High spin resonances in ^{12}C+^{12}C scattering

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Abstract

We report on new experimental data which reveal high spin resonances in ^{12}C+^{12}C scattering. We have measured excitation functions for the ^{12}C [^{12}C, ^{12}C(3_1^-) + ^{12}C(3_1^-)] reaction over the centre of mass energy range $E_{c.m.}$ = 31 to 45 MeV. Resonances have been observed at $E_{c.m.}$ = 32.5, 37.5 and 43 MeV. Detailed angular correlation measurements have been performed at the energy corresponding to the peak of each resonance. From an analysis of the angular correlations we suggest a dominant angular momentum of $J = 22$ at the highest energy. We interpret the results in terms of an α cluster model of superdeformed states in ^{24}Mg.

Key words: Nuclear reactions; ^{12}C(^{12}C,6α); E=31-45 MeV; excitation functions; spins; resonances; angular correlations.

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The ^{12}C+^{12}C system displays a wide range of resonant phenomena from the narrow resonances at energies near the Coulomb barrier [1, 2] to much wider structures in inelastic scattering data [3–6]. The origin of these resonances has always been a matter of some debate [7]. However for a number of years it has been suggested that there may be some connection between these resonances and the superdeformed configurations in ^{24}Mg predicted by various different models [2, 8–11]. If we consider the cranked Bloch-Brink α cluster model calculations of Marsh and Rae [9] then an interesting prediction of this model

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is that only two configurations can support total angular momenta of $J \geq 16\hbar$. One of these configurations, labelled F1 by Flocard et al. [11], has a well developed ^{12}C+^{12}C structure. The second structure is a 6α-chain state. Thus at high spins, well above the maximum that the compound nucleus ^{24}Mg can support at normal deformations, the system should show only resonances corresponding to a maximum of two comparatively simple configurations. In this paper we will not address the recent work on the 6α-chain state [12].

In their original paper Marsh and Rae [9] suggested that the resonances first discovered by Cormier et al. [3] should be associated with this F1 configuration. The predicted moment of inertia of the F1 band agrees with that of the Cormier resonances using the measured spin values [5, 6, 13, 14]. These resonances show up most clearly in the excitation function for the single and mutual excitation of the 4.43 MeV 2_1^+ state in ^{12}C. We will defer further detailed discussion of theoretical models to the end of this letter. Here we just note that in the Bloch-Brink model of ^{12}C the ground state rotational band and the 3_1^- state at 9.63 MeV share a common intrinsic shape, thus one might search for resonances in the inelastic scattering of ^{12}C+^{12}C to final states which also include the 3_1^- state. Together with the recent development of an angular correlation method for mutual excitation [15] this was the motivation behind our search for these new high spin resonances.

The 3_1^- state in ^{12}C decays predominantly via the ground state of ^{8}Be to three α particles. The necessary experimental techniques for detecting these α particles and reconstructing the ^{12}C excitation spectrum have been developed by a number of groups (e.g [16–18]). We use large 5 cm $\times$ 5 cm Si wafers subdivided into sixteen 3 mm wide strips which are independently instrumented. Signals are taken from both ends of the strips and these provide both the total energy and the position of the particle detected by any particular strip. The details of the operation and calibration of these detectors can be found elsewhere [19–21].

We have performed an excitation function measurement over the laboratory energy range 62 to 90 MeV in 2 MeV steps using 4 detectors in the 2 m scattering chamber at the Australian National University Tandem Laboratory (ANU). Two detectors were placed at 25° and 53° either side of the beam and at a distance of 125 mm from a 100 μgcm^{-2} natural carbon target foil. To reduce the amount of electronics required the strips of each neighbouring pair of detectors were connected electrically, so that signals were taken from each end of the double detector and from the centre where the strips were joined. Thus we required $3 \times 16 \times 2$ channels of electronics. This configuration has proved to be very effective [18] although the resolution of the detectors is reduced if compared to results from independent operation. The signals were processed conventionally using charge sensitive preamps followed by shaping amplifiers and peak sensing ADC's [19].

