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The ^{12}C and ^{16}O decay of ^{24}Mg states excited in the ^{12}C(^{16}O,^{24}Mg)α reaction

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Abstract

The population and decay of excited states in ^{24}Mg has been investigated through the ^{12}C(^{16}O,^{12}C^{12}C)α and ^{12}C(^{16}O,^{8}Be^{16}O)α reactions, at beam energies of 75, 85 and 115 MeV. The fragments from the breakup of the ^{24}Mg nucleus were detected in coincidence, permitting a study of both the excitation energies and the spins of the fissioning states. These measurements indicate a series of states in ^{24}Mg between 20 and 40 MeV with spins ranging from J=4 to 14 $\hbar$. The results are discussed in the context of the ^{12}C $+^{12}$ C quasimolecular scattering resonances and other ^{24}Mg breakup reactions.

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I. INTRODUCTION

There are a wide range of experimental techniques which may be used to probe highly excited nuclear states. Amoung these, breakup studies have proved extremely profitable, particularly in the case of light s-d shell nuclei. In this experimental approach the projectile-like nucleus is excited above particle decay thresholds in an interaction with a target nucleus and subsequently decays by particle emission. Experimentally, the excited states are then reconstructed following the coincidence detection of the breakup products. This technique has a number of key advantages, for example a broad spectrum of states can be accessed in a single measurement without the need for detailed excitation function studies and, moreover, the reconstruction of the angular correlations of the breakup fragments can in many circumstances lead to a model independent spin analysis.

The application of this technique to the nuclei ^{24}Mg [1,2], ^{28}Si [1,3] and ^{32}S [3,4] has provided evidence for symmetric and near symmetric fission in these light systems. For example, a sequence of ^{24}Mg excited states (E_x >20 MeV) are observed to decay into two ^{12}C nuclei. Similarly ^{28}Si and ^{32}S have been shown to breakup into $^{12}\mathrm{C} +^{16}\mathrm{O}$ and $^{16}\mathrm{O} +^{16}\mathrm{O}$ final states respectively. Considerable effort has been devoted to understanding the nature of these states and the breakup process, through the measurement of their spins and the study of reactions involving similar systems which differ by either one proton or one neutron. For example, the spin information [2] suggests that the ^{24}Mg states observed in the reaction $^{12}\mathrm{C}(^{24}\mathrm{Mg},^{12}\mathrm{C}^{12}\mathrm{C})^{12}\mathrm{C}$ may be associated with a rotational structure with a moment of inertia corresponding to a hyperdeformed nuclear state. Furthermore, the decay process is observed to be highly selective in that the breakup proceeds from only a few states in an excitation energy region in which there are several hundred states per MeV with similar spins. This selectivity may suggest that the fissioning states possess, for example a cluster-like structure. Moreover, a study of the breakup of the nucleus ^{25}Mg [5] into $^{12}\mathrm{C} +^{13}\mathrm{C}$ found no evidence for such a process, indicating a dependence on the details of the structure of these nuclei.

Excitation function measurements have also provided considerable evidence for such cluster structures [6]. For example, a whole spectrum of so called *quasimolecular* resonances are observed in the $^{12}C + ^{12}C$ system, and this phenomenon extends to numerous other reactions involving the interaction of s-d shell nuclei. Detailed spin and partial width analyses of these resonances suggest a common link with a molecular-like, dinuclear cluster structure. However, the complexity of the resonance structures in these systems has prevented a definitive understanding of their origin, and the precise nature and behaviour of the underlying cluster structure.

It is interesting to speculate if the same resonant states are observed in the breakup and resonant scattering measurements, i.e. if the same nuclear configurations play a dominant role in the fusion and fission processes. A high resolution measurement of the $^{12}C(^{24}Mg,^{12}C^{12}C)^{12}C$ reaction [7] does indeed indicate that the quasimolecular resonances are represented in the spectrum of breakup states. In principle, this link could provide a new insight into the nature of the quasimolecular resonances. Further, the much broader spectrum of processes which may be used to excite the resonant states, including inelastic excitation and single or multinucleon transfer reactions, may provide additional information on the structure of the states and their relationship to the ground state configurations. To this end, many breakup measurements have been performed, which in the ^{24}Mg system include; $^{12}C(^{24}Mg,^{12}C^{12}C)^{12}C$ [1,2,8], $^{12}C(^{24}Mg,^{16}O^{8}Be)^{12}C$ [9], $^{12}C(^{20}Ne,^{12}C^{12}C)^{8}Be$ [10], $^{12}C(^{20}Ne,^{16}O^{8}Be)^{8}Be$ [11], $^{12}C(^{24}Mg,^{20}Ne\,\alpha)^{12}C$ [11], $^{12}C(^{20}Ne,^{20}Ne\,\alpha)^{8}Be$ [11] and $^{12}C(^{16}O,^{12}C^{12}C)\alpha$ [12–15].

The studies of the $^{12}C(^{24}Mg,^{12}C^{12}C)^{12}C$ and $^{12}C(^{20}Ne,^{12}C^{12}C)^{8}Be$ reactions appeared to indicate that the breakup process proceeded through a series of ^{24}Mg states with a 4p-4h configuration. These states have been identified with the $^{20}Ne + \alpha$ cluster–like configuration which appears in the Alpha Cluster Model calculations of Marsh and Rae [16] and the hyperdeformed prolate minimum in the Nilsson–Strutinsky calculations of Leander and Larsson [17]. However, there is some evidence that different states are observed in the $^{12}C(^{16}O,^{12}C^{12}C)\alpha$ reaction and the $^{16}O + ^{8}Be$ and $^{20}Ne + \alpha$ decay channels [18]. These latter states may thus be probing a different type of ^{24}Mg configuration. Certainly, both the

Alpha Cluster Model and Nilsson–Strutinsky calculations predict the existence of a variety of deformed structures, including triaxial and oblate shape isomeric configurations. In order to test the hypothesis that different configurations are probed in different reactions, detailed measurements are required for a wide range of excitation energies, including the determination of spins of the decaying states. The data available at present in the literature are unfortunately incomplete, either in the sense that the spins of the states have not been identified or that the data are restricted to narrow intervals of excitation energy.

