Angular correlations from the $^{12}C+^{16}O$ breakup of ^{28}Si and $^{12}C+^{12}C$ breakup of ^{24}Mg

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An angular correlation analysis of the breakup fragments from the $^{12}C(^{24}Mg,^{12}C\,^{16}O)^{8}Be$ and $^{12}C(^{24}Mg,^{12}C\,^{12}C)^{12}C$ reactions is presented. For the $^{12}C+^{16}O$ breakup of ^{28}Si, spins of 13^{-}, $8^{+}(10^{+})$, and $(12,14)^{+}$ are assigned to states at excitation energies of 28.0, 33.4, and 34.5 MeV, respectively. The results are compared to the resonances observed in $^{12}C+^{16}O$ scattering studies and to the predictions of nuclear models. For the $^{12}C+^{12}C$ breakup of ^{24}Mg, previous spin assignments are verified and new assignments of (2^{+}), $6^{+}(8^{+})$, (6^{+}), and 8^{+} are proposed for states at 20.5, 23.8, 25.1, and 26.4 MeV, respectively.

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I. INTRODUCTION

Resonances observed in the collision cross sections of a variety of heavy ion systems have been a topic of interest for the past four decades. The most prominent examples are found in the $^{12}C+^{12}C$ and $^{12}C+^{16}O$ systems where the large partial widths for decay into the entrance channel and the rotational-like spin sequences have led to a description of the resonances in terms of molecular states possessing a large scale cluster structure [1,2]. In recent years, breakup reactions have been exploited in an attempt to establish a link between these heavy ion resonances and states of the respective compound nuclei.

The $^{12}C+^{12}C$ breakup of ^{24}Mg following inelastic scattering from a carbon target has been reported in a number of publications [3–8]. The excitation energy spectra, obtained from the relative energy of the breakup fragments, indicate that the breakup occurs from a series of states in ^{24}Mg in the excitation energy region $\sim$20–30 MeV. Studies of the angular correlations of the breakup fragments from the $^{12}C(^{24}Mg,^{12}C\,^{12}C)^{12}C$ reaction have yielded spin assignments for several of the states observed [5,6]. The energy-spin systematics were found to be consistent with the population of a highly deformed (3:1) rotational band in ^{24}Mg. Furthermore, the bandhead energy and moment of inertia implied by the data were similar to that of the resonances observed in $^{12}C+^{12}C$ scattering studies at energies just above the Coulomb barrier. This association was strengthened by a high resolution measurement of the $^{12}C(^{24}Mg,^{12}C\,^{12}C)^{12}C$ reaction [7] which found a direct correspondence between the energies, spins and widths of the breakup states at $\sim$22 MeV and that of the $^{12}C+^{12}C$ barrier resonances, suggesting that both processes probe the same structures in ^{24}Mg.

In contrast, the experimental situation for the $^{12}C+^{16}O$ system is not very clear. Although several experimental studies have observed the near-symmetric $^{12}C+^{16}O$ breakup of ^{28}Si via the $^{12}C(^{24}Mg,^{12}C\,^{16}O)^{8}Be$ reaction [3,9–12], only one tentative spin assignment has been reported to date, that of $J=(11\pm1)$ assigned by Freer [10] to the breakup state at $\sim$30 MeV. The limited spin information available for the breakup states has thus prevented a detailed comparison with the heavy ion resonances observed in $^{12}C+^{16}O$ scattering studies, and the connection between the resonant states populated by the two processes is still not established. In a comparative study of the $^{12}C+^{16}O$ breakup yield observed following the scattering of 170 MeV ^{24}Mg ions from targets of ^{12}C, ^{7}Li, and ^{9}Be, Curtis *et al.* [12] demonstrated that direct α transfer is the most likely mechanism populating the breakup states. The inference that particle transfer plays a key role is further supported by the small cross section measured for $^{12}C+^{16}O$ breakup following the inelastic scattering of 200 MeV ^{28}Si ions from a carbon target [9]. These results imply that the breakup states have little overlap with the ^{28}Si ground state configuration and that particle-hole excitations may be important.

In this paper we report on an analysis of data obtained for the $^{12}C(^{24}Mg,^{12}C\,^{16}O)^{8}Be$ and $^{12}C(^{24}Mg,^{12}C\,^{12}C)^{12}C$ reactions. These data were previously analyzed to extract cross section information relevant to the reaction mechanisms [8,12]. The angular correlations of the breakup fragments from the two decay channels have now been analyzed to obtain new information on the angular momenta of the decaying states. For the $^{12}C+^{16}O$ breakup of ^{28}Si, new spin assignments are proposed for three of the breakup states observed, allowing the first comparison between the breakup states and the molecular resonances observed in $^{12}C+^{16}O$ scattering studies. The experimental results are discussed in

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relation to the predictions of various nuclear models. For the $^{12}C+^{12}C$ breakup of ^{24}Mg, the data span a significantly larger angular range than previous experiments [5–7]. With the exception of one tentative earlier assignment, the present extended results support the spin assignments reported in earlier work [5,6]. In addition, new spin assignments are proposed for several other breakup states observed.

