Resonance spin assignments in $^{12}C+^{12}C(3^-)$ inelastic scattering from angular correlation methods

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Angular correlation techniques have been used to determine the spin of a strong resonance observed in the $^{12}C + ^{12}C(3^-;9.64$ MeV) inelastic scattering channel, at a bombarding energy of 33.5 MeV in the center-of-mass system. The alpha particles produced in the sequential decay $^{12}C(3^-)\rightarrow{}^{8}Be(g.s.) + \alpha_0$ were detected using four double-sided silicon strip detectors. The data are consistent with a spin assignment of $J^{\pi}=18^+$ for this resonance. The current results are compared to calculations of resonance behavior in this system from the band crossing model. [S0556-2813(96)03511-X]

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Resonance behavior in inelastic heavy-ion scattering has remained a topic of considerable interest for some three decades. From the first measurements in the early 1960s, the system which attracted the most attention was the $^{12}C + ^{12}C$ system [1,2]. Excitation functions for elastic and various inelastic scattering channels in this system displayed a wide variety of nonstatistical behavior, from very narrow resonances observed close to the Coulomb barrier, to strong, intermediate width structures at significantly higher bombarding energies. In particular, the region of center-of-mass energy between 10 and 40 MeV shows prominent intermediate-width resonances in nearly every inelastic-scattering channel studied. Cormier *et al.* observed several prominent structures in the inelastic 2^++g.s. and $2^+ + 2^+$ excitations [3]. The suggested spins of these resonances were conjectured to follow a rotational sequence, based upon systematic comparisons with the behavior of the elastic channel, and ranged from $10\hbar$ to $18\hbar$. Similar properties were also observed in a number of other inelastic channels, including the 3^-+g.s. and 0_2^++g.s. final states [4,5]. Angular distribution measurements to extract the dominant partial waves for a peak in the cross section near $E_{c.m.}=29.5$ MeV in the 0_2^++g.s. channel, although somewhat inconclusive, suggested a spin near $(16–18)\hbar$ for this structure [6].

Because of the richness of phenomena observed in this system, much speculation has arisen concerning the possible relationship between resonances observed in different inelastic scattering and reaction channels. While excitation-function peaks may appear at similar bombarding energies in different reaction channels, the mere appearance of such structures does not immediately imply that the underlying physics is the same. Additional spectroscopic information, such as unambiguous spin assignments, is needed to compare the experimental data for different reaction channels with each other, as well as with theoretical predictions.

As an example, in the $^{12}C+^{12}C$ system, reaction-model calculations using frameworks such as the band crossing model (BCM) were able to produce excitation curves which agreed qualitatively with the reported data for intermediate width structures in the angular-momentum-matched 2^++g.s., $2^+ + 2^+$, and 3^-+g.s. channels [7]. These calculations also predicted spins for these resonances. One test of the models of resonance behavior in this system would be a comparison between experimental and theoretical spin assignments. This information was, however, generally not available due to complications arising from non-spin-zero exit channels. In this case, simple angular distribution measurements lose their sensitivity to the angular momentum in the compound system due to the summation over magnetic substates of the spin of the excited scattered nucleus. In order to recover some sensitivity to the contributing angular momenta, radiation from the decay of the excited state in ^{12}C, for instance, either a gamma ray from the 2^+ state or an alpha particle from the 3^- level, can be detected, and the angular distribution of that radiation can provide information about the substate population of the excited nucleus.

These techniques have been successfully employed in studies of inelastic scattering to particle bound levels, by either the direct detection of the gamma rays from ^{12}C [8–10], ^{16}O [11], or ^{24}Mg [12,13], or from indirect measurements of the magnetic substate population via the line-shape broadening induced by the recoil of the gamma ray [14,15]. For alpha-particle unbound levels in ^{12}C, the situation is more difficult. In particular, the 3^- state in ^{12}C at 9.64 MeV decays almost entirely to the ground state of ^{8}Be, which in turn decays into two alpha particles. In order to deduce the population of magnetic substates in the excited ^{12}C nucleus and, in turn, the couplings of the various angular momenta involved in the reaction, the alpha particle which is emitted first must be identified and distinguished from the ones from the decay of the ^{8}Be. In essence, all three alpha particles must be detected and their angles and energies must be measured with sufficient precision such that the final state and the alpha particle emission angle can be identified. This technique has previously been applied to the determination of spin alignments in $^{12}C+^{12}C$ scattering [16–18].

