Angular correlations for α-particle decay in the reaction $^{12}C[^{12}C,^{12}C(3_1^-)\rightarrow{}^8Be(0_1^+)+\alpha]^{12}C^*$ at $E_{c.m.}=32.5$ MeV

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We present angular correlations in ''Basel'' coordinates for α-particle decay in measurements of $^{12}C[^{12}C,^{12}C(3_1^-)\rightarrow{}^8Be(0_1^+)+\alpha]^{12}C^*$ scattering at $E_{c.m.}=32.5$ MeV. A semiclassical model of the angular correlation function has been used to describe the observed angular correlations in the various exit channels. We demonstrate that the semiclassical result can be used even in the case where there are two nonzero spins in the exit channel if the decay products from both ejectiles are detected. We apply this new method to the mutual sequential breakup reaction $^{12}C[^{12}C,^{12}C(3_1^-)\rightarrow{}^8Be(0_1^+)+\alpha]^{12}C(3_1^-)\rightarrow{}^8Be(0_1^+)+\alpha$. We deduce that the scattering occurs dominantly to a final state with fully aligned spins and orbital angular momentum $L'=12$ or 14. [S0556-2813(96)01206-X]

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I. INTRODUCTION

New experimental studies of scattering reactions to states high above the 6α particle decay threshold in ^{24}Mg have revealed new resonant structure in the $^{12}C+^{12}C$ system. Most notably, it appears that the wide resonance first reported in the $^{12}C[^{12}C,^{12}C(0_2^+)]^{12}C(0_2^+)$ reaction at $E_{c.m.}=32.5$ MeV [1], with an unusually large strength of the scattering cross section at 90° (in the center of mass), may also be common to a number of other channels. We have previously reported on similar behavior for scattering to the $^{12}C(0_2^+)+^{12}C(3_1^-)$ and $^{12}C(0_2^+)+^{12}C(0_3^+)$ channels [2], whilst Freeman *et al.* [3] have found that the $^{16}O(0_1^+)+{}^8Be(0_1^+)$ channel also resonates at this energy with the characteristic 90° enhancement. This striking feature in the angular distribution originally suggested that the 32.5 MeV $0_2^++0_2^+$ resonance be considered as an approximate shape eigenstate [4,5], where many overlapping resonances with different L values are excited. It was thought that this deformed structure was consistent with the formation of a 6α linear chain configuration [6,7] (LCC) at $E_x=46.4$ MeV in ^{24}Mg. The cranked α-cluster model [6] predicts a band crossing between the ground state and chain α-cluster configurations in ^{24}Mg near $E_x=50$ MeV and $L=16$. This seemed to be confirmed by the observation of dominant angular momenta $L=14$ and 16 [1] in the reaction. However, the resonant strength recently discovered in other decay channels [2,3,8,9] at this energy presents a challenge to this interpretation. Since the dominant decay mode of a 6α LCC is expected to be through symmetric fission to two 3α LCC's or three ^{8}Be nuclei [13], the observation of strong resonance for scattering to nuclei with no relation to chain configurations is surprising. Moreover, the 0_2^+ state in ^{12}C is widely accepted as having at best only a limited overlap with a 3α LCC structure [10–12]. It is thus difficult to construct a 6α chain from two $^{12}C(0_2^+)$ states [13].

An alternative explanation of the $E_{c.m.}=32.5$ MeV resonances is provided by the band crossing model (BCM) [14]. This predicts excitation function enhancements in the $0_2^++0_2^+$, $0_2^++3_1^-$, and $0_2^++0_3^+$ channels at this energy, when realistic transition densities for ^{12}C [15] are included [16]. This model suggests that the structure of the $0_2^++0_2^+$ resonance can be understood in terms of a weakly coupled 3α plus 3α configuration, where the 3α particles do not necessarily form a chain state. The BCM predicts a dominant partial wave of $L=J=18$ for the $0_2^++0_2^+$ channel, somewhat larger than those in the experimental data ($L=14,16$ [1]). L is the orbital angular momentum and J the total spin. The $0_2^++3_1^-$ resonance is predicted to be the result of a similarly extended 3α structure coupled to an excited $^{12}C(3_1^-)$ core with stretched angular momentum $L=J-3$. This model has had some success in reproducing resonances at other energies in the $^{12}C+^{12}C$ system. The resonances discovered by Cormier *et al.* [17] in the $0_1^++2_1^+$ and $2_1^++2_1^+$ channels and those by Fulton *et al.* [18] for scattering to the $0_1^++0_2^+$ and $0_1^++3_1^-$ states are also observed in BCM calculations [14,16,19]. Note that only the more recent formulation of the BCM [16], which incorporates a distorted form factor for the 0_2^+ level in ^{12}C, can describe the excitation function enhancement seen in the angular momentum mismatched $0_1^++0_2^+$ channel.