The details of the data analysis are well described elsewhere [15, 18]. Briefly, a ^{12}C spectrum is reconstructed using energy and momentum conservation from the energies and positions of α hits on each side of the beam. For the coincident events most of our data comes from 5 fold hits, 3 on one side of the beam and 2 on the other. The energy and momentum of the sixth alpha particle can be deduced from the missing momentum and the missing energy calculated using the known Q value for the reaction. Once a ^{12}C excitation spectrum has been reconstructed for each side of the beam gates were placed on the 3_1^- peak in each spectrum. The excitation function was then produced by plotting the number of events detected simply normalised by the beam exposure at each energy. The results are shown in figure 1. The angle integrated yields cover the scattering angle range 45° to 125° in the centre of mass. No efficiency corrections have been applied to these data. It is clear that the cross section for the mutual excitation of the 3_1^- states shows three broad resonant-like structures in the energy region studied. For comparison in figure 1 we also show a Monte-Carlo simulation of the reaction which gives an estimate of the variation in detection efficiency assuming that all decays are isotropic in the centre of mass.

Recently we presented triple angular correlation measurements for the mutual 3_1^-+3_1^- inelastic channel at $E_{c.m.}$ = 32.5 MeV [15]. We suggested a dominant total angular momentum of $J = 18$ or 20 at this energy with a fully aligned configuration i.e. the partial wave in the final channel was $L' = J - 6$. Since the data in ref. [15] were not sufficient to distinguish between a dominant angular momentum of $J = 18$ or 20 we have recently made detailed angular correlation measurements at $E_{c.m.}$ = 32.5 MeV and in addition at energies of $E_{c.m.}$ = 37.5 and 43 MeV using a new detector array with new electronic instrumentation. The new detector array is part of MEGHA recently installed at the ANU by the UK Charissa collaboration [21]. This new facility allows us to mount and individually instrument 10 strip detectors with 320 channels of electronics. The charge sensitive preamps and amplifiers are basically of the same design as used previously but the ADC's have been replaced with custom designed fast voltage to time converters coupled to Lecroy 2277 TDC's [23]. We used 8 detectors which covered laboratory angles from 5° to 60° with an azimuthal range of ~100° on either side of the beam, giving a large efficiency for the detection of high particle multiplicities. This enabled us to use a thin target (10μgcm^{-2}). As a result the resolution obtained in these measurements is significantly improved.

Once the decay products of the two ^{12}C nuclei have been identified the angular correlation analysis proceeds using the Basal coordinate system as described in ref. [15]. The angular correlation depends on five angles, namely the primary scattering angle ϕ_B^* and the two decay angles χ_B and ψ_B of the ^{8}Be-α relative velocity with respect to the beam for each ^{12}C nucleus. We demonstrated in ref. [15] that the semiclassical angular correlation function for mutual decay could be approximated over the measured angular range by

$$W(\phi_B^*, \chi_B, \chi_B', \psi_B, \psi_B') \propto \frac{1}{\sin\phi_B^*} \left| \sum_{L'} a_{L'} \sin\left[\left(L' + \frac{1}{2} \right) \phi_B^* + k\chi_B + k'\chi_B' + \frac{\pi}{4} \right] \right|^2 d_{k0}^{I}(\psi_B)^2 d_{k'0}^{I'}(\psi_B')^2 + \frac{A^2}{\sin\phi_B^*} \quad (1)$$

where ψ_B,$\psi_B' \simeq \pi/2$. Here $a_{L'}$ is the amplitude for a single value of the partial wave in the final channel L' and A^2 is an incoherent background. The projections of the ^{12}C angular momentum on the z-axis, which is perpendicular to the reaction plane, are k and k'. In addition to resonant contributions, we expect contributions to the $^{12}\mathrm{C}(3_1^-)$+$^{12}\mathrm{C}(3_1^-)$ channel from direct mutual inelastic scattering. This direct process will lead to non-zero amplitudes in a number of partial waves and some of these contributions will add incoherently with the resonant amplitude. This is partially accounted for by the $A^2/\sin\phi_B^*$ term in equation 1.

