Termination of the $^{12}\text{C}(^{12}\text{C},^{12}\text{C}[3^-])^{12}\text{C}[3^-]$ band of resonances.

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Abstract

New experimental data for the $^{12}\text{C}+^{12}\text{C}$ reaction have been measured in the centre-of-mass energy range $E_{\text{c.m.}} = 40$ to $60$ MeV. Excitation functions for a number of single and mutual $^{12}\text{C}$ inelastic channels have been measured which include the $0_{gs}$, $2^+_1$, $0^+_2$, $3^-_1$, and $4^+_1$ $^{12}\text{C}$ states. All of the reactions display largely unstructured excitation functions over this energy range. The absence of further resonances in this energy region for the $^{12}\text{C}(^{12}\text{C},^{12}\text{C}[3^-])^{12}\text{C}[3^-]$ reaction confirms theoretical predictions of the termination of the band of resonances found at lower centre-of-mass energies in this channel.

Key words: Nuclear reactions; $^{12}\text{C}(^{12}\text{C},6\alpha)$; E=40-60 MeV; excitation functions; resonances; band termination.

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Heavy-ion resonance reactions have been studied extensively over the past few decades. In particular the $^{12}\text{C}+^{12}\text{C}$ reaction has drawn significant interest. A large number of resonances have been found in, for example, inelastic reactions including the population of the $2^+_1$, $0^+_2$, $3^-_1$, and $4^+_1$ $^{12}\text{C}$ states \cite{1, 2, 3, 4, 5, 6, 7, 8, 9}. One particular theoretical picture which has been used to provide an understanding of the resonances is one in which the resonances correspond to a molecular band. Structure models such as the Alpha Cluster Model (ACM) \cite{10}, Hartree-Fock (HF) calculations \cite{11} and Nilsson-Strutinsky
(NS) calculations \[12, 13\] predict a number of rotational bands whose energy-spin characteristics may be tested against experimental data. A particularly prominent set of resonances have been observed in the $^{12}\text{C}(2^+)+^{12}\text{C}(2^+)$ inelastic channel by Cormier et al. \[1, 2\], the energy-spin systematics of these resonances \[14, 15, 16, 17\] agree with that predicted by both the HF \[11\], ACM \[10, 18\] and cranked NS \[13\] calculations for the so called F1 configuration. In the ACM this structure corresponds to a triaxial arrangement of six alpha-particles, which resembles two touching equilateral triangles. Such a structure has a large overlap with two oblate $^{12}\text{C}$ nuclei with their deformation axes aligned. Spin alignment measurements \[19\] of the Cormier resonances are also consistent with the picture of two touching $^{12}\text{C}$ nuclei orientated as in the F1 configuration. The HF calculations predict that the F1 band should terminate at a spin of 20 $\hbar$ and the most recent ACM calculations suggest a terminating spin of 24 $\hbar$ \[8, 18\]. The cranked NS calculations \[13\] do not provide a prediction for the termination of the band. More recent measurements by Chappell et al. \[8\] of the $^{12}\text{C}(3^-)+^{12}\text{C}(3^-)$ inelastic scattering reaction shows evidence for the continuation of the band of Cormier resonances up to $E_{c.m.} = 43.0$ MeV ($E_x(^{24}\text{Mg}) = 57$ MeV) and a spin of 22 $\hbar$, very close to the predicted termination of the F1 band.

The present paper presents a study of inelastic $^{12}\text{C}+^{12}\text{C}$ scattering to states in which the $^{12}\text{C}$ nuclei are unbound to $\alpha$-decay (including the $^{12}\text{C}(3^-)+^{12}\text{C}(3^-)$ final state) in the centre-of-mass energy region $E_{c.m.} = 40$ to 60 MeV extending to higher energies than probed in earlier studies. These measurements provide the first experimental evidence for the termination of the band of resonances observed in the $^{12}\text{C}(3^-)+^{12}\text{C}(3^-)$ channel at a spin of 22 $\hbar$, intermediate between the predictions of the ACM and HF calculations.