The physics underlying the BCM is rather simple; namely, it predicts that molecular resonances should be dominated by an aligned coupling between the orbital angular momentum and intrinsic spin. One expects this result quite naturally given the negative Q value of these reactions. Such alignments have been observed in studies of ^{12}C on ^{12}C collisions for the single and mutual excitation of the $^{12}C(2_1^+)$ state using particle-γ-ray angular correlations [20–22]. Resonances in the cross section were found to be uniquely associated with a strong enhancement of the spin alignment, particularly in the mutual 2_1^+ channel [22]. These data suggest that the resonant configuration is characteristically different from that of the nonresonant weakly aligned background and that the respective orientation of the deformed ^{12}C nuclei plays a decisive role in this resonance behavior.

It would be interesting to make similar measurements of the alignment in the case of the resonances observed in the 3_1^- channels in the ^{12}C+^{12}C system, especially in order to test the hypotheses proposed to explain the 32.5 MeV resonances. Since the 3_1^- channels involve excitations to nuclear states above the decay threshold for particle emission, particle detection techniques for determining angular correlations and spin alignments must be used. One such method has been discussed previously and illustrated for the case of the sequential breakup reaction $^{12}\mathrm{C}[^{12}\mathrm{C},^{12}\mathrm{C}(3_1^-) \to {}^{8}\mathrm{Be}(0_1^+)+\alpha]^{12}\mathrm{C}(0_1^+)$ at $E_{\mathrm{c.m.}}=27$ MeV [23]. The data presented display a strong spin alignment at this energy which coincides with one of the resonances observed by Fulton *et al.* [18] in this channel.

Here, we report on similar measurements extended to the case of mutual sequential breakup. In particular, we have examined the data of Chappell *et al.* [2] and reconstructed $^{12}\mathrm{C}[^{12}\mathrm{C},^{12}\mathrm{C}(3_1^-)\to{}^{8}\mathrm{Be}(0_1^+)+\alpha]^{12}\mathrm{C}^*$ and $^{12}\mathrm{C}[^{12}\mathrm{C},^{12}\mathrm{C}(3_1^-)\to{}^{8}\mathrm{Be}(0_1^+)+\alpha]^{12}\mathrm{C}(3_1^-)\to{}^{8}\mathrm{Be}(0_1^+)+\alpha$ angular correlations at $E_{\mathrm{c.m.}}=32.5$ MeV. We choose to study these angular correlations using the ''Basel'' coordinate system [24] as was used in the particle-γ-ray correlation studies [21,22]. The theoretical angular correlation function reduces to a particularly simple form using a semiclassical approximation in Basel coordinates in which the physical interpretation of the data is transparent. This form of the correlation function also yields an efficient method of projection by which to study the correlation ridge structures in one dimension [25]. The ridge periodicity and projection gradient are related to the spins and angular momenta in the final state. As indicated above, we also present angular correlations for the mutual inelastic scattering $^{12}\mathrm{C}[^{12}\mathrm{C},^{12}\mathrm{C}(3_1^-)]^{12}\mathrm{C}(3_1^-)$. The simultaneous measurement of decay angles for the breakup of both recoil and ejectile nuclei provides a new technique by which to examine the spin orientation in sequential mutual breakup reactions. Although the results from our existing data are ambiguous we believe that important information can be extracted from both the single and mutual $^{12}\mathrm{C}(3_1^-)\to{}^{8}\mathrm{Be}(0_1^+)+\alpha$ correlation functions in a simple way. This paper is mainly concerned with the new simple technique for extracting reaction information from the mutual channel.