We have used an array of highly segmented double-sided silicon strip detectors (DSSD's) to carry out a measurement of this type for a strong resonance observed in the $^{12}C(^{12}C,^{12}C[3^-;9.64$ MeV$])^{12}C$ reaction at a center-of-mass

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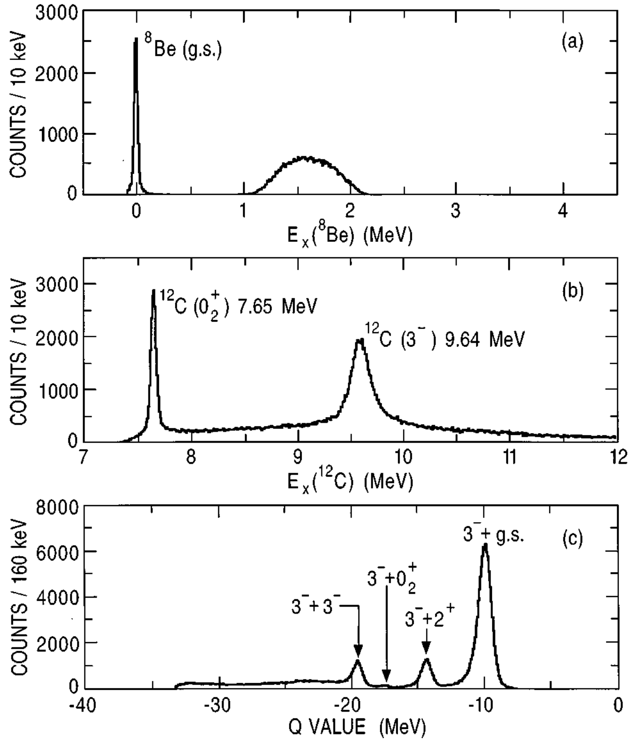

FIG. 1. (a) ^{8}Be excitation-energy spectrum, for events within the ^{12}C 3^- peak at 9.64 MeV, in (b). (b) ^{12}C excitation-energy spectrum obtained from three-alpha-particle coincidences in the DSSD array. The energies and momenta of two of the three alpha particles are consistent with a decaying ^{8}Be in its ground state. (c) ^{12}C-^{12}C Q-value spectrum for events, where the reconstructed ^{12}C was in its 3^- state at 9.64 MeV [see (b)].

energy of 33.5 MeV ($E_{\rm lab}$ = 67 MeV) [4,5]. The detectors used are described in [19,20], and are 5 cm×5 cm silicon wafers with the faces divided into crossed sets of 16 strips, yielding an effective pixel segmentation of 256 per detector. Two pairs of detectors were placed on either side of the beam, centered at angles of 15° and 35° relative to the beam axis, at distances of 17 and 14 cm from the target, respectively. Targets made from 50 μg/cm^2 ^{12}C foils were bombarded with ^{12}C beams from the ATLAS accelerator at Argonne National Laboratory at five energies between 59 and 75 MeV, spanning the region of the strong resonance at $E_{\rm lab}$ = 67 MeV reported in Ref. [4,5]. Energy and time-of-flight information for particles striking the array was recorded for all events in which at least three elements of the array triggered.

The data were analyzed using methods similar to those described in [21,22]. For each event in which three alpha particles were detected in the DSSD array, it was assumed that they were products of the decay of an excited ^{12}C nucleus. The alpha-particle angles and energies were used to calculate the excitation energy of the decaying ^{12}C. Furthermore, the relative momentum of each pair of alpha particles was checked to determine whether it was consistent with the decay of a ^{8}Be in its ground state [see Fig. 1(a)]. Figure 1(b) shows a spectrum of ^{12}C excitation energy from three-alpha-particle coincidence events, where two of the alpha particles were identified as coming from the decay of a ^{8}Be. The 0^+(7.65 MeV) and 3^-(9.64 MeV) states are clearly identified. The background beneath these peaks corresponds to real events in which the three alpha particles were not produced by a sequential ^{12}C→^{8}Be(g.s.)+α_0 decay. Figure 1(a) shows a representative two-alpha-particle relative energy spectrum, for events in which the ^{12}C was excited in its 3^-(9.64 MeV) level. The peak at E_X= 0 MeV is the ^{8}Be ground state, and the distribution of counts between E_X = 1 and 2 MeV represents events where one of the two alpha particles under consideration was actually the first alpha particle in the ^{12}C sequential decay. Only events in which the full decay sequence could be be unambiguously identified were retained in the subsequent analysis.