II. EXPERIMENT

The experimental work was performed using beams of 170 MeV ^{24}Mg ions, provided by the 14UD tandem Van de Graaff accelerator at the Australian National University, incident on a 380 $\mu g\,cm^{-2}$ natural carbon target. The breakup fragments were detected in coincidence in two Gas-Si-CsI hybrid detector telescopes centered horizontally on either side of the optical beam axis at laboratory angles of 16°. The silicon strip detectors housed in these telescopes had a surface area of 50 mm × 50 mm with the front face segmented into 16 resistive strips, each 3 mm in width. The strips were position sensitive along their length and were oriented horizontally and parallel to the detector plane, with the front face at a distance of 170 mm from the target position. These detectors also provided energy information for incident ions. Particle identification was achieved with standard $\Delta E-E$ techniques using energy loss information from 50 mm deep longitudinal ionization chambers situated directly in front of the strip detectors. The CsI(Tl) scintillation detectors positioned behind the strip detectors were used to veto pile-up events associated with energetic light particles penetrating the silicon wafer. The strip detectors were calibrated using beams of ^{12}C and ^{16}O ions elastically scattered from a 150 $\mu g\,cm^{-2}$ ^{197}Au target, allowing separate calibration parameters to be obtained for incident ^{12}C and ^{16}O ions, respectively.

The data for both the $^{12}C+^{16}O$ and $^{12}C+^{12}C$ breakup channels were recorded simultaneously. Following particle identification, the energies measured in the strip detectors were corrected for energy losses in the ionization chambers, the 3.5 μm thick mylar entrance windows of the hybrid telescopes and in passing through half of the target thickness (assuming that the interactions occur, on average, midway through the target). The energy of the undetected recoiling particle was determined from momentum conservation between the incoming beam (allowing for energy losses in the target) and the two detected fragments. Three-body final states in which all particles were emitted in the ground state were identified from the summed energy (equal to the beam energy plus the reaction Q value) of the three outgoing particles (for details of this selection, see Refs. [8,12]). For these events, the excitation energy of the nuclei undergoing breakup was determined from the relative center of mass energy between the detected fragments.

III. ANGULAR CORRELATIONS

Under certain conditions, the spins of the resonant states observed in a sequential breakup reaction may be determined in a model independent way from the angular correlations of the final state nuclei [13–15]. If the detection geometry is such that the breakup fragments are emitted approximately in the primary scattering plane, the angular correlations may be defined in terms of the two angles θ^* and ψ, where θ^* is the center of mass scattering angle of the resonant particle and ψ is the angle between the relative velocity vector of the breakup fragments and the beam direction.

For two spin-zero particles in the entrance channel, the initial angular momentum is due solely to the orbital motion of the projectile-target system. Taking the beam direction as the quantization axis, the system is thus initially in an $m_i=0$ substate. For scattering near $\theta^*=0°$, conservation of angular momentum then demands that the resonant particle with spin J be produced in an $m_J=0$ substate. If the resonant particle subsequently decays into two spin-zero fragments, the angular distribution of the breakup fragments can be described by a squared Legendre polynomial in $\cos\psi$ whose order is equal to the spin J of the decaying state. Furthermore, if the recoiling particle is also spin-zero then the decaying state will have natural parity, $\pi=(-1)^J$.

For scattering away from $\theta^*=0°$, higher magnetic substates contribute to the reaction yield and the angular correlations are expected to take a more complex form. However, if the reaction is dominated by a single partial wave l_i in the entrance channel (a reasonable assumption for heavy ion induced transfer and inelastic scattering reactions in which peripheral collisions dominate) then the correlation structure is not destroyed but becomes shifted in ψ by an amount proportional to the initial scattering angle θ^*. The double differential cross section for the sequential breakup process then takes the form [13],

$$\frac{d^2\sigma(\theta^*,\psi)}{d\Omega_{\theta^*}\,d\Omega_{\psi}} \propto |P_J(\cos(\psi+\Delta\psi))|^2, \tag{1}$$

where $\Delta\psi \propto \Delta\theta^*$. The shift of the correlation structure gives rise to a series of ridges in the $\theta^*-\psi$ phase space corresponding to the shifted maxima of the original Legendre polynomial function. For mismatched reactions ($Q \ll 0$), the dominant contribution to the cross section is expected to arise when the angular momenta involved in the reaction are coupled in the stretched configuration corresponding to the lowest centrifugal barrier, i.e., $l_i=l_f+J$ where l_f is the exit channel partial wave. Under these conditions, the gradient of the ridges is given by [14,15]

$$\frac{\Delta\theta^*}{\Delta\psi}=\frac{J}{l_f}=\frac{J}{l_i-J}. \tag{2}$$

By projecting the correlation data onto the ψ_0 ($\theta^*=0°$) axis at an angle parallel to the ridges, the spin of the decaying state may again be determined by comparing the periodicity, though not necessarily magnitude, of the projected correlations with that of the relevant squared Legendre polynomial in $\cos\psi_0$. This procedure can be advantageous experimentally as it utilizes all of the data. Once J is specified, the dominant partial waves involved in the reaction may be determined from the projection angle through Eq. (2).

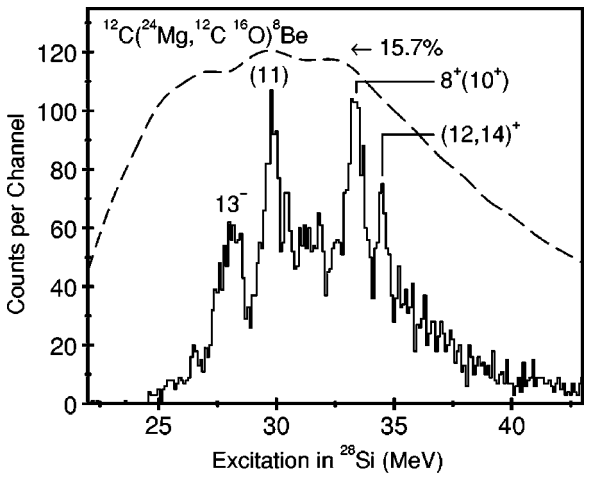

FIG. 1. The ^{28}Si excitation energy spectrum obtained via the $^{12}C(^{24}Mg,^{12}C\ ^{16}O)^{8}Be$ reaction. The dashed curve indicates the Monte Carlo predicted coincidence efficiency, which has a peak value of 15.7%.