II. ANGULAR CORRELATIONS IN BASEL COORDINATES

Particle decay angular correlation measurements have become well established in the study of heavy-ion sequential breakup reactions using the techniques of resonant particle decay spectroscopy [26,27]. A sequential breakup reaction, $a(A,A^*\to C+c)a$, consists of scattering a projectile A from a target a to form an intermediate nucleus A^* which then decays via particle emission to leave a three-body final state $C+c+a$. Mutual sequential breakup, $a(A,A^*\to C+c)a^* \to D+d$, is said to occur when both the ejectile (A^*) and recoil (a^*) nuclei are excited above the threshold for particle decay. The dependence of the direction of particle decay on the initial scattering angle can reveal many features of the reaction process. In particular, the gross structure of the angular correlations may be used to determine the spins of the nuclei, often in a model-independent manner, while the fine details may in conjunction with reaction models reveal the m-substate populations [28].

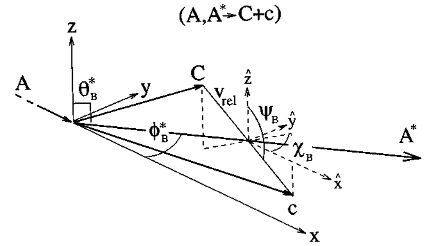

FIG. 1. Velocity vectors in the center of mass for the sequential breakup reaction $(A,A^*\to C+c)$ defining the correlation variables $(\theta_B^*=90°,\phi_B^*,\psi_B,\chi_B)$ in the ''Basel'' coordinate scheme.

The Basel coordinate system adopted in the present analysis is defined in Fig. 1. In this representation, the z axis is defined on an event-by-event basis to lie perpendicular to the reaction (xy) plane and x is taken as the beam direction. The trajectory of the ejectile nucleus A^* is then given by the angles θ_B^* and ϕ_B^*, where θ_B^* is fixed at 90° by definition. The angles ψ_B and χ_B characterize the breakup by defining the orientation of $\mathbf{v}_{\mathrm{rel}}$ (the relative velocity vector between the decay products C and c) with respect to the out-of-plane (z) and beam (x) axes. Most of the events considered here are restricted by the detector geometry to be in plane. We thus take $\psi_B=\pi/2$.

The semiclassical angular correlation function in Basel coordinates has been obtained previously [29]. In these coordinates, using the decay amplitude

$$(-1)^k e^{-ik\chi_B} d_{k0}^I\left(\frac{\pi}{2}\right), \tag{2.1}$$

the semiclassical angular correlation function for single excitation and a single incident (L) and final (L') partial wave reduces to

$$W(\phi_B^*,\chi_B)\propto \frac{1}{\sin\phi_B^*}\left|\sin\left[\left(L'+\frac{1}{2}\right)\phi_B^*+k\chi_B+\frac{\pi}{4}\right]\right|^2 d_{k0}^I\left(\frac{\pi}{2}\right)^2 \tag{2.2}$$

for a spin zero recoil. Here, k is the projection of ejectile spin (I) on the z axis.

The combined use of the Basel coordinate system and the semiclassical approximation results in considerable physical insight into the nature of the scattering reaction. The chosen z axis, perpendicular to the reaction plane, is also parallel to the orbital angular momentum vector $\mathbf{L}'$ semiclassically. Thus the angular momentum transfer in the reaction is $\mathbf{L}'-\mathbf{L}$ and the projection of this on the z axis must be equal to the projection (k) of the ejectile spin vector $\mathbf{I}$ on the z axis in this approximation. If $k=I$ then the vector $\mathbf{I}$ is fully aligned along $\mathbf{L}$ and $\mathbf{L}$ is exactly parallel to $\mathbf{L}'$. For reactions with a very negative Q value the dominant L' is generally much less than L so that the only important contribution to

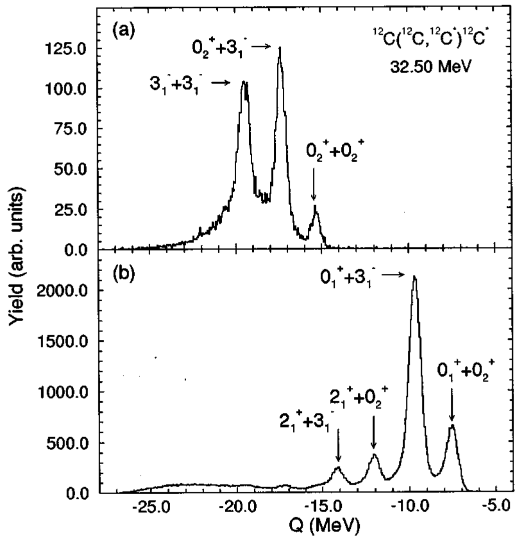

FIG. 2. Two-body Q value for $^{12}C^{*}+{}^{12}C^{*}$ events at $E_{c.m.}=32.5$ MeV reconstructed from (a) $3\alpha+3\alpha$ and (b) $3\alpha+1$ hits identified on either side of the beam direction.