Figure 1(c) shows a histogram of the inelastic scattering Q value for events in which the reconstructed ^{12}C was identified as being excited to the 3^- state. Several final states are identified, with the 3^-+g.s. excitation dominant at $Q=-9.64$ MeV. For events falling within this Q-value window, angular correlation data were extracted. The relevant angles for the angular correlation measurement have been described by Marsh and Rae [23]. These angles are the scattering angle of the ^{12}C nucleus in the center-of-mass system, $\theta_{\rm c.m.}$, and the angles of emission of the first alpha particle in the ^{12}C(α_0) decay in the rest frame of the excited ^{12}C nucleus (ψ,ϕ). The angle ψ is measured with respect to the beam direction, and the azimuthal angle ϕ is defined as 0 in the reaction plane.

A discussion of angular correlations of radiation from an excited state following inelastic scattering can be found in Ref. [24]. Here, the quantization axis is chosen to lie along the beam. For a particular ^{12}C scattering angle, the angular dependence of the alpha-particle yield is given by

$$W(\theta_{\rm c.m.},\psi,\phi)=\left|\sum_m a_m(\theta_{\rm c.m.})Y_{3m}(\psi,\phi)\right|^2, \qquad (1)$$

where the a_m are the reaction scattering amplitudes for magnetic substates with different values of m. These amplitudes are given by the expression

$$a_m(\theta_{\rm c.m.})\sim\sum_{l_i,l_f}\eta_{l_i,l_f}\langle l_f3-mm|l_i0\rangle Y_{l_fm}(\theta_{\rm c.m.},0), \qquad (2)$$

where l_i and l_f are the partial waves in the entrance and exit channels, respectively, η_{l_i,l_f} represents the complex scattering matrix element which couples them, and $\langle l_f3-mm|l_i0\rangle$ the usual Clebsch-Gordan vector coupling coefficient.

Simplifications in the form of the angular correlation can be achieved by making certain assumptions about the reaction mechanism and the nature of the quantities η_{l_i,l_f}. For the case of a single isolated resonance of spin J, only one value of $l_i=J$ contributes to the amplitude $a_m(\theta_{\rm c.m.})$. By symmetry, only odd values of the decay l value l_f can contribute to the cross section, in this case $l_f=J\pm1$ or $J\pm3$. For the case where only a single value of l_f takes part in the resonance decay, the angular correlation assumes a very simple form

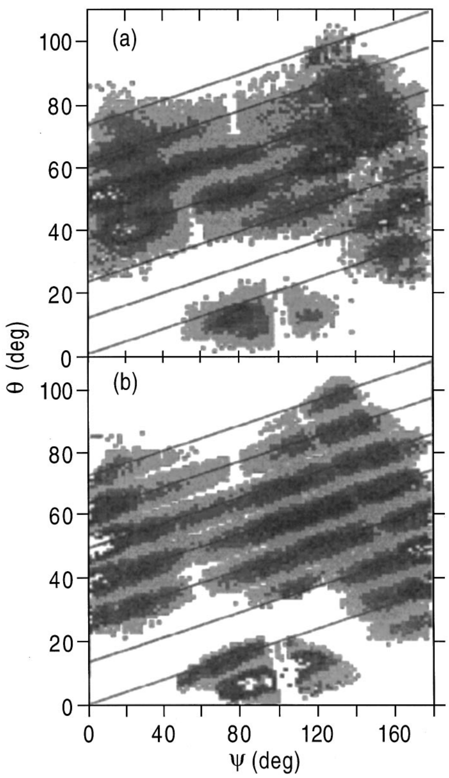

FIG. 2. (a) Experimental $^{12}C(3^-$; 9.64 MeV)-α angular correlation matrix for $E_{c.m.}=33.5$ MeV. (b) Theoretical angular correlation matrix, obtained with $J=18$, $l=15$, folded with the experimental acceptance determined from a Monte Carlo simulation of the detector array.