In this paper we present the results of a wide ranging study of the $^{12}C(^{16}O,^{24}Mg)\alpha$ reaction, in which the ^{24}Mg excited states decayed into the nuclei $^{12}C+^{12}C$ and $^{16}O+^{8}Be$. From the angular correlations of the decay products we are able to suggest spins for many of the states observed. These data span the excitation interval from 20 to 40 MeV, which contains most of the previously observed breakup states and quasimolecular resonances.

II. EXPERIMENTAL DETAILS

The $^{12}C(^{16}O,^{12}C\ ^{12}C)\alpha$ and $^{12}C(^{16}O,^{16}O\ ^{8}Be)\alpha$ reactions have been studied with ^{16}O beams of energies of 75, 85 and 115 MeV, provided by the Australian National University's 14UD tandem accelerator. The integrated beam exposures at the three energies were 5.8, 7.0 and 6.4 mC respectively. The target used in these measurements was a 50 μgcm^{-2} natural carbon foil.

The nuclei formed in the above reactions were detected in two gas-silicon hybrid detectors. The silicon elements of the detectors were 5×5 cm^2, 16 strip, position–sensitive silicon strip–detectors (PSSSDs) [19]. The strips were orientated horizontally which provided a measurement of the position of the incident nuclei in this plane to within $\sim$1 mm (this resolution is somewhat poorer than that cited in [19] due to the low energies of the detected nuclei), the out-of-plane position was determined from the vertical location of the active strip, and hence the position resolution in this direction was determined by the strip pitch (3.125 mm). The gas elements of the hybrid detectors possessed 5 cm deep active volumes and were operated at a pressure of 50 torr of propane, with 3.5 μm thick mylar windows. This relatively low gas pressure permitted the detection of ^{12}C and ^{16}O nuclei with energies as small as 15 and 18 MeV respectively, whilst still retaining sufficient charge (Z) resolution to perform particle identification. The use of a strip detector within the gas volume also allowed the identification of events in which ^{8}Be nuclei were produced, since the subsequent decay to two alpha particles could be identified in separate strips. The two hybrid telescopes were positioned symmetrically about the beam axis and covered the in–plane angular intervals 11.9° to 28.1° for the beam energies of 75 and 85 MeV, and 15.9° to 32.1° for the 115 MeV measurement.

These gas-silicon hybrid detectors provided a determination of the charge, energy and emission angle, and hence, by assuming the mass, the momenta for each of the detected nuclei could be calculated. From the recorded information and the principle of conservation of momentum, the momentum of the undetected recoil-like alpha-particle was determined. This measurement of the complete reaction kinematics permitted a detailed study of the decay processes giving rise to each particular final state.

The energy and position responses of the detector telescopes were calibrated using the elastic scattering of 45 and 65 MeV ^{12}C nuclei from ^{12}C, ^{27}Al and ^{197}Au targets.

III. DATA ANALYSIS AND RESULTS

A. The ^{12}C(^{16}O,^{12}C ^{12}C)α reaction

Figure 1a shows the three body Q–value spectrum for events in which two ^{12}C nuclei were detected and the energy of the unobserved alpha-particle was constructed from the measured parameters. The peaks in this spectrum correspond to the three possible combinations of the two ^{12}C nuclei being produced in their ground and first excited state (4.4 MeV). The Q–value resolution for this channel is $\sim$ 900 keV and is dominated by the energy resolution of the hybrid detectors.

This final state consisting of the two ^{12}C nuclei and one alpha-particle can be produced via two main processes; inelastic scattering of the ^{16}O projectile followed by the decay of the excited states into $^{12}C+\alpha$, or alternately the decay of ^{24}Mg excited states into $^{12}C+^{12}C$. In order to determine the relative contributions from these two processes the corresponding excitation energy in the three possible excited systems has been calculated. The excitation energy in the ^{24}Mg nucleus was calculated from a measurement of the relative velocities of the two ^{12}C nuclei,

$$E_x(^{24}Mg) = \frac{1}{2}\mu v^2_{rel(1-2)} + Q_{bu}, \tag{1}$$

where μ is the reduced mass of the decaying system, $v_{rel(1-2)}$ is the relative velocity of the two ^{12}C fragments and Q_{bu} (13.93 MeV) is the breakup threshold for this decay channel.

The excitation energies of the two possible ^{16}O nuclei were deduced from the reaction Q-value, calculated by assuming, in turn, that the two detected ^{12}C nuclei were the recoil particles in the reaction $^{12}C(^{16}O,^{16}O^*)^{12}C$,

$$E_x(^{16}O) = Q_{gs} + E_{beam} - E_{^{12}C} - \frac{P^2_{beam} + P^2_{^{12}C} - 2\mathbf{P_{beam}}.\mathbf{P_{^{12}C}}}{2M_{^{16}O}} \tag{2}$$

where Q_{gs} is the reaction Q-value for the case when the ^{12}C and ^{16}O nuclei are produced in the ground state (in this case Q_{gs}=0 MeV). Figure 2 shows a two dimensional spectrum of the possible ^{16}O excitations for the beam energy of 115 MeV. The horizontal and vertical lines in this spectrum correspond to ^{16}O excited states at 10.4, 11.1, 14.8, 16.2 and 21.0 MeV, which are in good agreement with the tabulated values for two rotational bands in this nucleus (10.4 MeV (4^+), 11.1 MeV (4^+), 14.8 MeV (6^+), 16.2 MeV (6^+) and 20.8 MeV (8^+)) [20]. On the other hand, the diagonal lines correspond to the decay of excited states in ^{24}Mg. In order to remove the dominant contribution from the ^{16}O excited states, only the data in the region above the loci of the 21.0 MeV ^{16}O excited states were selected for further analysis, a procedure also performed in references [12–15]. Figure 3a shows the resulting spectrum of ^{24}Mg excited states which decay into two ^{12}C nuclei.

A similar analysis was performed for the 75 and 85 MeV data, where dominant ^{16}O excited states were again removed in order to reduce the background contributions to the

^{24}Mg excitation energy spectra. In the case of the 75 MeV and 85 MeV data sets, the region above the 16.2 MeV ^{16}O excited states was selected for analysis of ^{24}Mg excited states, and the state at ~21 MeV was selectively removed. The resulting ^{24}Mg excitation energy spectra are shown in figures 3b and 3c. The three spectra indicate the existence of excited states over the interval $E_x(^{24}Mg)$=20 to 39 MeV. The widths of the states appear to be rather uniform, suggesting they are dominated by the experimental excitation energy resolution. The expected excitation energy resolution and the Q-value resolution have been estimated using Monte Carlo techniques. These simulations suggest that the Q-value resolution is ~1 MeV and the excitation energy resolution for the E_{beam}=115 MeV measurement is 480 keV, reducing to 350 keV for the E_{beam}=75 and 85 MeV data. These values are close to those observed in the data. This experimental resolution thus provides an upper limit for the widths of these states.