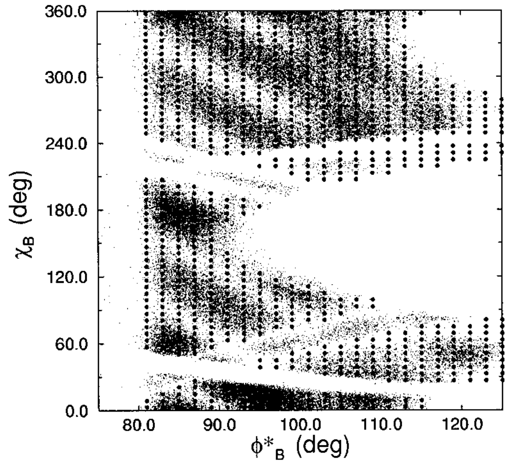

FIG. 3. The $^{12}C[^{12}C,{}^{12}C(3_1^-)\rightarrow{}^{8}Be(0_1^+)+\alpha\ ]^{12}C(0_1^+)$ angular correlation compared to the (ϕ_B^*,χ_B) phase space (shown as the grid of dots) defined by the detector geometry.

the cross section comes from the maximum possible value of k, namely, $k=I$. However, for $Q\simeq0$, there would be a distribution of possible k values although $k\simeq0$ may dominate. In such cases the alignment of **I** is not well defined and for any incident partial wave L there will be several exit partial waves L' contributing simultaneously. The direction of the vector **I** is then different for each possible partial wave L'. (Note that the semiclassical approximation assumes that $I\ll L$ so that the projection of $\mathbf{L}'-\mathbf{L}$ on the z axis is always assumed to be approximately $L'-L$ although $\mathbf{L}'$ may not be exactly parallel to **L**.)

III. EXPERIMENTAL DETAILS

The experimental method used in these measurements has been described in detail elsewhere [2]. Briefly, the setup consisted of three 25 cm^2, 500 μm thick position sensitive strip detectors (PSSD's), each segmented into 16 strips. The PSSD's were arranged with their centers 12 cm from the target at $+25°$, $+52°$, and $-32°$ in the horizontal plane relative to the beam direction. A natural carbon target foil of aerial density 90 μg cm^{-2} was used. This system allowed the scattering to channels above the multiple α-decay threshold to be studied. For example, Fig. 2 demonstrates the range of $^{12}C^{*}+{}^{12}C^{*}$ inelastic scattering channels identified in the present data at $E_{c.m.}=32.5$ MeV. The simultaneous detection of 3α + 3α hits on either side of the beam is characteristic of the scattering to states in $^{12}C^{*}$ above the α-decay threshold (7.37 MeV) [Fig. 2(a)]. For the similar case of 3α + 1 hits [Fig. 2(b)], the individual hit may correspond to either an intact ^{12}C nucleus below the breakup threshold or an α particle. In this spectrum, the $^{12}C^{*}(>7.37$ MeV) + $^{12}C^{*}$ (<7.37 MeV) case has been selected by comparing the two-body Q values for scattering to $^{12}C^{*}$ on either side of the beam. Events were discarded for which the Q values did not match to within 500 keV, thus reducing the background. Note that the overdetermination of reaction kinematics in these measurements also allows the reconstruction of 6α final states following the detection of only 5α coincidences. We therefore consider four-, five-, and six-fold particle-hit data in the following analysis.