$$W(\theta_{c.m.},\psi,\phi)=\left|\sum_m \langle l3-mm|J0\rangle Y_{lm}(\theta_{c.m.})Y_{3m}(\psi,\phi)\right|^2. \tag{3}$$

Generally, for inelastic scattering, kinematics favor the lowest possible l value, due to the reduced kinetic energy available in the exit channel. This situation is known as the aligned or stretched configuration, as semiclassically the spin of the excited nucleus is then aligned parallel to the orbital angular momentum vector.

With these properties of the angular correlation in mind, we examine in detail data obtained at an energy corresponding to the peak of a strong resonance observed in the $^{12}C(3^-)$+g.s. excitation, $E_{c.m.}=33.5$ MeV. Figure 2(a) contains a matrix of the experimental angular correlation, where the X and Y axes correspond to the angles ψ and $\theta_{c.m.}$, respectively. Here the data are integrated over the azimuthal acceptance of the experimental setup. The azimuthal acceptance depends upon the reconstructed laboratory scattering angles for the decaying ^{12}C , but can be approximated by a Gaussian function centered at $\phi=0$, with a width of $\Delta\phi\approx 25^o$. For comparison, a Monte Carlo simulation of the reaction and detector response, with an angular correlation calculated using Eq. (3) with a resonance spin of $J=18$ and a decay l value of 15, appears in Fig. 2(b). By examining the structure of the correlation function in Eq. (3), one finds that the slopes of the ridges of the experimental and theoretical correlations provide a unique signature for each combination of l and J [23]. For the aligned configuration in particular, where $l=J-3$, the slope $\Delta\theta/\Delta\psi=S/l$, where $S=3$ for the 3^- state in ^{12}C [23]. The dashed lines in Figs. 2(a) and 2(b) are calculated with a slope of $\Delta\theta/\Delta\psi=3/15$, corresponding to an aligned configuration with $l=15$ and $J^\pi=18^+$. This value is in excellent agreement with the measured slopes of the ridges in the experimental angular correlation, and supports an assignment of $J^\pi=18^+$ for the resonance at $E_{c.m.}=33.5$ MeV.

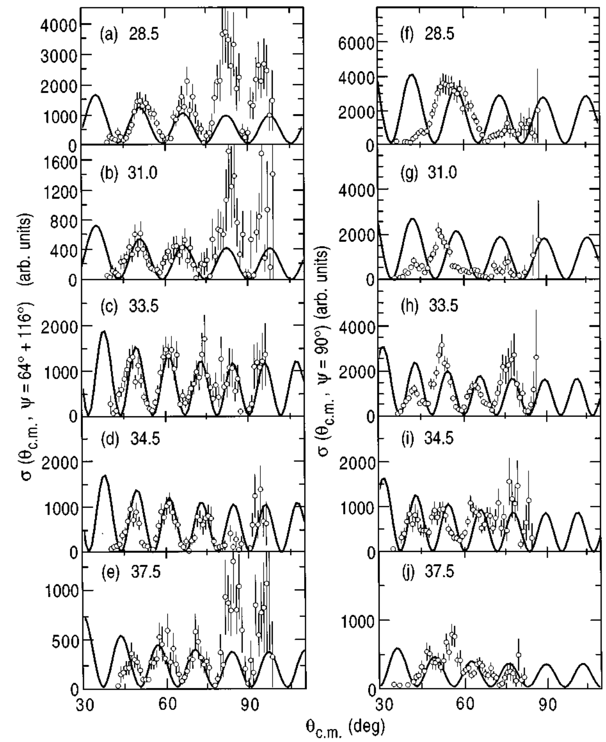

FIG. 3. Projections of angular-correlation matrices of the type shown in Fig. 2, onto the $\theta_{c.m.}$ axis for $\psi=64^o + 116°$ (a)–(e) and $\psi=90°$ (f)–(j). The center-of-mass energies are indicated in each panel. The curves represent squared associated Legendre polynomials $|P_{lm}(\theta_{c.m.})|^2$ of with $m=0$ (a)–(e) or 1 (f)–(j), and $l=11$ (a),(b),(f),(g), 15 (c),(d),(h),(i), and 13 (e),(j).

