Structures in the excitation functions of high lying inelastic channels of the $^{16}\text{O}+^{16}\text{O}$ system in the region $E_{\text{c.m.}}=26$ to $47$ MeV

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An excitation function measurement has been performed over the laboratory range 52–94 MeV investigating resonance phenomena in the single excitation $^{16}\text{O}(^{16}\text{O},^{16}\text{O}^{*}\rightarrow^{12}\text{C}_{\text{g.s.}}+\alpha)^{16}\text{O}_{\text{g.s.}}$ breakup reaction. A number of enhancements are observed in these excitation functions for excitation to the $4^{+}_{1}, 10.35$ MeV and $4^{+}_{2}, 11.09$ MeV excited states in $^{16}\text{O}$. The overlap between these and previously measured enhancements is discussed. Excitation functions for the $2^{+}_{1}, 9.84$ MeV and $2^{+}_{2}, 11.52$ MeV excited states are also presented.

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I. INTRODUCTION

The energy dependence of the cross sections of heavy-ion reactions has been a topic of considerable interest for over three decades [1]. The observation of resonances for elastic and inelastic reactions has provided substantial evidence for rotational bands of excited states in nuclei which may have clusterlike properties [2,3]. In particular the $^{12}\text{C}+^{12}\text{C}$ system has revealed a wide range of resonances, from narrow resonances at energies near the Coulomb barrier [1,4] to wider structures in inelastic scattering data [5,6]. Such resonance phenomena may be related to underlying cluster structure in these systems [7]. This paper is concerned with resonantlike structures observed in the $^{16}\text{O}+^{16}\text{O}$ system.

The data available on resonance phenomena in the $^{16}\text{O}+^{16}\text{O}$ system up to about 1986 have been summarized by Cindro [8]. As is the case with the more extensively studied $^{12}\text{C}+^{12}\text{C}$ system [3] the $^{16}\text{O}+^{16}\text{O}$ resonances indicate rotational characteristics. The moment of inertia associated with this rotation was found to be $\sim 47$ keV, in good agreement with the value of $\sim 43$ keV calculated for two $^{16}\text{O}$ nuclei in a dimolecular configuration [8].

Subsequent investigations of excitation functions for various $^{16}\text{O}+^{16}\text{O}$ reactions have mainly been concerned with inelastic channels, in particular the single and mutual excitation of $^{16}\text{O}^{*}$ to the $0^{+}_{2}, 6.05$ MeV and $3^{+}_{1}, 6.13$ MeV excited states. Pronounced correlated gross structure resonances have been observed in the excitation functions for the single and mutual excitation of $^{16}\text{O}^{*}$ to the $0^{+}_{2}, 6.05$ MeV excited state [9–11] up to center-of-mass energies of 40 MeV. Similar studies investigating the excitation functions for the single and mutual excitation of $^{16}\text{O}^{*}$ to the $3^{+}_{1}, 6.13$ MeV excited state have shown correlated resonances in both channels [12,13] up to $E_{\text{c.m.}}=40$ MeV.

The $0^{+}_{2}, 6.05$ MeV excited state in $^{16}\text{O}$ has been shown to be largely $4p-4h$ in nature and is well established [14] as having a $^{12}\text{C}_{\text{g.s.}}-\alpha$ structure. It is recognized as being the first member of a $K^{\pi}=0^{+}$ rotational band with the other band members being suggested to be the $2^{+}_{1}, 6.91$ MeV, $4^{+}_{1}, 10.35$ MeV, and $6^{+}_{2}, 16.28$ MeV excited states.