IV. RESULTS AND ANALYSIS

A. $^{12}C[^{12}C,{}^{12}C(3_1^-)\rightarrow{}^{8}Be(0_1^+)+\alpha]^{12}C(0_{1,2}^+)$ angular correlations

Figure 3 shows the $^{12}C(3_1^-)\rightarrow{}^{8}Be(0_1^+)+\alpha$ angular correlation pattern observed in the $^{12}C(3_1^-)+{}^{12}C(0_1^+)$ channel at $E_{c.m.}=32.5$ MeV. A series of prominent ridges can be seen in these data within a segmented detection boundary. The limits of this boundary agree well with the phase space coverage predicted by three-body kinematics [30] (Fig. 3). The small differences between the observed and calculated phase spaces in Fig. 3 arise from deficiencies in the kinematics simulation. Most importantly, the reaction proceeds to a four-body final state where $^{8}Be(0_1^+)$ further decays into 2α particles. In addition, the characteristic position-dependent energy thresholds of the PSSD's have not been accurately reproduced. The angular correlation pattern in this channel is compared with the loci of maxima in the correlation functions $W(\phi_B^*,\chi_B)$ [Eq. (2.2)], for a number of L' values and $k=3$, in Fig. 4.

The observed ridges are clearly 60° apart in χ_B; from Eq. (2.2) the spacing $\Delta\chi_B$ must be π/k and this yields $k=3$. The gradient of the ridges is $\Delta\chi_B/\Delta\phi_B^*=(L'+\frac{1}{2})/k$. Note that the semiclassical correlation function is independent of L' at $\phi_B^*=90°$. Since the present data span only a narrow range about $\phi_B^*=90°$, an unambiguous assignment of the dominant L' value in this channel is not possible. However, we may examine the structure in this correlation more closely by assuming possible ridge gradients and projecting the data onto the $\chi_B=0$, ϕ_B^* axis. This is equivalent to averaging the data along lines of constant $\phi_B^*+\chi_B k/(L'+\frac{1}{2})$, as in Fig. 5. This averaging process is advantageous since from Eq. (2.2) the angular correlation depends only on a linear combination of the angles ϕ_B^* and χ_B. If the data are dominated by a single combination of one L' and one k then the averaging

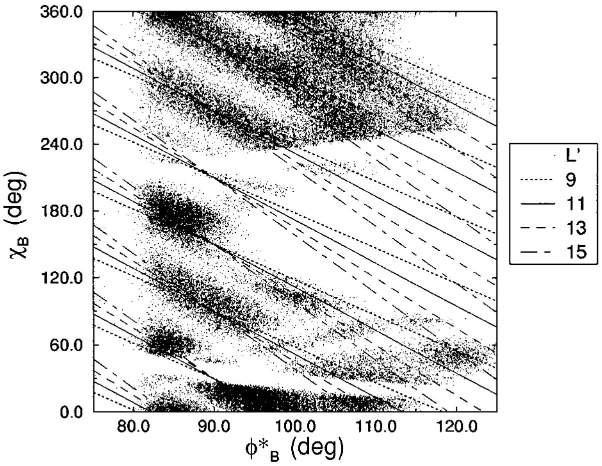

FIG. 4. The ^{12}C[^{12}C,^{12}C(3_1^-)→ ^{8}Be(0_1^+)+α]^{12}C(0_1^+) angular correlation overlayed with the calculated loci of maxima in the semiclassical correlation functions $W(\phi_B^*,\chi_B)$ for $k=3$ and the L' values indicated.

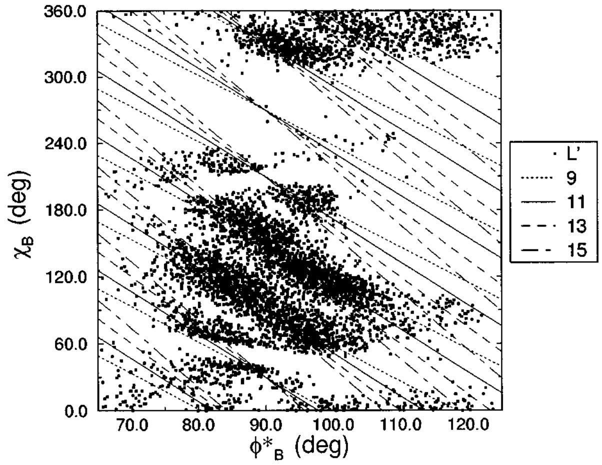

FIG. 6. The ^{12}C[^{12}C,^{12}C(3_1^-)→ ^{8}Be(0_1^+)+α]^{12}C(0_2^+) angular correlation and loci of maxima in the correlation functions $W(\phi_B^*,\chi_B)$ for $k=3$ and the L' values indicated.