In the high excitation energy region (E_x >25 MeV) the states appear well correlated in the three spectra. The difference in the reconstructed excitation energy of the states at the three different beam energies is <200 keV, consistent with the expected uncertainty of the absolute excitation energies of the states. Table 1 lists the energies of the states observed in the three measurements, in the instance that states were observed in more than one spectrum then the mean energy is quoted. In the region between 20 and 25 MeV, several states appear only at one beam energy. For example, a state at 23.4 MeV appears only at the 85 MeV beam energy and a state appears at 23.8 MeV only at the 75 MeV beam energy.

The solid curves shown in Figure 3 are the results of Monte Carlo calculations of the detection efficiency for the ^{12}C(^{16}O,^{12}C^{12}C)α reaction. This Monte Carlo code simulates the sensitivity and performance of the detection system, including the position dependent energy thresholds of the strip detectors, and also attempts to generate simulated particles with realistic energy and angular distributions. In the case of the above reaction the primary angular distribution was taken to reproduce the angular dependence observed in the ^{12}C(^{16}O,^{24}Mg)α reaction shown in Figure 8 of reference [15]. The decay angular distributions were modeled with a $1/sin\theta$ dependence. The effects of the restricted range of ^{16}O excitation energies imposed by the selective analysis of the data were also included.

Figure 6a shows the excitation energy spectra for the 85 and 115 MeV summed together. This spectrum is compared with the states observed by Bechara *et al.* [21] (vertical dotted lines) in the ^{12}C(^{16}O$, \alpha$)^{24}Mg* reaction. In the higher excitation energy region there appears to be reasonable agreement with the observed number of states and their energies, although a more detailed comparison is not possible due to the complexity of the spectra and the incomplete spin information and the possibility of systematic uncertainties in the energy calibration for both measurements. Furthermore, the measurements of Bechara *et al.* also indicate that the level density over the measured excitation energy region is higher than revealed in the present measurement, particularly at low energies. This may indicate that is this region the spectrum of states decaying into two ^{12}C nuclei is more complex than revealed in the present measurement.

B. The ^{12}C(^{16}O,^{16}O ^{8}Be)α reaction

The analysis of the ^{12}C(^{16}O,^{16}O^{8}Be)α reaction proceeded in a similar fashion to that for the ^{12}C(^{16}O,^{12}C^{12}C)α reaction, described in the preceding section. However, in this instance the ^{8}Be nuclei were identified via the reconstruction of the relative energy (using equation (1)) of the alpha–particles for all events in which two strips were active within a single telescope. The ^{8}Be ground state was identified as a sharp peak in the relative energy spectrum at an energy of 92 keV, and only these events were selected for further analysis. Figure 1b shows the Q–value spectrum for the reaction in which ^{8}Be and ^{16}O nuclei were detected. The two peaks correspond to the ^{16}O nucleus being formed in either the ground state (Q= -7.36 MeV) or the unresolved 6.0, 6.1 and 6.9 MeV excited states (Q= -13.9 MeV). The Q–value resolution in this instance is 1.7 MeV.

The remainder of the reaction kinematics were reconstructed assuming the final state particles were ^{8}Be, ^{16}O and ^{4}He nuclei. As in the preceding section, this final state can also result from a number of different reaction processes. For example, the decay of ^{12}C excited states into ^{8}Be $+ \alpha$, ^{20}Ne excited states into ^{16}O $+ \alpha$ or ^{24}Mg states into ^{16}O $+^8$ Be nuclei. The possible excitations of the nuclei ^{12}C and ^{20}Ne were calculated from the relations

$$E_x(^{12}C) = Q_{gs} + E_{beam} - E_{^{16}O} - \frac{P_{beam}^2 + P_{^{16}O}^2 - 2\mathbf{P_{beam}}.\mathbf{P_{^{16}O}}}{2M_{^{12}C}} \qquad (3)$$

$$E_x(^{20}Ne) = Q_{gs} + E_{beam} - E_{^8Be} - \frac{P_{beam}^2 + P_{^8Be}^2 - 2\mathbf{P_{beam}}.\mathbf{P_{^8Be}}}{2M_{^{20}Ne}} \qquad (4)$$

with Q_{gs}=0 and -2.63 MeV respectively. The excitation of the ^{24}Mg nucleus was calculated from equation (1) with Q_{bu}=14.14 MeV.

Figure 4 shows the reconstructed excitation energies of the ^{20}Ne and ^{12}C nuclei produced in the ^{12}C(^{16}O,^{8} Be)^{20}Ne* and ^{12}C(^{16}O,^{16} O)^{12}C* reactions, plotted for the E_{beam}=115 MeV data. This spectrum shows both horizontal and vertical loci, associated with states at excitation energies of 14.8 and 18.8 MeV in ^{12}C and 20.8 MeV in ^{20}Ne. The 14.8 MeV locus may be associated with the 15.1 MeV (1^+) ^{12}C state and the peak in the ^{20}Ne spectrum lies close to a state previously observed in this reaction at E_x(^{20}Ne)=21.06 MeV [22]. There are strong diagonal loci in this spectrum which may be attributed to excited states in ^{24}Mg decaying into the final state ^{16}O $+^8$ Be. In order to remove the "background" from the contaminant reactions, the data below E_x(^{12}C)=19 MeV have been excluded and the state at E_x(^{20}Ne)=20.8 MeV has been selectively removed. The resulting ^{24}Mg excitation energy spectrum is shown in Figure 5a.