In ref. [15] we showed that by making assumptions about the quantum numbers k and k' we could define a two-dimensional correlation function $W(\phi_B^*, X)$ where $X = \chi_B \pm \chi_B'$ and hence determine the dominant L' and angular momentum $J = L' + k + k'$ from the projections of the "ridge" pattern onto a single axis labelled by ϕ_P^*. In this letter we take a slightly different and more rigorous approach. We have performed a full Monte-Carlo simulation of the reaction. The positions of all the detectors are fed into this simulation along with minimum and maximum energy cuts for each detector. The angular correlation function (Eq. 1) is also fed into this simulation. We then pass these simulated data through our sort code and treat them exactly as we treat the true experimental data. So again we project the simulated angular correlation function onto a two-dimensional plane $W(\phi_B^*, X)$ and a single axis ϕ_P^*. But while in ref. [15] we simply looked for regular structure in the projections of the experimental data to identify the correct assumptions for L',k and k' in this case we first determine the optimum projection angle θ_P which maximises the peak to valley ratio in the one dimensional correlation pattern. (The projection angle $\theta_P = 180° - \mathrm{atan}(\Delta X/\Delta\phi_B^*)$ is defined as the angle between the ϕ_B^* axis and the line given by the gradient of the ridges $\Delta X/\Delta\phi_B^* = (L' + 0.5)/k$ in the correlation [15].) We then directly compare the projected correlation data with the Monte-Carlo predictions using the same projection angle for the simulated correlation matrix.

In figure 2 we show the two-dimensional correlation patterns for the data at $\mathrm{E}_{c.m.} = 37.5$ MeV assuming that $|k| = |k'|$ for $k = k'$ and $k = -k'$. As in ref. [15] we see that ridges result only from the assumption $k = k'$ and we can deduce that $k = 3$; this strongly suggests that the two ^{12}C nuclei are aligned. The correlation function for simulated data, assuming amplitudes $a_{14} = 0.95$

and $a_{16} = 0.32$ for $L' = 14$ and $L' = 16$ respectively and $k = k' = 3$, is also shown in the figure. The simulation reproduces the ridge pattern and data boundary. However, the data show a more complicated angular correlation structure than can be reproduced using only one or two partial waves in our simple model. Some of this is accounted for by the incoherent term A^2, but this is a very crude approximation. One dimensional projections of these data along the ridges are presented in figure 3. The errors in the data and Monte-Carlo projections are purely statistical and generally smaller than the size of the data points. For clarity they are not shown. We also show a comparison of Monte-Carlo calculations for three different consecutive partial waves at each centre of mass energy (figure 3a to 3c). Note that the different partial waves are out of phase away from the centre of the ϕ^*_P range for each energy. In figures 3d to 3f we compare the data with simulations for a coherent sum of two L' values and an incoherent background. The dominant L' values indicated in the figure are consistent with the optimum projection angle θ_P at each energy. We suggest that the dominant total angular momentum at 32.5 MeV is $J = 18$, which is consistent with our previous measurement [15], while the dominant total angular momenta at 37.5 and 43 MeV are suggested to be $J = 20$ and 22 respectively. We have angular correlation data for many other channels and these will be reported elsewhere [24]. Recently Wuosmaa et al. [25] reported an assignment of $J = 18$ at 33.5 MeV for the 0^+_1+3^-_1 channel. We also suggest a dominant total angular momentum of $J = 18$ and $L' = 15$ at 32.5 MeV in this channel. However, for the 0^+_2+3^-_1 channel we suggest a dominant total angular momentum of $J = 16$ and final partial wave $L' = 13$.

We now return to the interpretation of these results. We first assume that the spins of the resonances are equal to the dominant J value suggested by the angular correlations. The J values are then consistent with a rotational band with angular momenta up to $J = 22$. We assume that the direct components may also include non-aligned L' values although we have already noted that the angular correlations are dominated by the aligned partial wave. This is also true of the Cormier resonances whose alignment has been measured using gamma-ray angular correlations [26]. However, although this might indicate some alignment inside the angular momentum barrier, it may simply reflect the fact that the aligned barrier with $L' = J - 6$ is always the lowest barrier for any J value and thus we would expect the transmission factors to be much larger for this partial wave so that this may dominate any bias in the reduced widths themselves. Inside the barrier there are two limits of interest. The strong coupling limit applies to the Bloch-Brink α cluster model or the weak coupling limit typical of the Band Crossing Model(BCM) [27].

