0$ channels show resonant enhancements in the angle-summed cross sections at 14.79 and 17.30 MeV. At each of these two energies, the value of the resonating angular momentum is common to the α_0 and $^8Be_0$ channels, $l=10$ at 4.79 MeV and $l=12$ at 17.30 MeV.

4. When different laboratories investigate the same reaction in search of resonance phenomena, the same conclusions have been reached with different analysis techniques when they have the same type of data. However, experiments with different energy resolution and different angular ranges have shown different resonance conclusions.

5. The high density of structure in the excitation functions of Fig. 2 diminishes the utility of energy correlation between channels for the identification of resonances. We have quantified this by application of the statistical distribution of maxima test which shows very clearly that the energy correlations of cross section maxima identified in Fig. 2 follow a statistical distribution, implying a random energy distribution of cross section maxima. The distribution of maxima test becomes much more definitive for a larger number of channels.

6. Calculated small angle cross sections based on a statistical formation and decay of a high energy level density of the compound nucleus display all the general features of the measured cross sections.

We have identified several resonancelike features which have J^π signatures as reliably assigned as has been customary in the study of intermediate width heavy-ion resonances above the Coulomb barrier. In spite of this, the distribution of maxima test and the calculated cross sections lead us to the conclusion that these reactions are dominated by statistical processes and that no resonances of nuclear structure significance, other than supporting statistical structure, have been found. Although one of the structures, near $E_{c.m.}=15.1$ MeV, appears to possibly persist in the total production cross section of $^{28}Si^*$ as an increase of a few millibarns,[25] we point out that of the several hundred decay channels which contribute, fewer than one dozen would be required to show anomalies the order of those we have observed, in order to produce such an increase in cross section. Variations in total cross section need not imply a resonance.[4]

ACKNOWLEDGMENTS

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