A similar analysis was performed for the beam energies of 75 and 85 MeV, and the resulting excitation energy spectra as shown in Figures 5b and 5c respectively. For these latter energies there was no evidence for the decay of ^{12}C excited states, possibly due to the reduced excitation probability for the smaller incident energies, and the spectra correspond to the regions E_x(^{20}Ne) >17 MeV and E_x(^{20}Ne) >23 MeV for the beam energies 75 and 85 MeV respectively. The solid curves in this figure correspond to Monte Carlo calculations of the detection efficiency, as described in the preceding section. The decay of the ^{8}Be into two alpha–particles and their subsequent detection in two of the strips in the silicon strip detectors has been treated explicitly in this calculation. The ^{16}O $+^8$ Be decay channel can contain contributions from both odd and even spin states (as opposed to the $^{12}C+^{12}C$ channel which possesses only even spin states), and there is some evidence that the large widths of many of the structures results from contributions from several states. The states observed in this decay channel are listed in Table 2. The reconstructed excitation energy resolution is ~700 keV. This is slightly worse than for the ^{12}C+^{12}C decay channel which is a consequence of the reconstruction of the ^{24}Mg excitation energy from three particles rather than two. Figure 6b shows the combined spectrum for the 85 and 115 MeV beam energies compared with the spectrum of states observed by Bechara *et al.* [21] (vertical dotted lines).

C. Angular Correlation Measurements

The complete determination of the reaction kinematics for the above reactions permits the emission process in the primary ^{28}Si centre of mass system, and the subsequent decay from the ^{24}Mg excited states to be decoupled. In certain circumstances, this decoupling allows the decay process to be studied model independently and hence, through angular distribution measurements, the spins of the states to be unambiguously determined. In practice, rather than studying the angular distributions within the ^{24}Mg decay frame, the full angular correlations are analysed, which provides information on the dominant entrance channel angular momenta in addition to the spin of the state populated. These correlations are calculated as a function of the two in-plane or axial [23] correlation angles θ^* and ψ, where θ^* is the emission angle of the ^{24}Mg nucleus in the scattering (^{28}Si) centre of mass frame and ψ describes the subsequent decay process in the ^{24}Mg centre of mass system, with both angles measured with respect to the beam axis.

Figure 7 shows an example of an angular correlations for the $^{12}C+^{12}C$ decay of the state at 31.9 MeV. This spectrum demonstrates the nature of the angular correlations; there are a series of diagonal ridges. There are two independent methods for analysing such correlation patterns. The first of these is a study of the periodicity of the correlation structure. Since, in the above measurements, all the final state particles are in their ground states with zero spin (J^π=0^+), for $\theta^* = 0$ the ^{24}Mg nucleus is aligned in the m=0 magnetic substate (taking the quantization axis to be the beam direction). Hence, under the above constraint, the angular distributions of the decay products are described by Legendre polynomials of order J, where J is the spin of the ^{24}Mg excited state. At scattering angles away from θ^*=0, the magnetic substate populations of the ^{24}Mg nucleus are no longer constrained, and a variety of reaction amplitudes contribute to the angular distributions. However, rather than removing the structure in the correlations which is evident at θ^*=0, the correlation pattern becomes shifted such that

$$\frac{d^2\sigma}{d\theta^* d\psi} \propto |P_J(cos(\psi + \Delta\psi))|^2 \qquad (5)$$

where $\Delta\psi = \Delta\theta^* l_f/J$ and l_f is the final state grazing angular momentum in the ^{28}Si centre of mass system. Consequently, the θ^*–ψ correlations appear as a series of diagonal ridges which intercept the θ^*=0, ψ–axis at points corresponding to the maxima of the function $|P_J(cos\psi)|^2$. This result was arrived at by da Silviera [24] by considering the classical relationship between the angular momenta involved in the reaction, and later quantum mechanically by Marsh and Rae [25]. The spin of the ^{24}Mg states can thus be deduced through an examination of the ψ dependence of the correlations along the θ^*=0 axis. However, in this measurement the θ^*=0, ψ coverage is rather restricted and the statistical significance of the data is poor. Consequently, we have performed a projection of the correlations onto the θ^*=0 axis at an angle parallel to the ridge structure. This then results in angular distributions whose periodicity, but not necessarily amplitude, reflects the spin of the nucleus, J. Clearly the gradient of the ridge structure is also related to the spin of the state and the final state grazing angular momentum, and hence can be used as an independent determination of J. Further, if it is assumed that the entrance channel partial wave can be related to J and l_f through the relationship $l_i = J + l_f$, which is the "stretched" configuration corresponding to the lowest centrifugal barrier, then the ridge gradient may also be used to characterise l_i.

Figure 8 shows a series of the correlations, for the excited states observed in the $^{12}C + ^{12}C$ decay channel, projected at an angle which is consistent with the order of Legendre polynomial shown in the figure, i.e. assuming a fixed value of l_i for each beam energy. The quality of the correlations in general can be seen to increase with increasing excitation energy, and this is believed to be a consequence of either the increased density of states at the lower excitation energies, resulting in a number of states, with not necessarily the same spin, contributing to the data, or an increase in the level of background contributing to these spectra. Monte Carlo simulations of the breakup reaction have been used to provide an estimate of the resolution with which the correlation angles are reconstructed, given the energy and position resolution of the detectors. These calculations suggest that the uncertainties in θ^* and ψ are $\sim 5°$ and $\sim 2°$ respectively. The θ^* resolution is dominated by the size of the beam spot (1.5×1.5 mm^2) whereas the main factor effecting the reconstruction of the angle ψ is the position resolution of the detectors. Further, these calculations indicate that these resolutions remain constant for the three beam energies, and hence this is not an important effect in the change in quality of the correlations.

The analysis of angular correlations through the above projection procedure tends to be a subjective process. However, by requiring consistency between the periodicity of the projected data and the angle of projection, it is possible to be reasonably confident in many of the assignments. This degree of confidence depends to a large extent on the quality of the correlation structure and the number of minima and maxima spanned by the data. The data for the 31.9 MeV state is an example of a data set for which the spin can be assigned with a high degree of confidence. The diminishing structure at lower excitation energies implies that spins can be assigned with less certainty. For example, the states at 20.9 and 21.7 MeV possess correlations which suggest J=6 spin assignments, but for instance, J=4 cannot be excluded with a high degree of certainty. The spins suggested by the angular correlation analysis are listed in Table 1, where uncertain assignments are indicated by brackets. Typically the magnitude of this uncertainty is $\pm2\hbar$. The average values of the correlation gradients suggest that at the three centre of mass energies, 32.1, 36.4 and 49.3 MeV, the dominant entrance channel partial waves were l_i=16$\pm$1$\hbar$, 18$\pm$1$\hbar$ and 22$\pm$1$\hbar$. This trend is in general agreement with the sequence of resonances observed in ^{12}C+^{16}O reactions

[26,27], and the reported values of l_i=19 and 21 $\hbar$ at the centre of mass energies of 34.5 and 42.4 MeV respectively [15].