procedure enhances the statistics without any loss of information since the correlation is the square of a pure sine wave. However, even if the latter condition of a single combination of L' and k is true, we do not necessarily know *a priori* which values of L' and k dominate. These must be deduced from the experimental data. A convenient way to do this is to evaluate $\phi_B^*+\chi_B k/(L'+\frac{1}{2})$ on an event-by-event basis and histogram the data as a function of this variable. This can be done for several values of k and L'. When the correct choice of k and L' is made (which is equivalent to choosing the projection gradient) a regular sequence of maxima and minima should be seen in the one-dimensional projection of the correlation spectrum. If the wrong choice of k or L' is made and the data span a sufficiently large phase space in the ϕ_B^* and χ_B variables then the maxima and minima will be smeared out. As we noted our data are restricted in ϕ_B^* space and do not determine the gradient at all well. Since the correlation function is nearly independent of L' all projections show similar structure.

Figure 6 shows the ^{12}C(3_1^-)→^{8}Be(0_1^+)+α angular correlation pattern observed in the ^{12}C(3_1^-)+^{12}C(0_2^+) channel. One-dimensional projections of this correlation are given in Fig. 7. As was noted above the data do not determine L' well. However, note that if, in both of the above examples, the measured range of ϕ_B^* was extended the correlation analysis would determine L'. This is illustrated below for the mutual case where the range of angles obtained from our existing data set is larger.

B. Spin-orientation alignment in ^{12}C[^{12}C,^{12}C(3_1^-)]^{12}C(3_1^-) scattering

We will now consider the particle decay angular correlations for the mutual inelastic scattering ^{12}C[^{12}C,^{12}C(3_1^-)] ^{12}C(3_1^-). In this case, the variation over the possible m substates for recoil nuclei with spin destroys any ridge pattern in the simple (ϕ_B^*,χ_B) plot (Fig. 8). However, the present measurements allow us to investigate both the correlation angles χ_B and χ_B' for the breakup of both the ejectile and recoil nuclei simultaneously. The semiclassical angular correlation function for mutual excitation and decay can be obtained in a

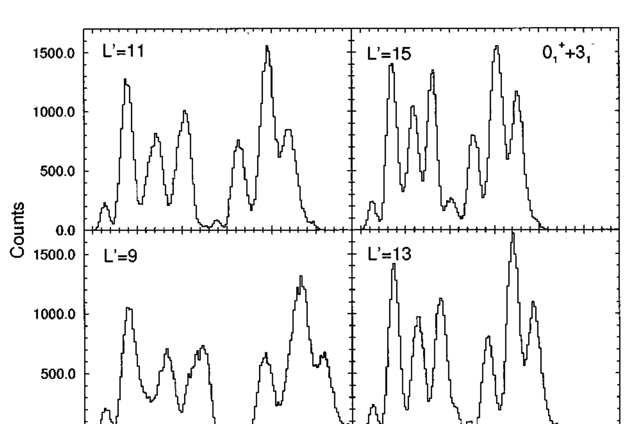

FIG. 5. One-dimensional projections of the $k=3$ angular correlation in the ^{12}C(0_1^+)+^{12}C(3_1^-) channel for a number of L' values.

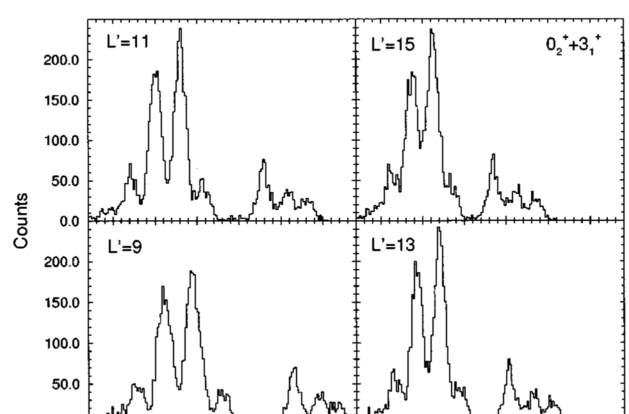

FIG. 7. One-dimensional projections of the $k=3$ angular correlation in the ^{12}C(0_2^+)+^{12}C(3_1^-) channel for a number of L' values.

