New excitation function measurement for $^{12}C+^{12}C$ inelastic scattering to α-unbound reaction channels

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13^{th} May 1997

Abstract

Excitation functions have been measured for several ^{12}C(^{12}C,^{12}C$^{*}\rightarrow 3\alpha$)^{12}C* reactions at centre-of-mass energies in the range $E_{c.m.}$ = 31 to 45 MeV. New resonant structures are observed near $E_{c.m.}$= 37.5 and 43.0 MeV in the ^{12}C(3_1^-)+^{12}C(3_1^-) channel. These new resonances correlate with pronounced structure in the angle integrated cross-section of several other ^{12}C+^{12}C inelastic channels which do not lead to a 6α final state. These results are considered in the context of a simple α-cluster model of ^{12}C.

PACS number(s): 25.70.Ef, 21.60.Gx, 27.30.+t, 27.20.+n

Key words: NUCLEAR REACTIONS, ^{12}C(^{12}C,^{12}C$^{*}\rightarrow 3\alpha$)^{12}C*, E=31-45 MeV, measured excitation functions, observed light heavy-ion resonances.

1 Introduction

The use of new segmented silicon strip detectors [1] has enabled the study of reactions leading to multi-particle final states. The ^{12}C+^{12}C system was one of the first to be studied using these detectors and new resonant behaviour has been discovered near $E_{c.m.} = 32-33$ MeV for scattering to ^{12}C(0_2^+)+^{12}C(0_2^+) and a 6α-particle final state [2]. In recent measurements in the same energy region, further resonant structures have been reported in the ^{12}C(0_2^+)+^{12}C(0_3^+), ^{12}C(0_2^+)+^{12}C(3_1^-), ^{12}C(3_1^-)+^{12}C(3_1^-) and ^{16}O(0_1^+)+^{8}Be(0_1^+) exit channels [3, 4, 5, 6, 7]. Several years ago Fulton *et al.* [8] also measured enhancements in the cross section for scattering to ^{12}C(0_1^+)+^{12}C(3_1^-) near $E_{c.m.} \sim 33$ MeV using more conventional techniques. These observations represent just a few of the many resonances recorded across a wide energy range in the ^{12}C+^{12}C system over the last three decades [9]. However, the new resonance reported by Wuosmaa *et al.* [2] has proved particularly difficult to interpret using conventional reaction models and has stimulated the proposal of a number of controversial explanations. The first observation of this resonance in scattering to ^{12}C(0_2^+)+^{12}C(0_2^+) [2] at $E_{c.m.} = 32.5$ MeV suggested an association with a 6α-chain state in ^{24}Mg near $E_x = 50$ MeV, as predicted by the cranked α-cluster model [10]. The strong increase in reaction cross-section observed at 90° in the centre-of-mass was explained by the new concept of an approximate-shape eigenstate [11, 12]. The subsequent observations of resonances near the same energy in other channels [3, 4, 5, 6, 7] are difficult to explain in terms of these hypotheses. Indeed, the simple band crossing model of Hirabayashi *et al.* [13] demonstrates that the resonances in the ^{12}C*+^{12}C* channels could also be described without requiring such an exotic intermediate state.