Figure 9 shows the projected angular correlations for many of the states observed in the $^{16}\mathrm{O} + ^{8}\mathrm{Be}$ decay channel. Clearly, the quality of the angular distributions do not match those observed in the $^{12}\mathrm{C} + ^{12}\mathrm{C}$ data, and correspondingly the level of confidence in the associated spins is reduced. However, it is possible to suggest spins for many of the states and these are listed in Table 2. Also presented in Table 2 are the spins which the correlations appear to exclude. In the instance that the correlations are consistent with two spins both are listed in the table, with the preferred spin in boldface type. Once again, this analysis suggests dominant entrance channel partial waves of l_i=16±1$\hbar$, 18±1$\hbar$ and 22±1$\hbar$ at the three energies, consistent with those measured in the $^{12}\mathrm{C} + ^{12}\mathrm{C}$ decay channel.

IV. DISCUSSION

The states observed in the $^{12}\mathrm{C}(^{16}\mathrm{O}, ^{12}\mathrm{C}^{12}\mathrm{C})\alpha$ reaction can be compared with those reported in previous studies of this system [12–15]. Costanzo *et al.* [12–14] have reported states at the excitation energies of 26.3, 27.3, 28.4, 29.2, 30.7 (12^+), 31.6 (12^+), 35.1 (14^+) and 36.5 MeV (14^+). We have previously reported states at 25.4, 26.2, 27.2 (10^+), 27.9 (12^+), 29.0 (12^+), 31.5 MeV (14^+) [15]. We believe that this latter sequence of states corresponds to states in the present measurement at 25.0 (8^+), 25.9+26.4 (10^+), 27.0 (10^+), 28.0+28.4 (10^+), 29.2 (12^+) and 31.9 MeV (12^+). There are discrepancies between these two latter measurements of -400 keV for low excitation energies and +400 keV at the other end of the excitation energy range, which is larger than the combined uncertainties quoted in the two measurements. However, we note that in the previous measurement detection efficiency was changing extremely rapidly at the two extremes of the excitation energy spectrum and this may have resulted in a distortion shifting the centroid energies of the states at the end of the spectrum towards the centre. The present measurement appears to confirm the findings of Costanzo *et al.* [14] for the states at 35.1 and 36.5 MeV, which we associate with the structures observed at 35.6 and 36.7 MeV, as both studies indicate J=14. We are also able to confirm the assignment of spins J=10 and 12 to the states at 27.2 and 29.0 reported in reference [15], which we associate with the peaks at 27.0 and 29.2 MeV in the present data. However, the spins assigned to the states at 27.9 (J=12) and 31.5 MeV (J=14) in reference [15] cannot be confirmed and we would suggest that these states are in fact J=10 (28.0 MeV) and 12 (31.9 MeV). The latter spin is in agreement with the assignment made by Costanzo *et al.* [12] for a state at 31.6 MeV, although there would appear to be an uncertainty in the absolute excitation energies in this last measurement[1].

It is also interesting to compare the present sequence of energies and spins with the so called quasimolecular resonances. For example, the results of James and Fletcher [28,29] from a measurement of the ^{12}C(^{12}C,^{16}O)^{8}Be reaction are listed in Table 3. The similarities of the two sets of states is compelling, as there appears to be good agreement both in terms of the energies and spins of almost all of the structures in the present data. This strongly suggests a link between the present data and the quasimolecular band observed in the ^{12}C(^{12}C,^{8}Be) reaction. Curtis *et al.* [7] have also reported on a possible link between the breakup states measured in the ^{12}C(^{24}Mg,^{12}C^{12}C)^{12}C reaction and J=4 quasimolecular resonances observed in ^{12}C +^{12}C reactions. This relationship appears to be verified by the present data.

A. Comparison with other breakup reactions

Figure 10 provides a comparison of the ^{24}Mg states observed in the ^{12}C +^{12}C decay channel, excited in the ^{12}C(^{16}O,^{24}Mg)α, ^{12}C(^{24}Mg,^{24}Mg)^{12}C and ^{12}C(^{20}Ne,^{24}Mg)^{8}Be reactions [10,8] [2]. The complexity of the three spectra make comparisons difficult. However,

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[1]The discrepancy in excitation energy is discussed in reference [15].

[2]Note that the states in Figure 11b have been shifted by 200 keV in order to coincide with those in Figure 11c as in reference [8].

Leddy *et al.* [8] have already commented on the similarity of the states observed in the ^{12}C(^{24}Mg,^{12}C^{12}C)^{12}C and ^{12}C(^{20}Ne,^{12}C^{12}C)^{8}Be reactions, although this is based on structural similarities and not measurements of spins or partial decay widths. Nevertheless, the similarities are striking. A measurement of the ^{12}C(^{24}Mg,^{12}C^{12}C)^{12}C reaction [2] indicated that the states at 21.0, 21.7, 22.2 could be associated with spin 4^+ and the states at 22.8 and 24.8, 6^+ and 8^+ respectively. Leddy *et al.* suggested that the states at 26.3 and 27.2 MeV in the ^{12}C(^{24}Mg,^{12}C^{12}C)^{12}C reaction possessed spins of $\geq 10^+$. In the present measurement we observe a strong 8^+ state at 25.0 MeV, and 10^+ states at 25.9, 26.4 and 27.0 MeV, in close proximity to the possible 10^+ states in the ^{12}C(^{24}Mg,^{12}C^{12}C)^{12}C reaction, suggesting some similarities between the two reactions. However, in the lower excitation energy region ($20 < E_x < 24$ MeV) there is disagreement. Where the present measurement indicates predominantly J=6 structures the previous study found J=4 states. Although we cannot completely exclude J=4 assignments for the 20.9 and 21.7 MeV states, it does appear that the excitation energy spectra in the ^{12}C(^{16}O,^{24}Mg)α reaction are more complex and structurally different in this region. Certainly there are several states in this reaction that have no counterparts in the ^{12}C(^{20}Ne,^{12}C^{12}C)^{8}Be reaction. For example, the states at 24.2, 25.9 and possibly 29.2 MeV. Due to the poorer resolution in the ^{12}C(^{24}Mg,^{12}C^{12}C)^{12}C measurement it is difficult to conclude if these states are present or absent. Any differences of course reflect the different reaction mechanisms populating the states in the three instances. The ^{12}C(^{20}Ne,^{24}Mg)^{8}Be reaction is likely to be dominated by alpha-transfer processes strongly populating 4p-4h states in ^{24}Mg, and hence is highly selective. Furthermore, the present measurement finds evidence for states at 35.1 and 36.5 MeV, whereas Murgatroyd *et al.* [10] found that states populated in the ^{12}C(^{20}Ne,^{24}Mg)^{8}Be reaction terminated at $\sim$33 MeV, again pointing to the selective population of states in the alpha-transfer reaction.