A more detailed analysis of the angular correlation can, under the simplifying assumptions described above, unambiguously determine the decay l value for the scattering reaction. By examination of Eq. (3), one observes that if the angular correlation in Fig. 2(a) is projected onto the $\theta_{c.m.}$ axis for particular values of $\psi=\psi_m$, where the associated Legendre polynomials $P_{3m}(\psi_m)=0$, only certain magnetic substates can contribute. For example, at an alpha-particle decay angle of $\psi_m=90^o$, all P_{3m} with even values of m are zero. In addition, the Clebsch-Gordan coefficients $\langle l3-mm|J0\rangle$ in Eq. (3) favor one choice of m depending upon the values of l and J. The $\theta_{c.m.}$ angle dependence of the correlation $W(\theta_{c.m.},\psi=90^o)$ then follows either $\sim|P_{l1}(\theta_{c.m.})|^2$, or $\sim|P_{l3}(\theta_{c.m.})|^2$, for $l=J\pm3$, or $l=J\pm1$, respectively. Conversely, if $\psi_m=\psi_1\approx 64^o$ or 116^o, then the $P_{3m}(\psi_1)=0$ for $m=1$. If the $m=3$ substate contribution is small, as in the case of a stretched configuration, then the correlation will follow $W(\theta_{c.m.},\psi_1)\approx|P_{lm}(\theta_{c.m.})|^2$, with $m=$ 0 and 2, and will display a minimum at $\theta_{c.m.}=90^o$.

Figures 3(a)–3(e) and 3(f)–3(j) contain projections of the

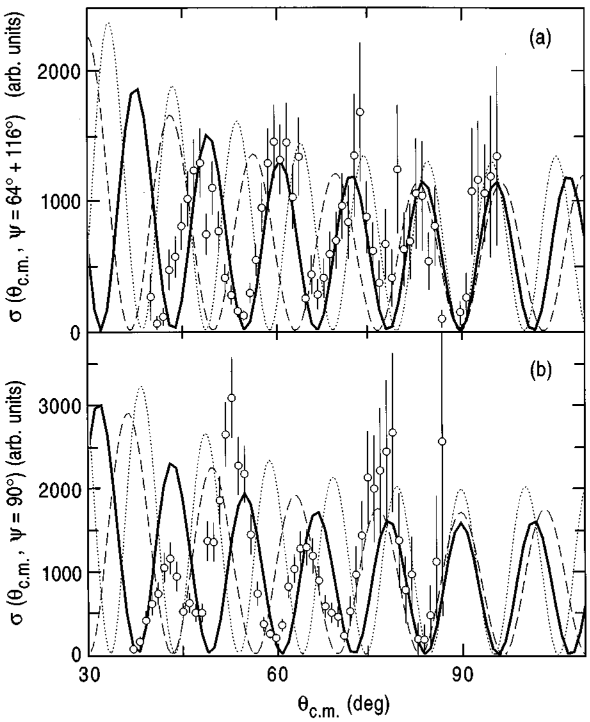

FIG. 4. Projections of angular-correlation matrices of the type shown in Fig. 2, onto the $\theta_{\mathrm{c.m.}}$ axis for (a) $\psi = 64^{\circ} + 116^{\circ}$ and (b) $\psi = 90^{\circ}$ at $E_{\mathrm{c.m.}} = 33.5$ MeV. The curves represent squared associated Legendre polynomials $|P_{lm}(\theta_{\mathrm{c.m.}})|^2$ with $l = 13$ (dashed curve), 15 (thick solid curve), and 17 (dotted curve), and $m = 0$ (a) and 1 (b).