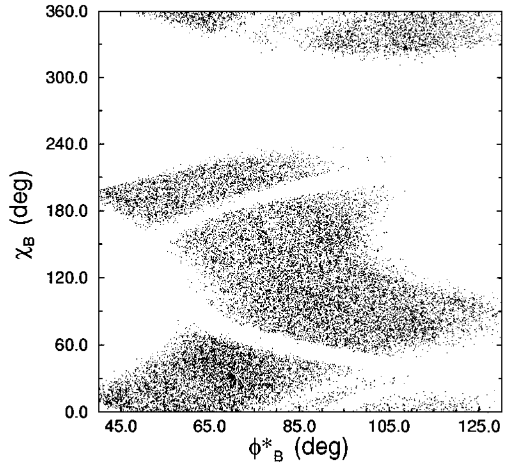

FIG. 8. The ^{12}C[^{12}C,^{12}C(3_1^-)→ ^{8}Be(0_1^+)+α]^{12}C(3_1^-) angular correlation.

similar way to that used by Hahne and Rae [29]. The decay amplitude for a specific k and k' for the case of two separate nuclei is

$$(-1)^k e^{-ik\chi_B} d^I_{k0}\left(\frac{\pi}{2}\right)(-1)^{k'} e^{-ik'\chi'_B} d^{I'}_{k'0}\left(\frac{\pi}{2}\right). \qquad (4.1)$$

Here k and k' are the projections of the two ^{12}C spins (**I** and **I**$'$) on the z axis and $k+k'$ is now identified with $L-L'$. Using the formalism of Hahn and Rae, this amplitude gives the final angular correlation function

$$W(\phi_B^*,\chi_B,\chi'_B)\propto \frac{1}{\sin\phi_B^*}\left|\sin\left[\left(L'+\frac{1}{2}\right)\phi_B^*+k\chi_B+k'\chi'_B+\frac{\pi}{4}\right]\right|^2 d^I_{k0}\left(\frac{\pi}{2}\right)^2 d^{I'}_{k'0}\left(\frac{\pi}{2}\right)^2 \qquad (4.2)$$

where again L' is the final state orbital angular momentum. If we assume that k and k' have equal magnitudes then we can plot the correlation as a function of $X=\chi_B\pm\chi'_B$. We find that ridge structure is observed in plots of ϕ_B^* versus X when $X=\chi_B+\chi'_B$ [Fig. 9(a)] but not when $X=\chi_B-\chi'_B$ [Fig. 9(b)]. Projections of these correlations are shown in Fig. 10. A regular sequence of peaks can be seen in the $X=\chi_B+\chi'_B$ projections for $L'=12$ and 14. No structure is observed for the $X=\chi_B-\chi'_B$ case. Note that again the ridges have a spacing of 60° in the $X=\chi_B+\chi'_B$ direction, suggesting that k and k' are predominantly both equal to 3. Also note that in this case the projected correlations do indeed provide some information on L'. Structure in the projected correlations is only visible if we assume L' to be either 12 or 14 in our event-by-event histogramming. Again a wider angular coverage would make this assignment unambiguous. These results imply that the ^{12}C(3_1^-) nuclei scatter dominantly with fully aligned spins, i.e., $K=k+k'=6$ and $L'=12$ or 14 in this channel. This is consistent with the very negative Q value for the reaction so that for each incident L only $L'=L-6$ contributes. This suggests a resonant spin of $J=L'+K=18$ or 20. Hence considerable information can be gleaned from these mutual angular correlations by the simple technique of