Previous studies of the ^{12}C(^{16}O,^{24}Mg)α reaction [15,21] have indicated that the ^{28}Si compound system plays an important role, and the alpha decay of the highly excited ^{28}Si nucleus to states in ^{24}Mg might not be expected to be as selective as alpha-transfer. This decay of the compound nucleus might be expected to populate higher spin states for which the angular momentum barriers are smaller. Statistical model calculations using the code STATIS [30] and the potentials from reference [30] (Table 4), for example, indicate that at E_{cm}=32 MeV, l_i=16 $\hbar$, there is an order of magnitude difference in the cross section for populating J=4 and J=6 state. The small probability for exciting J=4 states compared to J=6 may account for the difference in the ^{12}C(^{16}O,^{24}Mg)α and ^{12}C(^{24}Mg,^{24}Mg)^{12}C reactions, with the latter seemingly favouring the population of the lower spin states. Furthermore, there does appear to be some evidence for a possible J=6 state at 22.7 MeV in the present measurement which might correspond to the 6^+ state at 22.8 MeV observed in the ^{12}C(^{24}Mg,^{12}C^{12}C)^{12}C studies.

It might be possible to conclude from this comparison that the spectrum of breakup states is in fact complex, being composed of not only the 4p–4h configurations based on a ^{20}Ne ground state, strongly fed by alpha transfer, but also other configurations. Previously [3], the breakup or fission of ^{24}Mg has been linked with particular cluster configurations connected with shape isomeric minima in the deformed ^{24}Mg potential. The present data would be consistent with an interpretation that more than one cluster configuration contributes to this process and hence presumably more than one minimum or alternatively more complex structures within a single minimum.

B. The ^{16}O $+^{8}$ Be decay channel and statistical model calculations

In contrast to the similarities observed in the ^{12}C $+^{12}$ C decay channel, it is difficult to find the same level of agreement between the energies and spins of states observed in the ^{16}O $+^{8}$ Be and ^{12}C $+^{12}$ C final states in the present data. This may in part be the result of an increased density of states in the ^{16}O $+^{8}$ Be channel due to the inclusion of states with odd spins. Certainly, in the low excitation energy region ($20 < E_x < 24$ MeV) there appear to be states of similar spins in the two channels, and given the differences in the excitation energy spectra for the ^{12}C $+^{12}$ C decay channel at 75 and 85 MeV, differences between the two decay channels in this energy region may not be significant. However, in the higher excitation energy region ($E_x > 25$ MeV) there do appear to real and significant differences.

Figure 11 shows a comparison of the ^{16}O $+^{8}$ Be and ^{12}C $+^{12}$ C spectra at E_{beam}=115 MeV. In this instance the relative intensities of the states should indicate their preference for decay into these two channels. These spectra are clearly different. For example, there is no evidence for the strong J=10 state at 27.0 MeV in the ^{16}O $+^{8}$ Be decay channel. Also, apparently the ^{12}C $+^{12}$ C 12^{+} and 10^{+} states at 29.2 and 30.0 MeV respectively, appear to coincide with 10^{+} and 12^{+} states 28.8 and 30.1 MeV. However, given the uncertainty in the spin assignments for the ^{16}O $+^{8}$ Be channel, these may in fact be the same states. The ^{12}C $+^{12}$ C 12^{+} state at 31.9 MeV may have a counterpart at 31.6 MeV (12^{+}) in the ^{16}O $+^{8}$ Be data, but the 33.2 MeV (12^{+}) state would appear to be absent. Furthermore, the doublet of 10^{+} states which appear in the ^{12}C $+^{12}$ C spectrum at 28.0 and 28.4 MeV coincide with a minimum in the ^{16}O $+^{8}$ Be spectrum.

In order to assess the significance of the differences or similarities of the two spectra in Figure 11 we have performed a statistical model analysis of the decay probabilities using the code STATIS [30] and the optical model parameters given in Table 5 [31]. The results of these calculations are shown in Figure 11, where we have plotted the ratios Γ_{cc}/Γ_{OBe} and Γ_{cc}/Γ_{Tot}. There are two features which are important. The ^{12}C $+^{12}$ C decay channel opens before the ^{16}O $+^{8}$ Be channel, and the ratios of the decay probabilities above the barrier tend to Γ_{cc}/Γ_{OBe} ~0.6. Interestingly, the 10^{+} ^{12}C $+^{12}$ C decay probability peaks at 27 MeV with Γ_{cc}/Γ_{OBe} ~2. After correction for detection efficiency, the ~350 peak counts in the ^{12}C $+^{12}$ C spectrum for the 27.0 MeV 10^{+} state would correspond to ~45 ^{16}O $+^{8}$ Be counts for Γ_{cc}/Γ_{OBe} $\simeq$1 and half this value for statistical decay. Hence, the lack of evidence for this state in the ^{16}O $+^{8}$ Be channel is not surprising. If the possible 12^{+} state in the ^{12}C $+^{12}$ C channel at 31.9 MeV corresponds to the ^{16}O $+^{8}$ Be 12^{+} state at 31.6 MeV, then this indicates that Γ_{cc}/Γ_{OBe} ~1.5, which is agreement with statistical expectations. Similarly, if the states at 29.2 MeV (^{12}C $+^{12}$ C) and 28.8 MeV (^{16}O $+^{8}$ Be) both can be identified with $J^{\pi} = 12^{+}$, then this would suggest Γ_{cc}/Γ_{OBe} ~0.9, compared to the statistical expectation of 1.3. Finally, if also the states at 30.0 MeV (^{12}C $+^{12}$ C) and 30.1 MeV (^{16}O $+^{8}$ Be) have $J^{\pi} = 10^{+}$ then Γ_{cc}/Γ_{OBe} ~0.9 compared with the statically expected value of 0.5.