The $3^{+}_{1}, 6.13$ MeV excited state is proposed to be the $3^{+}$ member of a tetrahedral rotational band in $^{16}\text{O}$. This proposed band has an intrinsic spin sequence $0^{+}, 3^{+}, 4^{+}$ with the corresponding energies proportional to $J(J+1)$ [15]. The $4^{+}$ member is predicted at 10.2 MeV. However, the only $4^{+}$ excited state in $^{16}\text{O}$ in this excitation region is the $4^{+}_{1}$ at 10.35 MeV which has been assigned to the $K^{\pi}=0^{+}$ $4p-4h$ rotational band [16]. This assignment is justified by the fast $E2$ decay to the $2^{+}_{1}$ member of the same band at 6.91 MeV [17] which in turn has a fast $E2$ decay to the $0^{+}_{2}, 6.05$ MeV state which is believed to be the bandhead of this band [17]. The calculations of Buck et al. [18] predicted the energies, decay widths, and $E2$ transition values for many levels in $^{16}\text{O}$. Based on these calculations the $4^{+}_{1}, 10.35$ MeV state was proposed to have a structure of $^{12}\text{C}_{\text{g.s.}}+\alpha$, which fits in with the $4p-4h$ nature of the $K^{\pi}=0^{+}$ band. The $4^{+}$ excited state at 11.09 MeV in $^{16}\text{O}$ has been proposed to be the $4^{+}$ member of the tetrahedral band as an alternative candidate to the $4^{+}_{1}, 10.35$ MeV state [19,20].

In this paper we report an extension of studies of $^{16}\text{O}+^{16}\text{O}$ scattering to higher lying inelastic states, in particular the next highest spin states $4^{+}_{1}, 10.35$ MeV and $4^{+}_{2}, 11.09$ MeV. To perform such studies through conventional two-body scattering measurements would be quite complex as both $4^{+}$ states lie in a continuum of known states, around 10–11 MeV, with widths varying from a few keV to 2.5 MeV. It is reasonable to assume that resolving both $4^{+}$ states by means of an inelastic scattering measurement...
would be difficult. However, as both these states are above the \(\alpha\)-particle decay threshold, an alternative approach would be the measurement and subsequent reconstruction of the decay fragments.\(^{12}\)C+\(\alpha\). This technique has been implemented before in studies of the \(^{12}\)C+\(^{12}\)C system\(^{21}\) where states in \(^{12}\)C above the \(\alpha\)-particle decay threshold have been successfully reconstructed and resolved. This paper reports on a measurement of the excitation functions for single excitation to the 4\(^{1}\)\(^{+}\), 10.35 MeV and 4\(^{2}\)\(^{+}\), 11.09 MeV states in \(^{16}\)O via the \(^{16}\)O+\(^{16}\)O reaction, using such breakup measurement techniques.

II. EXPERIMENTAL DETAILS

The measurement was performed at the Australian National University (ANU) 14-UD accelerator using the new Charissa strip detector array located in the MEGHA scattering chamber\(^{22}\). Eight 500 \(\mu\)m thick, 50\(\times\)50 mm\(^2\) Si strip detectors were installed and covered an angular range of \(\theta_{lab} = 5^\circ\) to 65\(^\circ\) and an azimuthal angular range \(\Delta\phi = 120^\circ\) each side of the beam axis. This provided a wide coverage for the multiple detection of breakup fragments. Figure 1 illustrates the laboratory angles covered by the detectors. Each strip detector consisted of 16 position sensitive strips, 3 mm wide, which were independently instrumented. Signals taken from both ends of a strip were used to reconstruct the total energy and the emission angle of the particle detected by that strip. Details of the operation of these detectors can be found elsewhere\(^{23}\). Calibration, both energy and position, was achieved by the elastic scattering of \(^{16}\)O ions with a flash gold target (\(^{197}\)Au 5 \(\mu\)g cm\(^{-2}\) backed with 10 \(\mu\)g cm\(^{-2}\) of \(^{12}\)C).

An excitation function over the laboratory range 52–94 MeV in steps of 2–4 MeV was performed using a beam of \(^{16}\)O ions (~10 enA) accelerated onto a target of LiO (10 \(\mu\)g cm\(^{-2}\)) on a \(^{12}\)C backing (10 \(\mu\)g cm\(^{-2}\)). The target was made as thin as possible to reduce energy loss.