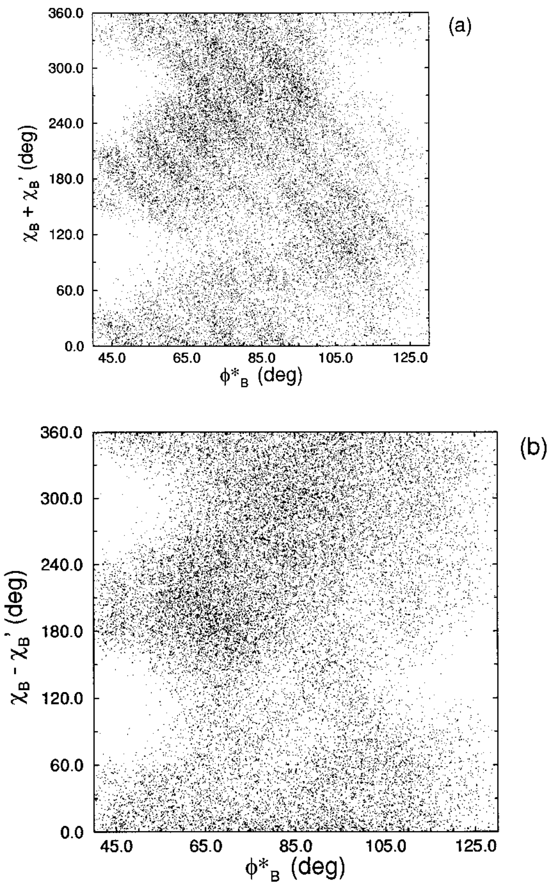

FIG. 9. ^{12}C[^{12}C,^{12}C(3_1^-)→ ^{8}Be(0_1^+)+α]^{12}C(3_1^-)→ ^{8}Be (0_1^+)+α angular correlations including consideration of the recoil breakup angle: (a) $X=\chi_B+\chi'_B$ and (b) $X=\chi_B-\chi'_B$.

projection of the three-dimensional correlation $W(\phi_B^*,\chi_B,\chi'_B)$ onto a single axis using various assumptions for k, k', and L'.

V. CONCLUSIONS

We have compared angular correlation measurements for ^{12}C[^{12}C,^{12}C(3_1^-)→^{8}Be(0_1^+)+α]^{12}C* scattering at

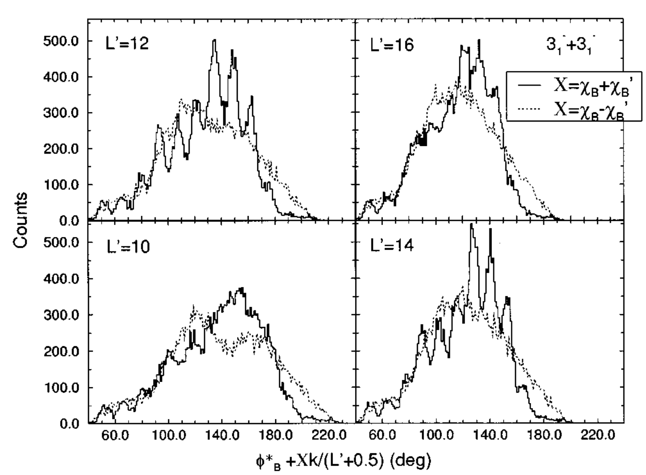

FIG. 10. Projections of the $W(\phi_B^*,X)$ angular correlations in the ^{12}C(3_1^-)+^{12}C(3_1^-) channel for $k=k'=3$ and the L' values indicated.

$E_{c.m.} = 32.5$ MeV to a semiclassical description of the correlation function in Basel coordinates. The present analysis suggests that the dominant partial wave in $^{12}C(3_1^-) + {}^{12}C(3_1^-)$ scattering at $E_{c.m.} = 32.5$ MeV is $L' = 12$ or 14 and that the dominant partial wave in the incident channel is $L = 18$ or 20 (the incident partial wave is equal to the total spin J). This result cannot be compared with the band crossing model of this reaction [16] since the mutual 3_1^- channel was not considered in those calculations. Our experimental results may be consistent with a new model of the 32.5 MeV resonance presented recently by Rae, Fry, and Merchant [31] but more extensive angular correlation data are required to make the dominant partial wave assignments less ambiguous, especially in the $0^+_{1,2} + 3_1^-$ channels. It will also be necessary to establish that the $3_1^- + 3_1^-$ channel is resonant at this energy. In the new model proposed by Rae, Fry, and Merchant, the $E_{c.m.} = 32.5$ MeV resonance is thought to be the result of the scattering of ^{12}C nuclei with threefold α-cluster symmetry and aligned spins. The present data indicate that a correlated full spin alignment between the deformed nuclei in the $^{12}C(3_1^-) + {}^{12}C(3_1^-)$ channel has been observed at $E_{c.m.} = 32.5$ MeV.

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