The correlation angles θ^* and ψ used in the present analysis were those obtained by initially projecting the data onto the breakup plane, as defined separately for each event by the two breakup fragments. This approach has been shown [13] to enhance the correlation structure for cases where the azimuthal components of the correlation angles sampled by the detection system deviate from zero.

The detection geometry of the present experiment resulted in a high sensitivity near $\theta^*=0°$ and $\psi=90°$. The acceptance typically spanned the angular ranges $\theta^*=0\rightarrow\pm40°$, $\psi=20\rightarrow130°$ and $\theta^*=0\rightarrow\pm25°$, $\psi=40\rightarrow140°$ for the $^{12}C+^{16}O$ and $^{12}C+^{12}C$ channels, respectively, although the detailed shape of the $\theta^*-\psi$ phase space sampled depended on excitation energy.

A. The $^{12}C(^{24}Mg,^{12}C\ ^{16}O)^{8}Be$ reaction

Figure 1 shows the excitation energy spectrum for the $^{12}C+^{16}O$ breakup of ^{28}Si populated in the $^{12}C(^{24}Mg,^{12}C\ ,^{16}O)^{8}Be$ reaction. The dashed curve indicates the predicted coincidence efficiency evaluated using a Monte Carlo code to simulate the scattering and subsequent breakup of the resonant particle [12]. The projected angular correlations for the four most prominent peaks at excitation energies of 28.0, 29.8, 33.4, and 34.5 MeV are shown in Fig. 2.

The periodicity of the projected correlation for the state at 28.0 MeV is consistent with a spin and parity assignment of 13^-, as shown in Fig. 2(a). The minimum at $\psi_0=90°$ indicates that the state is of negative parity. However, the high level of background suggests that in addition to the observed 13^- strength, unresolved states of other spin may also be contributing to the broad peak at 28.0 MeV. By restricting the data to include only high energy ^{16}O breakup fragments, Curtis *et al.* [12] found evidence for the fragmentation of this broad peak into two or more narrower states. This is consistent with the inference drawn from the high level of background in Fig. 2(a). A similar restriction on the ^{16}O energy was applied in the correlation analysis (implying a corresponding restriction on the ψ acceptance), but the resulting spectra provided no further spin information.

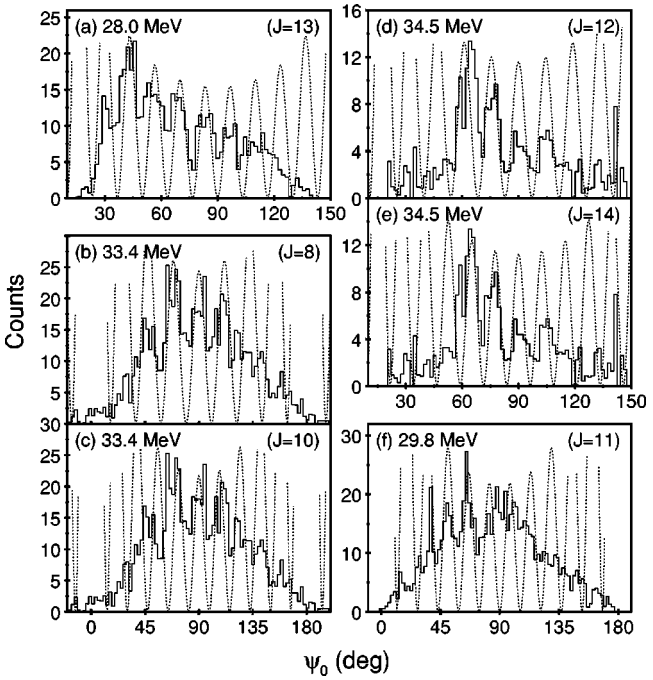

FIG. 2. Projected angular correlations for states observed in the $^{12}C+^{16}O$ breakup of ^{28}Si. The dotted curves correspond to squared Legendre polynomials of the order indicated on the figure.

Figures 2(b) and 2(c) show the projected angular correlation for the peak at 33.4 MeV, the maximum at $\psi=90°$ indicating that this state is of positive parity. The periodicity is best described by a squared Legendre polynomial of order 8, as shown in Fig. 2(b). However, the right-hand side of the correlation shows evidence of periodic structure corresponding to a spin of $J=10$ [Fig. 2(c)]. Thus, although a spin of $J=8$ is most likely, a spin of $J=10$ cannot be ruled out with certainty.

The projected angular correlation for the state at 34.5 MeV is shown in Figs. 2(d) and 2(e) overlaid with squared Legendre polynomials of order 12 and 14, respectively. Both of these polynomial functions give a reasonable description of the observed periodic structure and hence the data are unable to distinguish between a spin assignment of 12^+ or 14^+ for this state. The maximum at $\psi_0=90°$ indicates that this state is of positive parity.

Figure 2(f) shows the projected angular correlation for the state at 29.8 MeV, which was tentatively assigned a spin of $J=(11\pm1)$ in the earlier work of Freer [10]. The left-hand side of the correlation shows three maxima with a periodicity well described by an order 11 squared Legendre polynomial, while the right-hand side of the correlation shows no evidence of periodic structure. Although this result is, in itself, inconclusive, it provides some support for Freer's earlier assignment.