III. DATA ANALYSIS

The experimental trigger requirement was a total strip multiplicity of greater than or equal to 3 particle hits. In this way the measurement was then sensitive to the primary reaction of interest, \(^{16}\)O(\(^{16}\)O, \(^{16}\)O\(^{*}\) \(\rightarrow\) \(^{12}\)C g.s. + \(\alpha\))\(^{16}\)O g.s.. No explicit particle identification was used during the measurement but an iterative technique based on final state mass assumption and comparing the total momenta in the \(x\), \(y\), and \(z\) (beam) directions with simulated Monte Carlo data allowed the final states to be correctly identified. This technique is similar to previously used methods of final state state selection\(^{21}\).

Figure 2 shows the effect this iterative momentum gating procedure has on the total \(Q\)-value spectrum for all multiplicity 3 data determined from the summed measured energies of the final state particles. The three labeled peaks, 1, 2, and 3, in Fig. 2(a) represent a series of reactions with the same \(Q\) value prior to complete final state mass assignment. The substantially lower background level in Fig. 2(b) indicates that removal of the majority of \(^3\)Li and \(^{12}\)C recoil events has been successful. The offset of 1.8 MeV of the peaks in Fig. 2(a) is associated with errors in the calibration process at low energies due to the calibration with an \(^{16}\)O

FIG. 1. Angular coverage of the detectors used in the measurement.

FIG. 2. Three-body \(Q\) values, \(Q_3\), for \(E_{lab} = 73\) MeV of (a) raw multiplicity 3 data for a selection of reactions with all three target components and (b) data after the application of the various momentum and kinematic gates (described in the text). The dashed line represents the \(Q\) value with a ~1.8 MeV offset applied.
beam and the reaction process involved the detection of α particles. An additional offset was applied to correct for this. It can be seen from Fig. 2(b) that the reactions of interest are well isolated after the identification technique has been implemented. The background that is seen at negative Q values is attributed to reactions with a fourfold or greater final state where one or more of the final state nuclei has not been detected.

A software gate was then applied to the Q value spectrum in Fig. 2(b) in order to analyze the relevant reaction.

IV. RESULTS

The reaction $^{16}\text{O}^{16}\text{O},^{16}\text{O}^* \rightarrow ^{12}\text{C}_{\text{g.s.}},\alpha ^{16}\text{O}_{\text{g.s.}}$ was selected and the relative energy of the $^{12}\text{C}_{\text{g.s.}}$ and the α nucleus was then calculated [21]. This was then used to determine the excitation energy in the reconstructed $^{16}\text{O}^*$ parent nucleus. Figure 3 shows an excitation spectrum of $^{16}\text{O}^*$ for a center-of-mass energy of 36 MeV. Of particular interest in Fig. 3 are the excited states at 10.35 and 11.09 MeV as has already been discussed. Experimental yields for each of the states were then calculated for each beam energy used. The yields were determined by integrating the peaks in the excitation spectrum, which were fitted with a Gaussian distribution including a polynomial background term. The yields were then normalized for beam exposure at each of the different beam energies. The normalized experimental yields, proceeding from the $2^+_2$, 9.84 MeV, $4^+_1$, 10.35 MeV, $2^+_2$, 11.09 MeV, and $2^+_3$, 11.52 MeV excited states in $^{16}\text{O}$ are shown in Fig. 4. The relative detection efficiencies for each excitation energy determined from a Monte Carlo simulation incorporating the same angular cuts, energy thresholds, and resolutions as in the experimental data are also shown in Fig. 4. The profiles shown assume an exponential falloff for the primary scattering and an isotropic breakup of the excited states in $^{16}\text{O}$ in the center-of-mass frame and are seen to be smoothly varying with the center-of-mass energy.