In the strong coupling limit, inside the barrier the F1 alpha cluster model configuration is triaxial. Zhang [28] has performed angular momentum projected calculations for this configuration which give rise to a number of bands with different K values. For the lowest values of K, these bands are nearly degenerate (see figure 4). Despite this Zhang estimates that K mixing is quite small. Outside the barrier K is not a good quantum number and these strongly coupled configurations will have non zero reduced widths for several final state partial waves L', but as we discussed above the lowest partial wave will almost certainly dominate the total width. In Zhang's calculations K is the projection of the total spin along the longest axis of the system and this is parallel to the line joining the centres of the two ^{12}C nuclei. In this picture K must be less than or equal to the sum of the spins of the two nuclei, thus for the single excitation of one nucleus to the 2_1^+ state $K \leq 2$. The $K = 5$ and 6 bands can only be observed in the 3_1^-+3_1^- channel. In figure 4 we plot the centroids of the experimental resonances using our suggested J values where the error bars represent an estimate of the widths of the experimental gross structures.

In the weak coupling picture each gross peak is a combination of resonances in two or more channels [27]. Recently we have attempted coupled channels calculations with deep potentials derived from a folding model [22, 29]. Although we can obtain good agreement between theory and data for parameters such as the energies of the resonances and their widths the coupling potentials are very strong and without modification the results do not agree with the BCM calculations of ref. [27].

Unfortunately there are no detailed predictions of the energies and widths of the resonances in the ^{12}C(3_1^-)+^{12}C(3_1^-) channel for either the BCM or the Bloch-Brink model. Both models can accommodate the possibility of multiple resonances within each broad structure and we believe that both models will predict similar alignments. A challenge to the BCM is the observation of resonances in the ^{16}O+^{8}Be channel [22, 24] at the same energies as those in the ^{12}C(3_1^-)+^{12}C(3_1^-) channel. These resonances would fit naturally into any detailed alpha cluster model predictions.

In conclusion we have observed high spin resonances in ^{12}C+^{12}C scattering in the mutual 3_1^- channel. Assuming these resonances dominate the angular correlations at the centre of each peak in the excitation function we suggest that they have angular momenta up to $J = 22$. We believe that these resonances extend the sequence of broad resonances first observed by Cormier et al. [3]. A comparison of resonance energies and the suggested spins with theoretical calculations support this view. Above $J = 16$ we argue that the ^{12}C+^{12}C system should be much simpler to interpret since these high angular momenta cannot be supported by a ^{24}Mg nucleus of normal deformation. As a result the level density is much lower and the absorptive potential in this region should be weak aiding the observation of these resonances, the only significant absorption being due to other direct reaction channels.