The search for this band termination was performed at the Australian National University (ANU). An experiment was conducted using the new Charissa strip detector array located in the MEGHA chamber \[20, 21\]. The array was composed of eight 500 µm, 50×50 mm$^2$ Si strip detectors \[22\]. These covered an angular range of $\theta_{lab} = 5$ to 60°, and an azimuthal angular range $\Delta \phi \approx 100$ degrees each side of the beam axis. Each strip detector was divided into 16 position-sensitive strips, providing very high segmentation, and the possibility of measuring emission angles and thus momenta with the high precision required for the reconstruction of the reaction kinematics. $^{12}\text{C}$ beams of 50 enA intensity ranging from $E_{beam} = 80$ to 120 MeV were incident upon a 60 µg cm$^{-2}$ $^{12}\text{C}$ foil target, producing a data event rate of 5 kHz. The target thickness was found to increase by 25% during the run which was corrected for in the analysis of the reaction yields. The higher energies were obtained using the linear accelerator in conjunction with the pelletron tandem 14UD accelerator \[23, 24\]. Due to the high beam energies used and the limited detector thickness, events involving $\alpha$-particles with an energy in excess of $\sim 31$ MeV, experience punch-through (i.e. the particles did not stop in the silicon detectors) and thus only
a fraction of the $\alpha$-particle energy is deposited in the detector. A Monte-Carlo simulation of the reaction and detection process indicated that only 4.8% of events at the highest beam energy (120 MeV) experience punch-through for the mutual $^{12}$C$(3^{-\uparrow})$ channel. This fraction is much higher for the other dominant channels, and particularly for those involving the $^{12}$C$(4^{+\uparrow})$ state. Such processes do contribute to the overall background levels observed at the higher energies. However, the reconstruction methods employed in the analysis were able to clearly distinguish the punch-through events, suppressing this contribution to the background.

The experimental trigger requirement was a total strip multiplicity of greater than 3, this implies that the measurement is only sensitive to inelastic channels in which one of the $^{12}$C nuclei was excited into an $\alpha$-unbound state. Since the $\alpha$-decay of $^{12}$C feeds states in $^8$Be, all of which are unbound to $\alpha$-decay a three-$\alpha$ final state results. Such a decay process occurs for all but the $^{12}$C ground state and 4.4 MeV $(2^{+\uparrow})$ states. Thus, for inelastic channels involving a $^{12}$C nucleus in one of these bound states and the other $^{12}$C in an unbound state the final multiplicity will be 4. If, however, both $^{12}$C nuclei are excited to $\alpha$-decaying states then the final state multiplicity is then 6. The detection of only 5 of the 6 final state particles is sufficient to fully reconstruct the reaction kinematics. Further details of the reconstruction techniques can be found in [7, 8, 25, 26, 27, 28]. The $\alpha$-decay process is such that the three $\alpha$-particles are emitted into a cone with an opening angle which is small compared with the detector geometry. Thus if three hits are observed on one side of the beam axis there is a large probability that they arise from the decay of $^{12}$C. It should be noted that there was no explicit particle identification in these measurements, however the reaction kinematics may in fact be used to identify uniquely reaction products and decay channels. For example, the reconstruction of the excitation energy of the parent $^{12}$C nuclei from the momenta of the three $\alpha$-particles should identify which state was excited in the reaction process. Such a spectrum is plotted in Figure 1 for a final state consisting of 6 $\alpha$-particles, where the excitation energy for both $^{12}$C nuclei produced in the collision are reconstructed. The two dimensional spectrum reveals the mutual excitations of the $^{12}$C nuclei, and the excitation energies of the states are indicated on the projections. The dominant states in these spectra are the $0^{+\uparrow}$(7.6542 MeV), $3^{-\downarrow}$(9.641 MeV), $4^{+\downarrow}$(14.083 MeV) states. It is also possible to reconstruct the decay path for the $^{12}$C $\alpha$-decay, i.e. via the $^8$Be ground state or $^8$Be 3.04 MeV $(2^{+\uparrow})$ state. Also shown in Figure 1 is the decomposition of the excitation spectrum between these possible decay branches. As expected, the decay of the $4^{+\downarrow}$ state proceeds predominantly via the $^8$Be excited state, whilst the decay of the $0^{+\uparrow}$ state feeds the $^8$Be ground state. By placing two dimensional gates on the spectrum in Figure 1 it is possible isolate the various mutual excitations, and thus to extract the energy dependence of the various reaction yields.