Thus, there is perhaps some evidence for the statistical decay of ^{24}Mg excited states in the region $25 < E_x < 33$ MeV. However, the doublet of 10^+ states at 28.0 and 28.4 MeV would be expected to be represented in the $^{16}\mathrm{O} + ^{8}\mathrm{Be}$ spectrum by peaks of $\sim$70 and $\sim$100 peak counts respectively for statistical decay. The present data indicate that an upper limit for the ratio Γ_{cc}/Γ_{OBe} is 0.18$\pm$0.05. This value of Γ_{cc}/Γ_{OBe} has been determined by subtracting Gaussian peaks at 27.3 and 28.8 MeV with FWHM 0.7 MeV, and is a factor of 4 to 5 smaller than statistical model predictions. This difference would appear to be significant, although an important influence could be the proximity of these states to the $^{16}\mathrm{O} + ^{8}\mathrm{Be}$ barrier. For example, a 10% decrease in the depth of the $^{16}\mathrm{O} + ^{8}\mathrm{Be}$ real and imaginary potentials results in an increase of Γ_{cc}/Γ_{OBe} of 40% at 28 MeV. However, it should be noted that 10^+ states are observed strongly in the $^{12}\mathrm{C}(^{12}\mathrm{C},^{8}\mathrm{Be})$ reaction at excitation energies of 27.3, 27.8 and 28.3 MeV, and these are presumably unattenuated by the barrier.

Cosman *et al.* [32] observed that the structures in the elastic scattering channel which have large ^{12}C decay widths, are strongly represented in the p+$^{23}\mathrm{Na}^*(15/2^+)$ and α+$^{20}\mathrm{Ne}^*$ reaction channels, and in contrast the ^{16}O+^{8}Be resonance cross sections are small indicating only a weak link with the elastic scattering resonances. As a consequence, Cosman *et al.* speculated that the structure associated with the resonances must be closely linked to a $^{12}\mathrm{C} + ^{12}\mathrm{C}$ cluster structure rather than a configuration resembling the cluster components $^{16}\mathrm{O} + ^{8}\mathrm{Be}$. It is possible that the 28.0 and 28.4 MeV states in the present measurement also have large ^{12}C partial decay widths.

The particularly inviting possibility that the breakup process probes cluster-like configurations associated with a number of different minima can be explored using the Nilsson-Strutinsky calculations of Leander and Larsson [17]. These calculations indicate that in the case of ^{24}Mg there are 3 deformed minima at prolate, triaxial and oblate deformations which could play a role in the breakup process. The prolate minimum can be related to a cluster configuration [16,33] which has a large overlap with $^{12}\mathrm{C} + ^{12}\mathrm{C}$ and $^{20}\mathrm{Ne} + \alpha$ cluster structures, and has hence been linked with the quasimolecular or barrier resonances observed in $^{12}\mathrm{C} + ^{12}\mathrm{C}$ reactions. The triaxial minimum, on the other hand, has a dominant overlap with a ^{12}C $+^{12}$ C cluster structure and would be expected to decay extremely weakly to the ^{16}O $+^{8}$ Be final state. This feature could explain the absence of the 28.0 and 28.4 MeV 10^{+} states in the ^{16}O $+^{8}$ Be decay spectrum, if these states were associated with the decay through the triaxial minimum.

V. SUMMARY

The ^{12}C(^{16}O,^{12} C^{12}C)α and ^{12}C(^{16}O,^{16} O^{8}Be)α reactions have been studied at the beam energies of 75, 85 and 115 MeV. Evidence for the decay of ^{24}Mg states over the excitation energy interval $20 < E_x < 40$ MeV can be found in both reactions. We have performed an angular correlation analysis of the decay products and are able to suggest spins for many of the states. A comparison of the two decay channels indicates that some states may decay into the ^{12}C $+^{12}$ C and ^{16}O $+^{8}$ Be final states with statistical probabilities. However, more interestingly several states appear to favour the ^{12}C $+^{12}$ C decay channel. A comparison of resonant structures observed in the ^{12}C(^{12}C,^{16} O)^{8}Be reaction suggests that the states observed in the ^{12}C $+^{12}$ C decay channel may be linked with the so called quasi-molecular resonances in ^{24}Mg. There are also indications that the ^{24}Mg states excited in the ^{12}C(^{24}Mg,^{24} Mg) and ^{12}C(^{20}Ne,^{24} Mg) reactions which decay into two ^{12}C nuclei are also populated in the ^{12}C(^{16}O,^{24} Mg)α reaction. However, this latter reaction appears to be less selective in that a greater number of states are excited.

These studies would benefit from higher quality data for the ^{16}O $+^{8}$ Be decay channel in order to more precisely determine the spins of the ^{24}Mg states which decay into this final state, and this would provide a more concrete comparison with the ^{12}C $+^{12}$ C decay channel. Measurements of the partial decay widths of the states observed in the breakup reactions could also provide an important insight into the structure of these states. Further, a measurement of the ^{12}C(^{16}O,^{12} C^{12}C)α reaction at a significantly lower beam energy might be expected to more strongly populate the low spin states in the barrier region (E_x=20 MeV), which would provide an interesting comparison with the states observed in the $^{12}C(^{24}Mg,^{12}C^{12}C)^{12}C$ reaction and the low spin quasimolecular resonances.

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$E_x(^{24}Mg)$	J	$E_x(^{24}Mg)$	J	$E_x(^{24}Mg)$	J
20.9	(6)	25.9	(10)	31.9	12
21.7	(6)	26.4	(10)	(32.5)	(12)
22.7	(4/6)	27.0	10	33.2	12
23.4	(4)	28.0	10	35.6	14
23.8	(6)	28.4	10	36.7	(14)
24.2	(8)	29.2	12		
25.0	8	30.0	10		

$E_x(^{24}Mg)$	Possible spins	Excluded spins
20.8		
22.1	6,8	
23.1	6	
23.0		
23.4	8	
24.8	9,**11**	8,10,12
25.7	9,**11**	8,10,12
26.7		
27.3	**9**,11	8,10,12
28.8	**10**,12	8,9,11
30.1	10,**12**	11
31.6	(12)	
32.5	13	10,12,14
33.4	**11**,13	10,12
34.2	11	10,12