The angular correlations obtained for the other, less prominent, peaks observed in Fig. 1 show no convincing evidence of periodic structure. This was confirmed by projecting the correlation data at a range of angles, all of which

TABLE I. Summary of the $^{12}C+^{16}O$ breakup states in ^{28}Si and $^{12}C+^{12}C$ breakup states in ^{24}Mg for which spin assignments have been proposed. The present results are compared to spin assignments reported in previous work [5,6,10]. The $\Delta\theta^*/\Delta\psi$ values and deduced entrance channel partial waves (l_i) obtained in the present work are also given.

Nucleus	Excitation (MeV)	Spin assignment Present work	Previous work	Ref.	Gradient $\Delta\theta^*/\Delta\psi$	Deduced l_i ($\hbar$)
^{28}Si	28.0	13^-			0.74 ± 0.03	30.6 ± 0.7
	29.8	(11)	(11 ± 1)	[10]	(0.44 ± 0.03)	(36.0 ± 1.7)
	33.4	$\left\{\begin{array}{c}8^+\\(10^+)\end{array}\right\}$			0.37 ± 0.03	$\left\{\begin{array}{c}29.6\pm1.8\\(37.0\pm2.2)\end{array}\right\}$
	34.5	$\left\{\begin{array}{c}12^+\\14^+\end{array}\right\}$			0.85 ± 0.04	$\left\{\begin{array}{c}26.1\pm0.7\\30.5\pm0.8\end{array}\right\}$
^{24}Mg	20.5	(2^+)			(0.10 ± 0.03)	(22.4 ± 6.6)
	21.1	4^+	4^+	[5]	0.17 ± 0.03	27.5 ± 4.3
	21.9	4^+	4^+	[5]	0.17 ± 0.03	27.5 ± 4.3
	22.3	4^+	4^+	[5]	0.17 ± 0.04	27.5 ± 5.9
	22.9	6^+	6^+	[5,6]	0.30 ± 0.04	26.0 ± 2.8
	23.8	$\left\{\begin{array}{c}6^+\\(8^+)\end{array}\right\}$			$\left\{\begin{array}{c}0.24\pm0.03\\(0.38\pm0.04)\end{array}\right\}$	$\left\{\begin{array}{c}31.0\pm3.2\\(29.0\pm2.3)\end{array}\right\}$
	24.6	8^+	8^+	[5,6]	0.41 ± 0.04	27.5 ± 1.9
	25.1	(6^+)			(0.34 ± 0.05)	(23.7 ± 2.7)
	26.4	8^+	$\geqslant10^+$	[6]	0.42 ± 0.05	27.1 ± 2.3

produced structureless projections similar to that seen on the right-hand side of Fig. 2(f). The lack of structure could be due to neighboring states of similar spin but different parity contributing to a single peak in the excitation energy spectrum of Fig. 1, such that the structure in the combined angular correlations is lost. This is discussed briefly in Ref. [12] in the context of a preliminary analysis of the present angular correlation data. Also, the lower peak to background ratio for these weaker states further adds to the difficulty of discerning any correlation structure. Another possibility is that the assumptions underlying the analysis of the angular correlations break down for certain states. However, since periodic structure is observed for the most strongly populated states in Fig. 1, the latter explanation seems less likely.

Based on the angles used to project the data, the values of l_i, the entrance channel partial wave, implied by each of the spin assignments discussed above are listed in Table I. A value of $l_i\approx30\hbar$ is obtained from the spin assignments of $J=13$, 8, and 14 to the states at 28.0, 33.4, and 34.5 MeV, respectively, while the alternative assignments for the latter two states yield significantly different l_i values. The consistency of the deduced l_i values thus favors the $J=8$ and $J=14$ assignments for the 33.4 and 34.5 MeV states. However, different values of l_i are in principle possible for the same reaction mechanism and hence the alternative spin assignments are not excluded.

B. The $^{12}C(^{24}Mg,^{12}C\ ^{12}C)^{12}C$ reaction

Figure 3 shows the excitation energy spectrum for the $^{12}C+^{12}C$ breakup of ^{24}Mg populated in the $^{12}C(^{24}Mg,^{12}C\ ^{12}C)^{12}C$ reaction. The projected angular correlations for the states observed are shown in Fig. 4 overlaid with squared Legendre polynomials of the order indicated on the figure. Due to the symmetric nature of the $^{12}C+^{12}C$ decay channel, all of the states observed have even spin and positive parity. The spin assignments proposed for these states are listed in Table I, together with the corresponding values of l_i implied by the angles used to project the data.

When incrementing angular correlation spectra, it is desirable to keep the size of the angular bins the same for all states in order to avoid introducing any bias into the spin

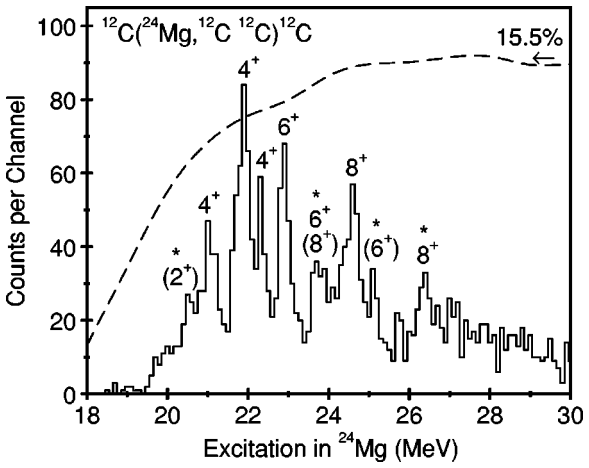

FIG. 3. The ^{24}Mg excitation energy spectrum obtained via the $^{12}C(^{24}Mg,^{12}C\ ^{12}C)^{12}C$ reaction. The dashed curve indicates the Monte Carlo predicted coincidence efficiency, which has a peak value of 15.5%. Asterisks indicate new spin assignments proposed in the present work.