The excitation function for the mutual $^{12}$C$(3^{-\downarrow})$ excitation is shown in Figure
2, with a direct comparison with the previous data of Chappell et al. The data of Chappell et al. were not normalised for target thickness nor detector efficiency, but only integrated beam current. Hence the results presented here have been normalised to the $E_{c.m.} = 42$ MeV data point of their measurements for a comparison of the structure. Note also that the two experiments do not cover exactly the same centre-of-mass angular range. Also the present data do not extend low enough in energy to clearly observe the decrease in cross section below the $E_{c.m.} = 43$ MeV resonance. It is clear that no further resonances are observed in this extended energy range, but only a smooth attenuation of the reaction yield. Also shown in Figure 2 are the detection efficiencies calculated with Monte Carlo simulations. These calculations show that the detection efficiency increases with increasing centre-of-mass energy, and thus the decrease in the reaction yield cannot be explained by decreasing acceptances. Thus, we believe that this result shows the termination of the mutual $3^{-}_1$ band of resonances and thus the highest spin member of the band is $J = 22\hbar$ at $(E_x(^{24}\text{Mg}) = 57$ MeV).

Figures 3 and 4 show the excitation functions for the various reaction channels which have been observed in the present measurement. These figures show the experimental cross sections deduced from the normalization to the integrated beam current, and from calculations of the detection efficiency evaluated as a function of the centre-of-mass energy. We note that the cross sections calculated here are in good agreement with earlier measurements, and that in all instances the statistical errors are smaller than the data symbols. In Figures 3a and 3b we observe $^{12}\text{C}$ single and mutual excitations respectively, involving the $0^+_{2}, 3^{-}_{1}$ and the $4^+_{1}$ channels. It is clear that none of the channels involving the $0^+_{2}, 3^{-}_{1}$ and $4^+_{1}$ states possess the type of resonant structure that is present at lower energies in the $^{12}\text{C}(3^{-}_{1}) + ^{12}\text{C}(3^{-}_{1})$ channel. The $^{12}\text{C}_{gs} + ^{12}\text{C}^*$ reactions generally show a steady decrease in strength with increasing energy. The increase in yield as the energy decreases towards $E_{c.m.} = 44$ MeV is consistent with earlier measurements of these reactions where a resonance was observed in the $^{12}\text{C}_{gs} + ^{12}\text{C}(3^{-}_{1})$ and $^{12}\text{C}_{gs} + ^{12}\text{C}(0^+_{2})$ reactions at $E_{c.m.} = 41$ MeV. There is perhaps some evidence for a small enhancement in the cross section in the $^{12}\text{C}_{gs} + ^{12}\text{C}(4^+_{1})$ reaction close to $E_{c.m.} = 44$ MeV. Enhancements are also observed in the $^{12}\text{C}(3^{-}_{1}) + ^{12}\text{C}(3^{-}_{1})$ and $^{12}\text{C}(4^+_{1}) + ^{12}\text{C}(4^+_{1})$ mutual excitations, shown in Figure 3b, at the same energy. This is close to the large peak previously observed in the $^{12}\text{C}(3^{-}_{1}) + ^{12}\text{C}(3^{-}_{1})$ reaction at $E_{c.m.} = 43$ MeV.

Figures 4a and 4b present the remaining mutual channels which have significant yield in this energy range. Again although broad structures are present, there is no evidence that strong resonances have been observed. There is some indication of enhancements at $E_{c.m.} = 44$ MeV in the $^{12}\text{C}(2^+_{1}) + ^{12}\text{C}(3^{-}_{1})$, $^{12}\text{C}(4^+_{1}) + ^{12}\text{C}(3^{-}_{1})$, $^{12}\text{C}(0^+_{2}) + ^{12}\text{C}(3^{-}_{1})$ and $^{12}\text{C}(0^+_{2}) + ^{12}\text{C}(4^+_{1})$ reactions, and the $^{12}\text{C}(3^{-}_{1}) + ^{12}\text{C}(4^+_{1})$ channel shows weak evidence for a further structure at $E_{c.m.} = 46$ MeV. But, in general all of the reaction channels demonstrate a rather smooth en-
ergy dependence over the measured energy range. It is clear that over the centre-of-mass energy range $E_{c.m.}=40$ to 60 MeV that the inelastic reactions involving the population of α-particle unbound states are dominated by those which include the excitation of the 14.083 MeV (4+) state. Thus, coupled channel calculations which attempt to reproduce the energy dependence of the inelastic scattering over this energy region must include the coupling to this state. For example, a number of coupled channel studies of the energy dependence of the inelastic channels have been performed [30, 31, 32] which do not include such couplings.