In addition, an angular correlation investigation enabled a dominant partial wave ($L$, orbital angular momentum component) value to be associated with some of the enhance-
ments observed in Fig. 4. The details of this angular correlation analysis are not described here but can be found elsewhere [24,25] and are similar to those used by Chappell et al. [26]. Briefly, after isolation of a specific decay had been achieved, a two-dimensional plot of the angles $\phi'$ against $\chi'$ (defined formally in the Basel coordinate system in Ref. [25]) was made. The angles $\phi'$ and $\chi'$ are the azimuthal components of $\theta'$ and $\psi'$, where $\theta'$ represents the primary scattering angle in the center-of-mass frame and $\psi'$ characterizes the breakup by defining the orientation of the relative velocity vector between the decay fragments. This was then compared to a simulated angular correlation plot, assuming a semiclassical angular correlation function [25], where the simulated data are subject to the same cuts as the real data. An example of these two plots is given in Fig. 5 for the $4^+_2$, 11.09 MeV excited state in $^{16}$O. By projecting the real and simulated data onto the $\phi'$ axis at an angle $\theta_p$, which defines the optimum projection angle needed to maximize the peak to valley ratio of the ridge structure observed, the value of $L$ can be varied in the simulations so that the periodicity of the simulated data matched the experimental data. The $L$ value was assigned to the enhancement when the best match was achieved. The one-dimensional projections of the experimental and simulated angular correlations used to determine the $L$ value of the enhancements observed in this work are shown in Figs. 6–8. Figures 6–8 show the projections for decay, for a selection of possible $L$ values, from the $4^+_1$, 10.35, $4^+_2$, 11.09, and $2^+_1$, 11.52 MeV states, respectively. The optimum projection angle $\theta_p$ and the center-of-mass energy are given in each figure. The assigned orbital angular momentum values $L$ are shown in Fig. 4.

V. DISCUSSION

The excitation functions shown in Fig. 4 display a number of enhancements at various center-of-mass energies, some of which have a dominant partial wave associated with them. If we assume stretched coupling, then the total angular momen-

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FIG. 5. Angular correlation for the reaction $^{16}$O($^{16}$O,$^{16}$O*) → $^{12}$C_{g.s.} + $\alpha$ $^{16}$O_{g.s.} for decay from the $4^+_2$, 11.09 MeV excited state in $^{16}$O at $E_{\text{c.m.}} = 36$ MeV. (a) Experimental data (b) simulation data assuming $k=4$ (spin of the state) and $L=22$ (orbital angular momentum component).

FIG. 6. One-dimensional projection of the measured angular correlation structure (solid line) on to a single axis ($\phi'$) for the reaction $^{16}$O($^{16}$O,$^{16}$O*)$[4^+_1$, 10.35 MeV] → $^{12}$C_{g.s.} + $\alpha$ $^{16}$O_{g.s.}, compared with simulated angular correlation projections (dotted line) on to the same axis. The $k$ and $L$ values chosen for the simulation are shown on each plot. (a) The $E_{\text{c.m.}} = 30$ MeV enhancement, (b) the $E_{\text{c.m.}} = 36$ MeV enhancement.
tum or spin $J$ of the enhancement is equal to $L+k$, where $k$ is the intrinsic angular momentum projection, or spin of the excited state, and $L$ is the previously discussed orbital angular momentum component.

A. The $4^+, 10.35$ MeV and $4^+, 11.09$ MeV excitation functions

1. $4^+, 10.35$ MeV excitation function

All three enhancements observed in this excitation function, at $E_{\text{c.m.}} \approx 30$ MeV, 36 MeV, and 39 MeV, seem to overlap with enhancements observed in the excitation functions for other exit channels associated with the $^{16}\text{O}+^{16}\text{O}$ system. The peak observed at $E_{\text{c.m.}} \approx 30$ MeV has a similar center-of-mass energy to the enhancement observed in the excitation function for single excitation to the $3^-, 6.13$ MeV state [13]. Pate et al. assigned this observed enhancement a spin of $J=20$ or 22. We have been able to assign a spin of $J=22$ or 24 to the peak observed in this investigation and therefore there appears to be some agreement. The structure observed at $E_{\text{c.m.}} \approx 36$ MeV also appears to overlap with that observed in the same measurement performed by Pate et al. The assigned spin of $J=26$ or 28 is in good agreement with

FIG. 7. One-dimensional projection of the measured angular correlation structure (solid line) on to a single axis ($\phi'$) for the reaction $^{16}\text{O}(^{16}\text{O},^{16}\text{O}^*_{4^+}, 11.09 \text{ MeV}) \rightarrow ^{12}\text{C}_{\text{g.s.}} + \alpha)^{16}\text{O}_{\text{g.s.}}$, compared with simulated angular correlation projections (dotted line) on to the same axis. The $k$ and $L$ values chosen for the simulation are shown on each plot. (a) The $E_{\text{c.m.}}=36$ MeV enhancement, (b) the $E_{\text{c.m.}}=40$ MeV enhancement, and (c) the $E_{\text{c.m.}}=40.5$ MeV enhancement.