Rae, Fry and Merchant have recently suggested that the resonances involving the 3_1^- state in ^{12}C may result from the scattering of ^{12}C nuclei (which have threefold α-cluster symmetry) with aligned intrinsic spins [14]. The angular correlation analyses of the ^{12}C(3_1^-)+^{12}C(0_2^+,3_1^-) channels at $E_{c.m.}$ = 32.5 MeV by Chappell and Rae [15] and the ^{12}C(0_1^+)+^{12}C(3_1^-) channel at $E_{c.m.}$ = 27 MeV by Davis *et al.* [16] reveal spin alignments which are consistent with this interpretation. In a semi-classical model [14], the cross-section enhancements are a result of resonances dominated by a 3α+3α molecular configuration in the ^{12}C(3_1^-)+^{12}C(3_1^-) channel where the spins of the two ^{12}C nuclei lie perpendicular to the plane of the α's and are parallel to L', the orbital angular momentum in the final channel. This is analogous to the accepted description of the resonances discovered by Cormier *et al.* [17] involving the 4.43 MeV 2_1^+ state in ^{12}C [14, 18, 19]. In this latter case the resonances have been described in terms of a ^{12}C+^{12}C configuration where the spins of the two ^{12}C nuclei must lie in the plane of the three α particles in each ^{12}C [14]. If this interpretation of the $E_{c.m.}$ = 32.5 MeV resonances in the 3_1^-+3_1^- channel is correct we may expect to find a band of resonances in the mutually excited 3_1^- channel at centre-of-mass energies corresponding to the excitation of different values of the orbital angular momentum L', analogous to the observations of Cormier *et al.* [17].

Here, we report on measurements of the scattering of ^{12}C+^{12}C to states above the α-decay threshold across centre-of-mass energies in the range $E_{c.m.}$ = 31 to 45 MeV. Two new resonances are observed in the ^{12}C(3_1^-)+^{12}C(3_1^-) channel. These are correlated with pronounced structure in the angle integrated cross section of several ^{12}C*+^{12}C* final states.

We attempt to make spin assignments but the present data do not provide definitive results. However, the results are compatible with a rotational band hypothesis.

2 Experimental Details

The data were recorded using ^{12}C beams provided by the 14UD tandem Van de Graaff accelerator at the Australian National University. The beams were accelerated over selected laboratory energies in the range 62–90 MeV onto a self-supporting natural carbon target foil of aerial density 100 μg cm $^{-2}$. Multiple particle exit channels were measured using an array of four 25 cm^2 500 μm thick position sensitive strip detectors (PSSD's), each segmented into sixteen 5 cm (long) by 3 mm (wide) strips. The PSSD's were arranged with centres 125 mm from the target at $+25°$, $+53°$, $-25°$, and $-53°$ in the horizontal plane relative to the beam direction and with the position sensitive strips oriented horizontally. PSSD's of the type used generate 32 data channels, one for each end of the sixteen strips. However, the maximum number of analogue-to-digital converters (ADC's) available for the experiment was limited to 96. In order to reduce the number of ADC channels required, the detectors were operated in two pairs using a novel "doubled" configuration [3] whereby the adjacent strip end contacts between each of the two detector pairs were connected electrically. Charge created at either of these ends passed to the same preamplifier-amplifier-ADC combination from which timing information was also generated. Particle hits could be assigned to the correct detector by examining the ratio of signals from the two uncoupled ends. Thus, the detector system consisted of 32 independent elements, 16 on either side of the beam direction, and in principle allowed for the simultaneous measurement of energy, position and arrival time for up to 32 particles, providing no two particles struck the same or adjacent "doubled" strips. The response of the detector array was calibrated using low energy elastic scattering of a ^{12}C beam (E_{lab} = 30 MeV) from 5 μg cm^{-2} ^{197}Au (on a 10 μg cm^{-2} natural carbon backing) and 100 μg cm^{-2} ^{27}Al targets. The method is described in ref. [20].

No explicit particle identification was used in these measurements since the overdetermination of reaction kinematics was sufficient to allow reconstructions in terms of hit multiplicities with a low degree of background contamination. This system allowed the scattering to channels above the multiple α-decay threshold to be studied. Only those events were recorded during the experiment for which a minimum of four coincidences were detected with at least three hits in one of the PSSD pairs. These four, five and sixfold particle hit data were then subjected to a detailed analysis. For example, each hit in a sixfold event could be unambiguously assigned to an α particle on measurement of a total reaction Q value $\simeq -14.6$ MeV (Fig. 1). Similarly, the undetected α particle in fivefold coincidences could be reconstructed from the missing momentum and the 6α final state studied.