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References

[1] E. Almqvist, D.A. Bromley and J.A. Keuhner, Phys. Rev. Lett. 4 (1960) 515.
[2] K.A. Erb and D.A. Bromley, Treatise on Heavy Ion Science (Plenum, New York, 1984), Vol. 3, p. 201.
[3] T.M. Cormier et al., Phys. Rev. Lett. 40 (1978) 924 and 38 (1977) 940.
[4] B.R. Fulton, T.M. Cormier and B.J. Herman, Phys. Rev. C 21 (1980) 198 .
[5] W.D.M. Rae, P.R. Keeling and S.C. Allcock, Phys Lett 184B (1987) 133.
[6] W.D.M. Rae, P.R. Keeling and A.E. Smith, Phys Lett 198B (1987) 49.
[7] K.A. Erb et al., Phys. Rev. C 22 (1980) 507.
[8] R.R. Betts and W.D.M. Rae, in Proceedings of the Int. Nucl. Phys. Conf., Harrogate U.K., 1986 (IOP Publishing Ltd, Bristol 1987).
[9] S. Marsh and W.D.M. Rae, Phys. Lett. 180B (1986) 185 .
[10] G. Leander and S.E. Larsson, Nucl. Phys. A239 (1975) 93.
[11] H. Flocard, P.H. Heenen, S.J. Kreiger and M.S. Weiss, Prog. Theor. Phys. 72 (1984) 1000.
[12] A.H. Wuosmaa et al., Phys. Rev. Lett. 68 (1992) 1295.
[13] Y. Sugiyama et al., Phys. Lett 159B (1985) 90.
[14] O. Tanimura, R. Wolf and U.Mosel, Phys. Lett. 120B (1983) 275 and 128B (1983) 375.
[15] S.P.G. Chappell and W.D.M. Rae, Phys. Rev. C 53 (1996) 2879.
[16] N.J. Davis et al., Nucl. Inst. and Methods A330 (1993) 165.
[17] A.H. Wuosmaa, R.R. Betts, M. Freer and B.R. Fulton, Annu. Rev. Nucl. Part. Sci. 45 (1995) 89.
[18] S.P.G. Chappell et al., Phys. Rev. C 51 (1995) 695.
[19] N. Curtis et al., Nucl. Inst. and Methods A351 (1994) 359.
[20] S.P.G. Chappell, W.D.M. Rae and P.M. Simmons, Nucl. Inst. and Methods A396 (1997) 383.
[21] R.L. Cowin, S.P.G. Chappell, D.L. Watson, N.M. Clarke, M. Freer, B.R. Fulton, G.K. Dillon, W.D.M. Rae, R.A. Cunningham, J. Lilley, C.D. Jones and P. Lee, to be published in Nucl. Inst. and Methods A.
[22] W.D.M. Rae, S.P.G. Chappell and P.Fry, Nuovo Cimento 110A (1997) 1001.
[23] R.A. Hunt et al., to be published.
[24] S.P.G. Chappell et al., to be published.
[25] A.H. Wuosmaa et al., Phys. Rev. C 54 (1996) 2463.
[26] D. Konnerth et al., Phys. Rev. Lett. 55 (1985) 588.

[27] Y. Kondo, Y. Abe and T. Matsuse, Phys. Rev. C 19 (1979) 1356.
[28] J. Zhang, D.Phil thesis, University of Oxford (unpublished).
[29] P. Fry, D.Phil thesis, University of Oxford (unpublished).
[30] J. Zhang and W.D.M. Rae, Nucl. Phys. A564 (1993) 252.

Figure Captions

Fig. 1. Experimental excitation functions for the $^{12}C^*(3^-_1)$+$^{12}C^*(3^-_1)$ channel. Also shown is a Monte-Carlo calculation of the detection efficiency as a function of $E_{c.m.}$.

Fig. 2. Experimental angular correlations $W(\phi^*_B, X)$ at $E_{c.m.} = 37.5$ MeV assuming $|k| = |k'|$ and (a) $k = -k'$ or (b) $k = k'$. (c) Monte-Carlo simulation for $a_{14} = 0.95$, $a_{16} = 0.32$ and $k = k' = 3$ (without the incoherent background).

Fig. 3. Comparisons of measured and simulated angular correlations projected onto a single axis using the optimum projection angle θ_P indicated at each of the three centre of mass energies. (a–c) Simulation for three consecutive L' values and no incoherent background. (d–f) Simulation including a coherent contribution of two partial waves and an incoherent background. (The background is shown as the dotted curves in the figures scaled by a factor of 0.5 for clarity). (d) $E_{c.m.} = 32.5$ MeV with $a_{12} = 0.92$, $a_{14} = -0.39$ (e) $E_{c.m.} = 37.5$ MeV with $a_{14} = 0.95$, $a_{16} = 0.32$ (f) $E_{c.m.} = 43.0$ MeV with $a_{16} = 0.98$, $a_{18} = -0.22$. The projection angles $\theta_P = 103°, 101.5°$ and $100.5°$ yield $L' = 12.5, 14.2$ and 15.7 respectively which is consistent with our assignments.

Fig. 4. Angular momentum projected α-cluster model calculations for the F1 configuration in ^{24}Mg [28] and the resonances in the present data and those of Cormier [3, 5, 6, 13, 14] assuming our suggested J values.