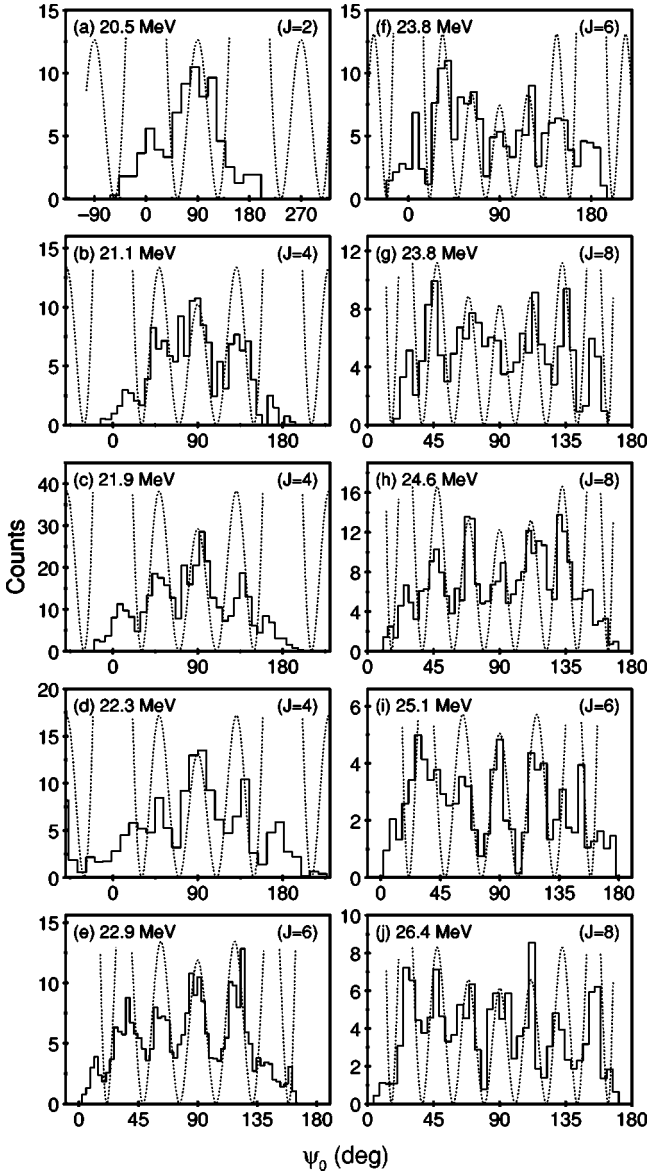

FIG. 4. Projected angular correlations for states observed in the $^{12}C+^{12}C$ breakup of ^{24}Mg. The dotted curves correspond to squared Legendre polynomials of the order indicated on the figure.

assignments obtained. However, the low statistics obtained for the $^{12}C+^{12}C$ channel did not allow this and different bin sizes were required depending on the statistics obtained for a given state. During offline analysis, angular correlation spectra were incremented for each state using a range of angular bin sizes. The spectra shown in Fig. 4 correspond to the smallest bin sizes allowed by the statistics.

The spins assigned to the states at 21.1 (4^+), 21.9 (4^+), 22.3 (4^+), 22.9 (6^+), and 24.6 MeV (8^+) are consistent with previous work [5,6] (allowing for an uncertainty of $\sim$150 keV in the absolute excitation energy calibration expected for breakup experiments of this kind [6,7]). From these spin assignments, an average value of $l_i=(27.2\pm3.8)\hbar$ is deduced for the entrance channel partial wave and is consistent with the value of $l_i\approx27\hbar$ obtained in the coupled channels calculation of Ref. [8] and with the value of $l_i\approx29\hbar$ obtained in the DWBA calculation of Ref. [13].

Structure was also observed in the projected angular correlations obtained for states at 20.5, 23.8, 25.1, and 26.4 MeV. Despite low statistics, the wide ψ_0 coverage has allowed the periodicity of the projected correlations to be determined for many of these states.

The projected angular correlation for the state at 20.5 MeV is shown in Fig. 4(a) and is consistent with a spin assignment of $J=2$, from which a value of $l_i=(22.4\pm6.6)\hbar$ is implied by the angle of projection. Although this l_i value is lower than that obtained for states of known spin, the large uncertainty (due to the low spin assigned to this state and the shallow gradient of the ridge structure) means that the difference is not statistically significant. The state at 20.5 MeV is thus tentatively assigned a spin of $J=2$ and is a candidate for the 2^+ member of the hyperdeformed band.

The ridge structure in the angular correlation obtained for the state at 23.8 MeV was not well defined. The data have thus been projected at two angles chosen to enhance the periodic structure in the projected correlations. The resulting projections are shown in Figs. 4(f) and 4(g) overlaid with squared Legendre polynomials of order 6 and 8, respectively. The data are most consistent with a spin assignment of $J=6$ to this state although a $J=8$ assignment cannot be ruled out with certainty. Similar values of l_i are implied by the two spin assignments each of which is consistent, within errors, with the value obtained for states of known spin (cf. Table I).