FIG. 8. One-dimensional projection of the measured angular correlation structure (solid line) on to a single axis ($\phi'$) for the reaction $^{16}\text{O}(^{16}\text{O},^{16}\text{O}^*_{2^+}, 11.52 \text{ MeV}) \rightarrow ^{12}\text{C}_{\text{g.s.}} + \alpha)^{16}\text{O}_{\text{g.s.}}$, compared with simulated angular correlation projections (dotted line) on to the same axis. The $k$ and $L$ values chosen for the simulation are shown on each plot. (a) The $E_{\text{c.m.}}=36$ MeV enhancement, (b) the $E_{\text{c.m.}}=37$ MeV enhancement.
the spin deduced from our measurement, \( J = 26 \) or \( 28 \).

The \( E_{\text{c.m.}} = 30 \) MeV and \( 36 \) MeV enhancements observed in this work also overlap well in terms of energy with two similar structures reported by Balamuth et al. [9]. However, the spins assigned in this measurement, a single excitation to the \( 0^+_2 \), \( 6.05 \) MeV excited state in \( ^{16}\text{O} \), were \( J = 18 \) and \( J = 22 \) for the \( E_{\text{c.m.}} = 30 \) MeV and \( 36 \) MeV structures, respectively, and are not in agreement with the spins we have assigned at these center-of-mass energies.

The peak observed at \( E_{\text{c.m.}} = 30 \) MeV is also partially correlated with a structure observed in the excitation function for single excitation to the \( 0^+_2 \), \( 6.05 \) MeV state at \( E_{\text{c.m.}} \approx 29.3 \) MeV measured by Barrow et al. [10]. This structure was assigned a dominant partial wave of \( L = 20 \) or \( 22 \) (assuming stretched coupling, \( J = 24 \) or \( 26 \)) and therefore overlaps reasonably well with our measured peak. The slight discrepancy between the energies of these structures may be associated with the broadness of the peak at \( 30 \) MeV in the present measurement. An enhancement has also been observed for elastic scattering in the \( ^{16}\text{O} + ^{16}\text{O} \) system at \( E_{\text{c.m.}} \approx 29.5 \) MeV by Maher et al. [27]. However, this was assigned a spin of \( J = 18 \) or \( 20 \).

No spins were assigned to the bump observed in this work at \( E_{\text{c.m.}} \approx 39 \) MeV because of the low statistics at this energy making comparisons with other enhancements difficult.

2. \( 4^+_2 \), 11.09 MeV excitation function

The enhancement observed in this excitation function at \( E_{\text{c.m.}} \approx 36 \) MeV (assuming stretched coupling \( J = 26 \)) overlaps with a structure observed by Pate et al. [13] in the single excitation of \( ^{16}\text{O} \) to the \( 3^-_1 \), 6.13 MeV state (assigned spin was \( J = 26 \) or \( 28 \)).

An overlap in energy is also seen between the enhancement observed at \( E_{\text{c.m.}} = 36 \) MeV and the enhancement observed by Balamuth et al. at \( E_{\text{c.m.}} \approx 36 \) MeV [9] for the single excitation to the \( 0^+_2 \), 6.05 MeV excited state. However, the spin assigned by Balamuth et al. was \( J = 22 \) which does not agree with our assigned spin of \( J = 26 \). A similar conclusion can also be drawn upon comparing the structures observed in this measurement and in the results reported by Balamuth et al. at \( E_{\text{c.m.}} \approx 39 \) MeV where the spins were assigned values of \( J = 26 \) and \( J = 24 \) respectively.

Additional overlaps in terms of energy between our enhancements at \( E_{\text{c.m.}} \approx 36 \) MeV and \( E_{\text{c.m.}} \approx 39 \) MeV and the work of Wells et al., mutual excitation to the \( 3^-_1 \), 6.13 MeV [12], and Pate et al. [13], respectively, can be made. The authors, in both cases, were unable to assign spins to these enhancements making further comparison difficult.