The simultaneous detection of a "jet" of 3α particles is characteristic of the scattering to ^{12}C* above the α decay threshold (7.37 MeV). The direct breakup of the two states in ^{12}C of interest here, namely the 7.65 MeV 0_2^+ and the 9.63 MeV 3_1^-, to 3α particles is negligible [21]. Hence we consider only those 3α events correlated as ^{8}Be(0_1^+)+α to originate from a ^{12}C nucleus. Typical excitation energy spectra reconstructed from the momenta and energies of the detected alpha particles in ^{8}Be$\rightarrow 2\alpha$ and ^{12}C$^*\rightarrow^8$Be$(0_1^+)+\alpha$ events are shown in figure 2. The large angular coverage provided by the paired PSSD's gives a greater efficiency for detecting ^{12}C$(3_1^-)\rightarrow 3\alpha$ decays than reported in previous measurements [2, 3].

In fourfold coincidences, grouped as $3\alpha + 1$ hits, the single hit corresponds to either an α-particle or a ^{12}C nucleus below the breakup threshold. We select the ^{12}C(>7.37 MeV)+^{12}C(<7.37 MeV) events and reduce the ^{12}C(>7.37 MeV)+α background by requiring that the two body Q values for scattering to ^{12}C* on either side of the beam direction agree to within 500 keV. The range of ^{12}C+^{12}C inelastic scattering channels identified in the present data is shown in figure 3.

3 Results

Angle integrated cross sections have been extracted from data of the type illustrated in figure 3 at each centre-of-mass energy ($E_{c.m.}$) sampled. The excitation functions are presented in figures 4 and 5 for the 3α+3α and 3α+1 hit events, respectively. The data have been normalized to beam exposure (q_c) including corrections for deadtime in the data acquisition system such that Yield = Counts/q_c in units of 10^4 C^{-1}. The estimated laboratory cross-section is also shown in figures 4 and 5. However, in these measurements, laboratory cross sections are not of significant help in deciding what the true reaction cross sections are to the different excited states. Since we are dealing with a many particle final state it is not practical to bin the data into a multi-dimensional differential cross-section. Instead the variation of detector "efficiency" with centre-of-mass energy and scattering channel has been modelled using a simple Monte Carlo technique. The method assumes that the primary scattering and subsequent decays in the reaction are isotropic in the centre-of-mass. This is unrealistic but the only possible simple assumption. The simulation incorporates the rejection of events where the final state particle energies lie below the detection threshold (which is position dependent for the PSSD's used). Multiple hits in the same PSSD strip were also vetoed when performing the calculations. These gross assumptions do not allow an absolute value for the detection efficiency to be determined. Clearly, the primary scattering distribution is dependent upon reaction mechanism and the subsequent breakup for states with spin is not isotropic. However, the percentage "efficiencies" calculated in this way can be compared between different channels and centre-of-mass energies in order to give some measure of the detection "efficiency" effects in the data. The results of these relative "efficiency" simulations are shown in figure 6. In all cases the detection "efficiency" varies smoothly with $E_{c.m.}$. It is clear that the reconstruction of scattering channels from sixfold data is considerably less efficient than for the fourfold data. Similarly it is clear that the detection "efficiency" for the 3_1^- state in ^{12}C is much smaller than that for the 0_2^+ state.

The resonant behaviour of the observed cross sections near 32.5 MeV in the 0_2^++0_2^+ and 0_2^++3_1^- channels (fig. 4) is consistent with previously reported measurements in this energy region [2, 3]. Interestingly, we detect more events in the 3_1^-+3_1^- channel than in the 0_2^++0_2^+ or 0_2^++3_1^- eventhough it is by far the most difficult channel to detect with the lowest "efficiency" for 3α+3α events. A large increase in yield for scattering to this channel is also observed near $E_{c.m.} = 37.5$ and 43.0 MeV. The scattering to the $0_2^+ + 0_2^+$ and $0_2^+ + 3_1^-$ final states in this new energy range is rather weak by comparison.