The projected angular correlation for the state at 25.1 MeV, shown in Fig. 4(i), is consistent with a spin assignment of $J=6$ which yields a value of $l_i=(23.7\pm2.7)\hbar$. However, due to the low statistics this spin assignment remains tentative.

Figure 4(j) shows the projected angular correlation for the state at 26.4 MeV. The periodicity of the data is consistent with a spin assignment of $J=8$. From the angle of projection, this implies a value of $l_i=(27.1\pm2.3)\hbar$ in good agreement with that obtained for states of known spin. Leddy *et al.* [6] have proposed a spin of $J\geqslant10$ for this state. However, their assignment was based on the lack of structure observed in the angular correlation for this state whereas structure was observed in the angular correlation for the 8^+ state at 24.6 MeV. The authors thus concluded that the state at 26.4 MeV must have a spin $J\geqslant10$ such that the experimental resolution was insufficient to resolve the more rapidly varying correlation structure. In the present work, the angular correlation for this state was found to be inconsistent with a $J=10$ spin assignment and the state at 26.4 MeV is assigned a spin of $J=8$ on the basis of the observed periodicity.

IV. DISCUSSION

In Fig. 5(a), the spin assignments proposed for the breakup states observed in the $^{12}C(^{24}Mg,^{12}C\,^{16}O)^8Be$ reaction are shown on an energy vs $J(J+1)$ plot. Both the 12^+ and 14^+ assignments for the state at 34.5 MeV are indicated, and the alternative assignments for the 29.8 and 33.4 MeV states are indicated by horizontal lines. For comparison, the molecular resonances observed in $^{12}C+^{16}O$ scattering stud-

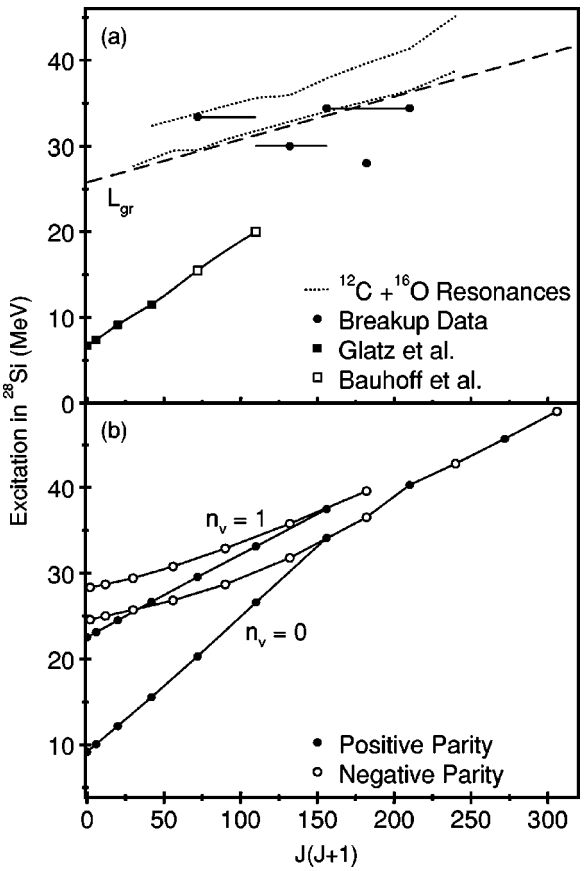

FIG. 5. (a) Energy-spin systematics of the breakup states observed via the $^{12}C(^{24}Mg,^{12}C\ ^{16}O)^{8}Be$ reaction (circles), the molecular resonances observed in $^{12}C+^{16}O$ scattering studies (between dotted lines), and the prolate band built on the 6.69 MeV (0_3^+) level (squares). The dashed line indicates the grazing angular momentum (L_{gr}) for the $^{12}C+^{16}O$ channel. (b) The four molecular bands predicted by the two-center cluster model calculations of Baye and Heenen [27].

ies [1,2], for which firm spin assignments have been made, are indicated by the region between the dotted lines. The data suggest some overlap between the breakup states and the $^{12}C+^{16}O$ heavy ion resonances, particularly for the states at 33.4 and 34.5 MeV which would favor the 12^+ assignment to the latter. However, the 13^- strength observed at 28.0 MeV in the present work does not correlate with the known molecular resonances in the $^{12}C+^{16}O$ system for which spins of $J\approx 5$ or $6\,\hbar$ are expected in this energy region. This may imply that either there is no association between the breakup states and the heavy ion resonances, or that the spectrum of states is more complex and may involve more than one cluster band.