$^{12}C(^{12}C,^{8}Be)^{16}O$				Present data	
E_{cm}	E_x	Γ_{cm}	J	E_x	J
9.05	23.0		6		
9.98	23.9	200	6	23.8	(6)
10.30	24.2	(200)	8	24.2	(8)
10.45	24.4	(400)	6		
10.62	24.6	300	8		
10.96	24.9	300	8	25.0	8
11.20	25.1	<450	(6)		
11.38	25.3	200	8		
11.90	25.8	500	8	25.9	(10)
12.36	26.3	300	8	26.4	(10)
12.98	26.9	340	8		
13.37	27.3	300	10	27.0	10
13.87	27.8	240	10	28.0	10
(14.15)			8		
14.36	28.3	340	10	28.4	10
15.35	29.5	~700	10	29.2	12
16.13	30.1	<400	10	30.0	10
16.45	30.4	<400	10		
17.19	31.1	320	10		
17.78	31.7	500	12	31.9	12
(18.6)		300	10		
18.8	32.7	~500	12	32.5	12
19.46	33.4	230	12	33.2	12

Channel	V_1 (MeV)	V_2 (MeV)	R_r (fm)	a_r (fm)	W_1 (MeV)	W_2 (MeV)	R_i (fm)	a_i (fm)	Shape	R_c (fm)
$n + ^{27}Si$	48.2	-0.3	3.75	0.65	11.5	0	3.75	0.47	Surf.	0.
$p + ^{27}Al$	52.2	-0.3	3.75	0.65	11.5	0	3.75	0.47	Surf.	3.75
$\alpha + ^{24}Mg$	54.4	0	4.90	0.53	9.8	0	4.90	0.53	Vol.	4.04
$^{8}Be + ^{20}Ne$	14.0	0	6.10	0.49	0.4	0.15	6.10	0.49	Vol.	6.10
$^{12}C + ^{16}O$	17.0	0	6.49	0.49	0.80	0.20	6.10	0.15	Vol.	6.49

Channel	V_1 (MeV)	V_2 (MeV)	R_r (fm)	a_r (fm)	W_1 (MeV)	W_2 (MeV)	R_i (fm)	a_i (fm)	Shape	R_c (fm)
$n + ^{23}Mg$	48.2	-0.3	3.56	0.65	11.5	0	3.55	0.47	Surf.	0.
$p + ^{23}Na$	56.0	-0.55	3.56	0.65	13.5	0	3.56	0.47	Surf.	3.41
$\alpha + ^{20}Ne$	50.0	0	4.94	0.59	2.0	0	4.94	0.46	Vol.	5.16
$^{8}Be + ^{16}O$	14.0	0	6.10	0.49	0.4	0.15	6.10	0.49	Vol.	5.42
$^{12}C + ^{12}C$	14.0	0	6.18	0.35	0.82	0	6.41	0.56	Vol.	5.49

Figure captions.

Fig. 1. Q-value spectra for the reactions (a) ^{12}C(^{16}O,^{12}C^{12}C)α and (b) ^{12}C(^{16}O,^{16}O^{8}Be)α.

Fig. 2. The final state interaction in the ^{12}C(^{16}O,^{12}C^{12}C)α reaction at E_{beam}=115 MeV. The plot shows the two reconstructed ^{16}O excitation energies corresponding to an association of the recoil α-particle with either of the two detected ^{12}C nuclei. The horizontal and vertical loci correspond to ^{16}O excited states, and the diagonal loci correspond to ^{24}Mg excited states.

Fig. 3. The ^{24}Mg excitation energy spectra for the reaction ^{12}C(^{16}O,^{12}C^{12}C)α at the beam energies (a) 115 MeV, (b) 85 MeV and (c) 75 MeV. The solid curve is the calculated detection efficiency.

Fig. 4. The final state interaction in the ^{12}C(^{16}O,^{16}O^{8}Be)α reaction at E_{beam}=115 MeV. The plot shows the reconstructed ^{12}C (horizontal loci) and ^{20}Ne (vertical loci) excitation energies. The diagonal loci correspond to the decay of ^{24}Mg excited states.

Fig. 5. The ^{24}Mg excitation energy spectra for the reaction ^{12}C(^{16}O,^{16}O^{8}Be)α at the beam energies (a) 115 MeV, (b) 85 MeV and (c) 75 MeV. The solid curve is the calculated detection efficiency.

Fig. 6. The combined $^{24}\mathrm{Mg} \rightarrow ^{12}\mathrm{C} + ^{12}\mathrm{C}$ (a) and $^{24}\mathrm{Mg} \rightarrow ^{16}\mathrm{O} + ^{8}\mathrm{Be}$ (b) excitation energy spectra for the 85 and 115 MeV data. The vertical dotted lines in both parts of the figure correspond to the excitation energies of the ^{24}Mg states observed in the ^{12}C(^{16}O, α) reaction [21]. The length of the lines indicate the cross section with which the state was observed to be excited.

Fig. 7. The θ^*-ψ angular correlation for the 31.9 MeV, 12^+ state observed in the $^{12}C + ^{12}C$ decay channel.

Fig. 8. The projected angular correlations for the ^{24}Mg states observed in the $^{12}C + ^{12}C$ decay channel. The solid lines correspond to Legendre polynomials of the order indicated on the figure.

Fig. 9. The projected angular correlations for the ^{24}Mg states observed in the $^{16}O + ^{8}Be$ decay channel. The solid lines correspond to Legendre polynomials of the order indicated on the figure.

Fig. 10. A comparison of the ^{24}Mg excited states observed in the $^{12}C + ^{12}C$ decay channel, populated in the reactions (a) $^{12}C(^{16}O,^{24}Mg^*)$, (b) $^{12}C(^{24}Mg,^{24}Mg^*)$ [8] and (c) $^{12}C(^{20}Ne,^{24}Mg^*)$ [10,8].

Fig. 11. A comparison of the E_{beam}=115 MeV excitation energy spectra with the results of the statistical model calculations using the code STATIS [30] and the potentials given in Table 4.

Table captions

Table 1. Excitation energies and spins of ^{24}Mg states observed in the $^{12}C + ^{12}C$ decay channel.

Table 2. Excitation energies and possible spins of ^{24}Mg states observed in the $^{16}O + ^{8}Be$ decay channel. Spins which are also apparently excluded are listed.

Table 3. A comparison between the quasimolecular resonances observed in the $^{12}C(^{12}C,^{8}Be)$

reaction [28], and the $^{12}C + ^{12}C$ breakup states from the present measurement.

Table 4. The potentials used in the ^{28}Si statistical model calculations, from reference [30].

Table 5. The potentials used in the ^{24}Mg statistical model calculations, from reference [31].