Crude estimates of the relative partial decay probabilities have been calculated for the three resonant energies of interest. The probability for decay to channel A relative to channel B is given approximately by

$$\frac{N_A}{N_B} \simeq \frac{\mathrm{Yield_A}}{\mathrm{Yield_B}} \frac{\mathrm{Efficiency_B}}{\mathrm{Efficiency_A}} \tag{1}$$

where the yield in each scattering channel is normalized by the detection "efficiency". The uncertainty here is due to the assumptions made in the "efficiency" calculation for the primary and breakup angular distributions. The crude partial decay probabilities are shown relative to the $0_2^+ + 0_2^+$ channel in Table 1, from which all other combinations can be extracted. Although the $0_2^+ + 0_2^+$ and $0_2^+ + 3_1^-$ channels (fig. 4) do not show much resonant behaviour except at $E_{c.m.} \simeq 32.5$ MeV, the 3α+1 events (fig. 5) do show correlated enhancements with the resonances in the $3_1^- + 3_1^-$ channel. Note that the estimated relative yield in the $3_1^- + 3_1^-$ channel is approximately equal to that in the $0_1^+ + 3_1^-$ channel at $E_{c.m.} =$ 37.5 and 43.0 MeV.

We have performed a simple angular correlation analysis in Basel co-ordinates on the $3_1^- + 3_1^-$ channel at $E_{c.m.} = 37.5$ MeV. The co-ordinate system and method are described in ref. [15]. Briefly, the semiclassical angular correlation function for mutual excitation and decay may be written as

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

where L' is the final state orbital angular momentum. k and k' are the projections of ejectile and recoil spin (I) on the axis perpendicular to the plane of the primary scattering. We can examine projections of the three-dimensional correlation $W(\phi_B^*, \chi_B, \chi_B')$ between the primary scattering angle ϕ_B^* and the subsequent decay angles (in the scattering plane) χ_B and χ_B' using various assumptions for k, k' and L'. In particular, if k and k' have equal magnitudes we can write $X = \chi_B \pm \chi_B'$. This gives either one of two possible two-dimensional correlation functions $W(\phi_B^*, X)$ which can be projected onto a single axis. Such projections are shown in figure 7. Periodic structure is only visible in the projected correlations for $X = \chi_B + \chi_B'$ ($k = k'$) and $L' = 14$ or 16. The peak structure apparent in the $L' = 12$ spectrum is not regular and typical when using the incorrect assumption for k, k' or L' (see ref. [15]). This suggests that the scattering at $E_{c.m.} = 37.5$ MeV may occur dominantly to nuclei with fully aligned spins, i.e., $K = k + k' = 6$ and orbital angular momentum $L' = 14$ or 16. This is consistent with the very negative Q value for the reaction, so that for each incident partial wave L only $L' = L - 6$ contributes. This suggests a possible resonant spin of $J = L = 20$ or 22. Previously [15] we reported $L' = 12$ or 14 for the 32.5 MeV resonance and we deduced a J value of 18 or 20. This is consistent with the assignment $J = 18$ in a recent measurement of scattering to the ^{12}C(3_1^-)+^{12}C(0_1^-) channel at the nearby energy $E_{c.m.} = 33.5$ MeV [22]. We note that the level of background in the projected correlation spectra at $E_{c.m.} = 37.5$ MeV (Fig. 7) is higher than that measured previously at $E_{c.m.} = 32.5$ MeV (Fig. 10 in ref. [15]). We believe that the increased background is due to experimental problems associated with non-linear detection response and not the significant contribution of additional partial waves or non aligned channels in the scattering at $E_{c.m.} = 37.5$ MeV. This is illustrated in figure 8 where we cannot resolve the previously observed correlation structure (Fig. 10 in ref. [15]) in the present data at $E_{c.m.} = 32.5$ MeV. However even with the poorer detector performance it does appear that the new measurement may be consistent with a rotational band of resonances with spins differing by two units of angular momentum.