Hartree-Fock [16,17], Nilsson-Strutinsky [18,19], and α-cluster model [20,21] calculations for the ^{28}Si nucleus predict two almost degenerate lowest energy solutions corresponding to oblate and prolate deformations. The oblate and prolate solutions each have an $(sd)^{12}$ shell model configuration and may be classified according to the irreducible representations of the special unitary group SU(3) with quantum numbers $(\lambda,\mu)=(0,12)$ and (12,0), respectively [22]. The oblate solution is assigned to the ground state band while the prolate solution has been assigned [16] to the experimental band [23] built on the 6.69 MeV (0_3^+) level. In the α-cluster model [20,21] and Hartree-Fock [17] calculations, this prolate configuration has an axially symmetric $^{12}C_{g.s.}+^{16}O_{g.s.}$ cluster structure which has prompted the suggestion [21] that higher members of the corresponding band may be populated in $^{12}C+^{16}O$ elastic scattering. Since this prolate configuration may be reached by the addition of an α cluster to the ^{24}Mg ground state [9], it has further been suggested [9,10,12] that the breakup states seen in the $^{12}C(^{24}Mg,^{12}C\ ^{16}O)^{8}Be$ reaction may also correspond to this prolate configuration. This would link the breakup states to the band built on the 6.69 MeV (0_3^+) level. The 0^+–6^+ members of this prolate band, as observed by Glatz *et al.* [23] via the $^{25}Mg(\alpha,n\gamma)$ reaction, are included in Fig. 5(a) together with the 8^+ and 10^+ band members (which were not observed in Ref. [23]) as predicted by the α-cluster model calculations of Bauhoff *et al.* [20]. While the higher spin scattering resonances could reasonably be associated with this prolate band, the low spin resonances are clearly inconsistent with such an association. Branford *et al.* [24] pointed out that the $^{12}C+^{16}O$ resonances at center of mass energies below $\sim$17 MeV (corresponding to a ^{28}Si excitation energy of $\sim$33.8 MeV) are observed mainly in α-particle exit channels while those at higher energies are observed in inelastic channels. Such selectivity in the decay modes of different resonances would be expected if more than one cluster band in ^{28}Si is populated.

In addition to the oblate and prolate solutions discussed above, the α-cluster model calculations of Zhang *et al.* [21] also predict several excited configurations in ^{28}Si, including a triaxial structure related to an $(sd)^8(fp)^4$ shell model configuration. This triaxial configuration is classified according to the irreducible representation of the group SU(3) with quantum numbers $(\lambda,\mu)=(20,4)$ [19], and the 4-particle–4-hole character implies that members of the corresponding band should be observed in α transfer onto ^{24}Mg. Within the molecular oscillator model of Harvey [25], this $(sd)^8(fp)^4$ configuration may be described by a $^{12}C_{g.s.}+^{16}O_{g.s.}$ cluster structure with the symmetry axis of the oblate ^{12}C fragment aligned perpendicular to the line joining the centers of the two fragments. However, no corresponding minimum has been observed in Nilsson-Strutinsky calculations [18,19]. Ragnarsson and Aberg [19] have studied the $(sd)^8(fp)^4$ configuration within the framework of the rotating harmonic oscillator and predicted the corresponding rotational band to lie several MeV above the prolate $(sd)^{12}$ band. The absence of a corresponding minimum in the Nilsson-Strutinsky potential energy surface was attributed [19] to the large signature splitting of the lowest *fp* shell orbitals making it energetically less favorable to excite four rather than two (unlike) particles into the *fp* shell. The $(sd)^8(fp)^4$ band is thus expected to lie at much higher energies [the α-cluster model calculations [21], for example, place the $(sd)^8(fp)^4$ bandhead 13 MeV above that of the prolate $(sd)^{12}$ band] and is a good candidate for association with the $^{12}C+^{16}O$ molecular resonances observed at energies near the Coulomb barrier for

which strong α-decay modes are observed [24].

Baye and Heenen have performed two-center cluster model calculations for the $^{12}C+^{16}O$ system [26,27]. In both a static microscopic model based on the generator coordinate method (GCM) [26] and a dynamic study of $^{12}C+^{16}O$ elastic scattering [27], two positive parity and two negative parity bands were predicted and were labeled with a quantum number n_v representing the level of excitation in the relative motion of the two fragments. The results of the latter calculation [27] are shown in Fig. 5(b). In the limit of zero separation between the fragments, the lowest positive parity configuration was found to reduce to the prolate $(sd)^{12}$ configuration [21] of a single harmonic oscillator potential [26]. Due to the similar masses of the two fragments, the corresponding negative parity band, obtained by exciting one particle into the *fp* shell, was predicted to begin at somewhat higher energies. The 13^- strength observed at 28.0 MeV in the breakup data lies along the extrapolated trajectory of the experimental prolate band [Fig. 5(a)] near the region where the two $n_v=0$ bands are predicted to meet, and could thus be evidence for the lowest $(n_v=0)$ negative parity band shown in Fig. 5(b). This state lies well below the grazing angular momentum (L_{gr}) for the $^{12}C+^{16}O$ channel [1], indicated by the dashed line in Fig. 5(a), and its observation in the breakup data thus requires the penetration of a significant centrifugal barrier, implying a strong cluster structure. The $n_v=1$ bands predicted by Baye and Heenen could reasonably be linked to the triaxial $(sd)^8(fp)^4$ configuration, and the corresponding negative parity configuration, which have been assigned above to the $^{12}C+^{16}O$ barrier resonances. Since both the prolate $(sd)^{12}$ and triaxial $(sd)^8(fp)^4$ configurations may be populated in α transfer onto ^{24}Mg, the $^{12}C(^{24}Mg,^{12}C\,^{16}O)^8Be$ reaction could be probing both of these structures.

There is little evidence for structure above $\sim$35 MeV in Fig. 1, even though the predicted coincidence efficiency in this energy region would suggest that evidence for states, if they exist, should be observed. At the energy employed in the present work, the linear and angular momentum matching requirements are best satisfied for α transfer to states in ^{28}Si with spins $J=(11\pm3)$ [12], however, the matching probability for populating states with spin $J\geqslant15$ at excitation energies near 35 MeV is still significant. The absence of structure at higher energies is thus an interesting result and may reflect an upper limit to the angular momentum allowed by the reaction, as discussed below. However, it is noted that other factors, such as the suppression of the $^{12}C_{g.s.}+^{16}O_{g.s.}$ decay mode due to the opening of other decay channels, could also be involved.