We have presented data showing the termination of the mutual $^{12}$C(3−) band of resonances as predicted by the cranked Bloch-Brink α-cluster model of Marsh and Rae [10]. This would confirm the predictions that the $2^+ + 2^+$ and $3^- + 3^-$ resonances are associated with the triaxial F1 configuration in $^{24}$Mg. The observation that the band terminates at a spin of 22 $\hbar$, intermediate between the ACM and HF calculations should allow these models to be further refined. We have also presented excitation functions for the dominant single and mutual $^{12}$C reaction channels in this energy range. On the whole these reactions appear to possess a smooth energy dependence, and lack of distinct structures in the excitation functions indicates that resonant processes are not dominant over the energy range $E_{c.m.}=40$ to 60 MeV. These measurements indicate that over this energy range that reactions involving the population of the 14.083 MeV (4+) state dominate over other inelastic scattering reactions involving the population of states above the $^{12}$C α-decay threshold.

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Figure Captions

Fig. 1. The reconstructed $^{12}\text{C}$ excitation energies for six fold $^{12}\text{C}^*^{12}\text{C}^*$ events at 120 MeV. The one dimensional projections indicate excitation energies of the states observed in the reaction. The strength of the decay of each state via either the $^8\text{Be}$ ground state or first excited state is indicated by the ancillary lines on the one dimensional spectra. Also indicated on the two dimensional spectrum are the gates used to filter the data for angular correlation and cross-section measurements to be performed (horizontal and vertical dotted lines).

Fig. 2. Experimental excitation functions for the $^{12}\text{C}^{(12}\text{C},^{12}\text{C}[3^-])^{12}\text{C}[3^-]$ channel. Results are shown for a comparison with the previous data of Chappell [8] with the present data. Also indicated are the Monte Carlo simulation for the detection efficiencies for each of the experimental data sets. Note that the present data have been normalised to the $E_{c.m.}=43$ MeV data point of the previous measurement [8].

Fig. 3. Experimental excitation function for the (a) $^{12}\text{C}^{(12}\text{C},^{12}\text{C}[0^+],3^-],4^+]^{12}\text{C}(\text{g.s.})$ reactions, and (b) for the mutual $^{12}\text{C}(0^+, 3^-, \text{and } 4^+)$ reactions.

Fig. 4. Experimental excitation function for the observed channels in the $^{12}\text{C}(2^+)+^{12}\text{C}^*$ reactions, and (b) the $^{12}\text{C}(0^+)+^{12}\text{C}(3^-)$, $^{12}\text{C}(0^+)+^{12}\text{C}(4^+)$ and $^{12}\text{C}(3^-)+^{12}\text{C}(4^+)$ reactions.
\( \sigma \text{(mb)} \)

\( 12^C(12^C, 12^C^*) 12^C_{gs} \)

\( 0^+ \times 10 \)

\( 4^+ \)

\( 3^- \)

\( \sigma \text{(mb)} \)

\( 12^C(12^C, 12^C^*) 12^C^* \)

\( 4^+ 4^+ \)

\( 0^+ 0^+ \times 500 \)

\( 3^- 3^- \)

\( E_{\text{c.m.}} \text{ [MeV]} \)
\( ^{12}\text{C}(^{12}\text{C},^{12}\text{C}^{*})^{12}\text{C}[2^+] \)

\( ^{12}\text{C}(^{12}\text{C},^{12}\text{C}^{*})^{12}\text{C}^{*} \)

\( ^{12}\text{C}(^{12}\text{C},^{12}\text{C}^{*})^{12}\text{C}^{*} + 2 \)

\( ^{12}\text{C}(^{12}\text{C},^{12}\text{C}^{*})^{12}\text{C}^{*} + 3 \times 10 \)

\( ^{12}\text{C}(^{12}\text{C},^{12}\text{C}^{*})^{12}\text{C}^{*} + 4 \times 10 \)

\( ^{12}\text{C}(^{12}\text{C},^{12}\text{C}^{*})^{12}\text{C}^{*} + 5 \times 10 \)
Normalised Yield ($10^4$ C$^{-1}$)

$E_{c.m.}$ [MeV]

Efficiency (%)