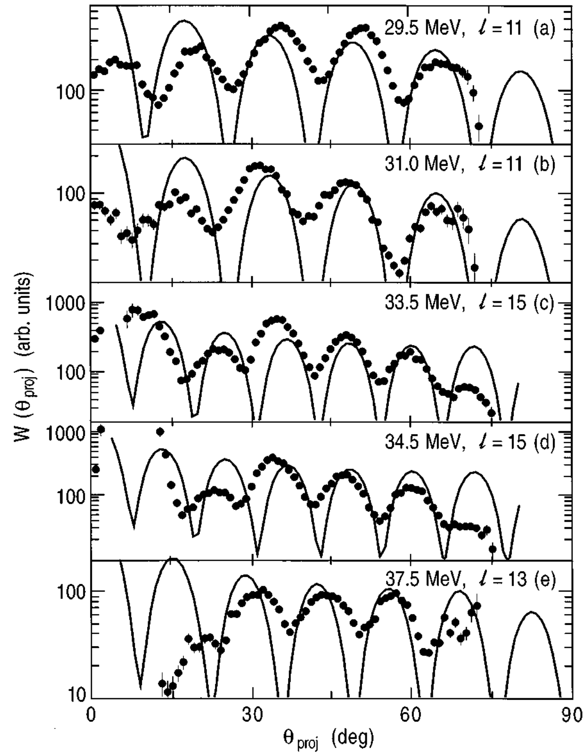

FIG. 5. Projections of angular-correlation matrices of the type shown in Fig. 2, along lines in the $\theta_{\mathrm{c.m.}}$-ψ plane with slopes of $\Delta\theta_{\mathrm{c.m.}}/\Delta\psi = 3/l$, where $l = 11$ (a),(b), 15 (c),(d), and 13 (e). The center-of-mass energies are indicated in each panel. The solid curves are squared Legendre polynomials calculated with the above l values.

angular correlation matrices onto the $\theta_{\mathrm{c.m.}}$ axis for projection angles of $\psi = 64^{\circ}$, 116° and for $\psi = 90^{\circ}$, respectively, at five center-of-mass energies. For the even magnetic substate projections [Figs. 3(a)–3(e)], the angular distributions are all regular and oscillatory, with minima which reach zero cross section at $\theta_{\mathrm{c.m.}} = 90^{\circ}$. This result implies that the aligned configuration is in fact dominant in all cases, as expected from the kinematics of the reaction. For the $\psi = 90^{\circ}$ projections in Figs. 3(f)–3(j) the results are not as clear cut. At the peak energy, however, the projections for $\psi = 90^{\circ}$ also display a regular oscillatory pattern. The solid curves in Figs. 3(a)–3(e) and 3(f)–3(j) represent associated Legendre polynomials $|P_{lm}(\theta_{\mathrm{c.m.}})|^2$ with $m = 0$ and 1, respectively, for the l values listed in the caption. For additional comparison, Figs. 4(a) and 4(b) show the data obtained at the peak of the resonance ($E_{\mathrm{c.m.}} = 33.5$ MeV), plotted with associated Legendre polynomial curves calculated assuming $l = 13$ (dashed curve), 15 (thick solid curve), and 17 (dotted curve). The $l = 15$ curves clearly provide the best description of the data at this energy. Under the conditions of an aligned configuration, this l value corresponds to a resonance spin of $J^{\pi} = 18^{+}$. At center-of-mass energies immediately below the resonance, $l = 11$ appears to be dominant, and above $l = 13$ yields the best fit to the data, although in neither case are the results as conclusive as the on-resonance data at $E_{\mathrm{c.m.}} = 33.5$ and 34.5 MeV, and these results likely reflect the contributions of other partial waves.

A final, somewhat more model-dependent analysis can be applied to the correlations in Fig. 2. As discussed above, the slopes of the ridges in the angular correlation contain information about the participating angular momenta. Under the simplifying assumptions outlined above, the correlation data can be rotated by a predetermined amount, depending on the values of l and J, and then projected onto the $\theta_{\mathrm{c.m.}}$ axis, where the projected angular correlation follows the behavior of that expected at $\psi = 0^{\circ}$, where only the $m = 0$ substate can contribute. Thus, the projected angular correlation should follow a simple squared Legendre polynomial form $W(\theta_{\mathrm{proj}}) \sim |P_l(\cos\theta_{\mathrm{proj}})|^2$.