B. Comparison of the \( 4^+_1 \), 10.35 MeV and \( 4^+_2 \), 11.09 MeV excitation functions

The peaks observed in the \( 4^+_1 \), 10.35 MeV and \( 4^+_2 \), 11.09 MeV excitation functions are at very similar center-of-mass energies. Of the three most notable peaks at \( E_{\text{c.m.}} \approx 30 \), 36, and 39 MeV only the 36 MeV enhancement can be compared directly as it has been assigned a spin in both excitation functions whereas incomplete spin assignments for the other structures restrict comparison. The values for the \( E_{\text{c.m.}} \approx 36 \) MeV enhancement agree well, \( J = 26 \) or 28 for the \( 4^+_1 \), 10.35 MeV excitation function and \( J = 26 \) for the \( 4^+_2 \), 11.09 MeV excitation function. The spins in both excitation functions agree more favorably with the work of Pate et al. [13] than that of Balamuth et al. [9].

The similarity between the excitation functions despite the strong structural difference between the two states suggests that strong coupling is occurring in the \( ^{16}\text{O} + ^{16}\text{O} \) reaction or that the structure is dominated by resonances in the
entrance (elastic) channel. In this regard it should be noted that the relative population of these states may be important. The enhancement observed in the $4_2^+$, 11.09 MeV excitation function has a much greater beam normalized yield, within the resolution of the measurement, suggesting that single excitation to this state is the dominant process and favored by the $^{16}\text{O}+^{16}\text{O}$ reaction.

**C. The $2_3^+$, 9.84 MeV and $2_3^+$, 11.52 MeV excitation functions**

Two possible peaks may be observed at $E_{\text{c.m.}}=32$ MeV and 36 MeV in the $2_3^+$, 9.84 MeV excitation function. The structure at 36 MeV overlaps with the excitation function for single [13] and mutual [12] excitation to the $3_1^+$, 6.13 MeV state in $^{16}\text{O}$. However, due to the low statistics in this excitation function no firm spin assignments were possible.

The enhancement at $E_{\text{c.m.}}=37$ MeV in the $2_3^+$, 11.52 MeV excitation function overlaps well with a structure observed in the excitation function for mutual excitation to the $2_0^+$, 6.05 MeV excited state also at $E_{\text{c.m.}}=37$ MeV [11]. Furthermore, the spins determined by Wimer et al., $J=20$ or 22, agree well with the spins determined in this measurement, $J=22$ or 24.

**VI. SUMMARY**

In conclusion, we have presented measurements, using the MEGHA strip detector array at the Australian National University (ANU), on the beam normalized yield for the reaction $^{16}\text{O}(^{16}\text{O},^{12}\text{C}_{g.s.}+\alpha)^{16}\text{O}_{g.s.}$, proceeding from excited states in $^{16}\text{O}$ above the particle decay threshold sampled over the center-of-mass energy range $E_{\text{c.m.}}=26$–47 MeV.

Various enhancements in the excitation functions for excitation to the $4_1^+$, 10.35 MeV and $4_2^+$, 11.09 MeV excited states have been reported and their energies and spins have been compared with previous work. The similarity of these excitation functions, despite the strong structural difference between the two states, suggests that strong coupling occurs in the $^{16}\text{O}+^{16}\text{O}$ system. Excitation functions for the excitation to the $2_3^+$, 9.84 MeV and $2_3^+$, 11.52 MeV levels in $^{16}\text{O}$ have also been presented.

In a previous publication Wimer et al. produced a useful table (Table I in Ref. [11]) summarizing the resonances in the $^{16}\text{O}+^{16}\text{O}$ system for which spins have been measured. To aid comparison, Table I in this paper is an extension of this, incorporating the new measurements from this work. It should be noted that any overlap between enhancements observed in this and previous work must be tentative due to the broadness of the structures seen and the broad energy step of the excitation function performed. This study has shown that the measurements can be carried out and that there is structured yield in the excitation functions. It is suggested that any future work on this system should utilize a finer energy step in measuring the excitation function.

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