For the prolate $(sd)^{12}$ configuration, the maximum (even) spin that can be formed from the spins of the 12 particles in the *sd* shell is $J=14$, while for the $(sd)^8(fp)^4$ configuration, the maximum (even) spin is $J=22$ [this suggests that the higher spin resonances in Fig. 5(b) are associated with the $n_v=1$ bands, rather than the $n_v=0$ bands]. However, in a strict $(fp)^4$ α-transfer picture, the maximum (even) spin that the reaction can populate, without invoking excitation of the ^{24}Mg core, is $J=12$. This value and that of $J=14$ for the $(sd)^{12}$ configuration mentioned above, are consistent with the $J=(12,14)$ assignment to the highest energy state observed in the breakup data, suggesting that although the $^{12}C+^{16}O$ cluster states may, in principle, extend to higher excitation energies, and thus higher spins, it is unlikely that they will be observed in α transfer. Other reaction mechanisms, on the other hand, may not be subject to the same restrictions and could be able to observe higher spin states. A previous study of the $^{12}C(^{20}Ne,^{12}C\,^{16}O)\alpha$ [28] reaction, for example, observed evidence for breakup occurring from states in ^{28}Si well above 35 MeV, although no spin information was obtained. Such alternative entrance channels could thus provide a means of studying the higher energy breakup states.

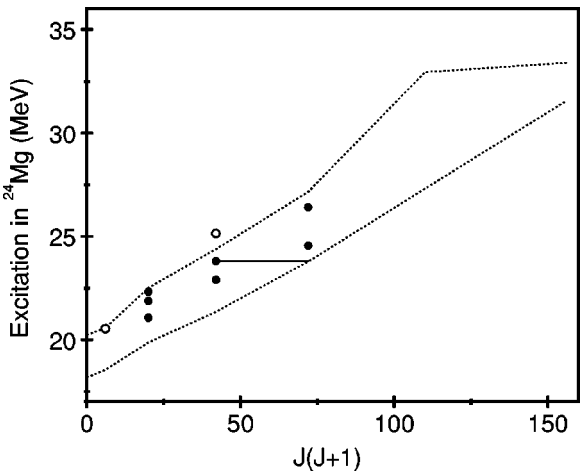

FIG. 6. Energy-spin systematics of the breakup states observed via the $^{12}C(^{24}Mg,^{12}C\,^{12}C)^{12}C$ reaction (circles), and the molecular resonances observed in $^{12}C+^{12}C$ scattering studies (between dotted lines). Open circles indicate tentative spin assignments and the horizontal line indicates an alternate spin assignment which was not excluded by the data.

In contrast to the situation for ^{28}Si, for the ^{24}Mg breakup states a number of spin assignments have previously been measured and a convincing association between the breakup states and the $^{12}C+^{12}C$ barrier resonances has been established [7]. The present data add further support to this interpretation as illustrated in Fig. 6, which shows the energy-spin systematics of the breakup states observed in the $^{12}C(^{24}Mg,^{12}C\,^{12}C)^{12}C$ reaction. The $^{12}C+^{12}C$ molecular resonances observed in scattering studies [1,2], for which firm spin assignments have been made, are indicated by the region between the dotted lines. The $^{12}C+^{12}C$ breakup states and barrier resonances have previously been assigned (see Ref. [29]) to the prolate (D1) configuration (with an $\alpha-^{16}O-\alpha$ or $^{16}O-\alpha-\alpha$ cluster structure) predicted by α-cluster model [30] and Hartree-Fock calculations [31]. In the shell model limit, this structure corresponds to an $(sd)^4(fp)^4$ configuration which is linked to the reflection asymmetric prolate minimum in the Nilsson-Strutinsky potential energy surface of ^{24}Mg [18].

V. SUMMARY

The angular correlations of the breakup fragments from the $^{12}C(^{24}Mg,^{12}C\,^{16}O)^8Be$ and $^{12}C(^{24}Mg,^{12}C\,^{12}C)^{12}C$ reac-

tions have been analyzed. New spin and parity assignments of 13^-, $8^+(10^+)$, and $(12,14)^+$ have been proposed for $^{12}C+^{16}O$ breakup states in ^{28}Si at excitation energies of 28.0, 33.4, and 34.5 MeV, respectively. The spins assigned to the states at 33.4 and 34.5 MeV are consistent with the energy-spin systematics of the molecular resonances observed in $^{12}C+^{16}O$ scattering studies. However, this is not the case for the 13^- strength observed at 28.0 MeV, suggesting that the spectrum of breakup states is more complex. A comparison with the predictions of α-cluster model and two-center cluster model calculations suggests that the prolate $(sd)^{12}$ and triaxial $(sd)^8(fp)^4$ configurations in ^{28}Si may play an important role in both the breakup data and the scattering data.

For the $^{12}C+^{12}C$ breakup of ^{24}Mg, the data confirm the spin assignments of 4^+, 4^+, 4^+, 6^+, and 8^+ previously assigned to breakup states at 21.1, 21.9, 22.3, 22.9, and 24.6 MeV. In addition, new spin assignments of (2^+), $6^+(8^+)$, (6^+), and 8^+ are proposed for states at 20.5, 23.8, 25.1, and 26.4 MeV, respectively. The data support an association between these breakup states and the $^{12}C+^{12}C$ barrier resonances.

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