Figure 5 contains examples of such projections for the five energies studied. The projected data have been corrected for the acceptance of the apparatus using the Monte Carlo simulation described above. In each case, the angle for the projection was chosen by making a particular choice for the decay l value; the angle of the projection α is then given by $\tan\alpha = 3/l$, which is appropriate for a stretched configuration with $l = J - 3$. The curves in Figs. 5(a)–5(e) are pure Legendre polynomials of order $l = 11$–15 as indicated in the caption. As before, at $E_{\mathrm{c.m.}} = 33.5$ MeV, the data are consistent with a dominant l value of $l = 15$ and a resonance spin $J^{\pi} = 18^{+}$. Below and above the peak energy, these projections are also consistent with the results obtained at particular alpha-particle angles ψ, with $l = 11$ for $E_{\mathrm{c.m.}} < 33.5$ MeV and $l = 13$ for $E_{\mathrm{c.m.}} = 37.5$ MeV. Here, as well as with the previously described analysis, the shapes of the off-resonance angular correlations are dramatically different from the one obtained at the peak, suggesting that the l and

J^π values extracted there represent a departure from the background, and can truly be associated with the resonance observed at that energy.

All of the analyses of the current correlation data are consistent with a resonance spin assignment of $J^\pi = 18^+$, decaying through $l = 15$. It is interesting to compare this result with the predictions of various theoretical calculations for resonance behavior in this system. One well-known model for resonance behavior in the $^{12}C+^{12}C$ system is the band crossing model (BCM) [7]. The BCM calculations qualitatively reproduced the resonance features of the excitation functions reported for the single and mutual 2^+ and single 3^- excitations. In addition, for the 3^-+g.s. excitation, the expected angular momenta were $J = 14$ from $E_{c.m.} = 25$ to 30 MeV, $J = 16$ from 30 to 35 MeV, and $J = 18$ from 35 to 40 MeV. The resonance near $E_{c.m.} = 33$ MeV was attributed to $J = 16$, in disagreement with our current measurements, which suggest $J^\pi = 18^+$ for this structure. In these calculations, the model parameters have been adjusted to match a reported 12^+ resonance in the elastic scattering channel. It is interesting to point out that the angular momenta deduced from the correlation data away from the resonance peak appear consistent with the partial waves suggested by the BCM results. This result could imply that while the nonresonant scattering cross section might be well described by simple potential scattering models or dominated by kinematical considerations, the strong nonstatistical resonances likely have a different origin that may lie in the nuclear structure of the compound system. The results of the current measurements may also be compared to the magnetic substate angular distribution data of Sugiyama *et al.* [25] for $^{12}C+\ ^{12}(2^+)$ inelastic scattering in the region at several strong resonances between $E_{c.m.} = 10$ and 40 MeV. In the 2^++g.s. channel, the data were also consistent with resonances spins two units of angular momentum higher than previously thought.

In conclusion, particle-particle angular correlation techniques have been used to study resonance behavior in the $^{12}C+^{12}C(3^-, 9.64$ MeV) reaction at center-of-mass energies near a strong peak in the excitation function for this channel. The results are consistent with a spin assignment of $J^\pi = 18^+$ for the resonance observed at $E_{c.m.} = 33.5$ MeV, decaying through an aligned configuration with an l value of 15. A recent study of spin alignments in $^{12}C+^{12}C$ inelastic scattering to the mutal 3^- excitation at $Q = -19.28$ MeV suggested the same value for the entrance channel angular momentum at a nearby energy of $E_{c.m.} = 32.5$ MeV [18]. This spin assignment is inconsistent with the predictions of the BCM, although the off-resonance angular correlations suggest angular momenta that more closely follow the trends predicted by this simple model. In addition, the resonance spin is different from the partial waves which dominate the cross section in the $0_2^+ + 0_2^+$ channel ($l = 14$–16), where a broad cross section enhancement has been observed centered at nearly the same energy [21,22]. This difference suggests that the features which appear in these very different reaction channels are most likely unrelated to each other. The sensitivity introduced by these experimental techniques suggests that they will prove useful for the study of other similar reactions populating unbound final states.

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