Insufficient data and poor detector performance in the present measurements similarly prevented the extraction of angular momenta at the other resonant energy ($E_{c.m.} = 43$ MeV) in the ^{12}C(3_1^-)+^{12}C(3_1^-) channel. The unambiguous determination of the angular momenta in other channels was also not possible due to the poor statistics and the fact that our angular coverage in the centre-of-mass frame around 90° is not sufficient to distinguish different L' values (see ref. [15]).

It should be noted that the only way to increase the efficiency for these measurements is to extend the experimental sensitivity over a much larger solid angle. Placing detectors closer to the beam would increase the solid angle but reduce the angular resolution and make the identification of reaction channels ambiguous. Hence the only practical solution is to use many more detectors. The "array" of four 16-strip PSSD's used here generated 96 signals which was the maximum number that could be accommodated by our data-readout system. Thus these investigations are fundamentally very challenging and await the development of even larger highly segmented detector arrays and associated data acquisition.

4 Conclusion

We have measured excitation functions for several ^{12}C(^{12}C,^{12}C$^*\rightarrow$ 3α)^{12}C* reactions at centre-of-mass energies in the range $E_{c.m.}$ = 31 to 45 MeV. New resonances have been observed near $E_{c.m.}$= 37.5 and 43.0 MeV in the ^{12}C(3^-_1)+^{12}C(3^-_1) channel. These resonances appear to be correlated with enhancements in the cross-section of several other ^{12}C+^{12}C inelastic channels which do not lead to a 6α final state. The resonance spin at 32.5 MeV is most likely different from the dominant partial waves in the $0^+_2+0^+_2$ channel ($l = 14, 16$ [2]). The mutual 0^+_2 channel also shows little structure in the excitation function as compared to the scattering to ^{12}C(3^-_1)+^{12}C(3^-_1) across the measured energy range $E_{c.m.}$ = 31 to 45 MeV, except at 32.5 MeV. These differences suggest that these two reaction channels are populated by different mechanisms.

The unified description of resonance structures observed in the ^{12}C+^{12}C system remains one of the longstanding problems of nuclear physics. These data in α-unbound reaction channels extend the systematics of these phenomena to higher energies and will serve as a test of theoretical models at higher excitation.

Our data suggest that the resonances at $E_{c.m.}$ = 32.5 and 37.5 MeV are two units of angular momentum apart. This is consistent with the model presented by Rae, Fry and Merchant [14], where the resonances are thought to be the result of the scattering of ^{12}C nuclei with threefold α-cluster symmetry and aligned spin. It will be necessary to establish the spin alignment systematics of the resonances before any detailed comparison can be made with competing models of the reaction mechanics. Such experiments are planned using the new “MEGHA” array [23] being installed by the “Charissa”[1] collaboration at the Australian National University, Canberra.

Acknowledgments

The financial support of the U.K. Engineering and Physical Sciences Research Council is acknowledged. This work was performed under an agreement between the E.P.S.R.C. and the A.N.U..

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Figure Captions

Fig. 1. Total Q value spectra for five and sixfold coincidences at $E_{c.m.} = 32.5$ MeV.

Fig. 2. Excitation energy in (a) ^{8}Be and (b) ^{12}C* deduced from 2α and ^{8}Be(0_1^+)+α $\rightarrow 3\alpha$ hits respectively at $E_{c.m.} = 32.5$ MeV.

Fig. 3. ^{12}C*+^{12}C* scattering channels identified at $E_{c.m.} = 32.5$ MeV. from (a) 3α+3α events and (b) 3α+1 hits on either side of the beam direction.

Fig. 4. Experimental excitation functions for ^{12}C(^{12}C,^{12}C$^{*}\rightarrow 3\alpha$)^{12}C$^{*}\rightarrow 3\alpha$ channels.

Fig. 5. Experimental excitation functions for ^{12}C(^{12}C,^{12}C$^{*}\rightarrow 3\alpha$)^{12}C*(<7.37 MeV) channels.

Fig. 6. Monte Carlo relative "efficiency" profiles for the detection of 3α+3α (filled symbols) and 3α+1 hits (open symbols) for the channels indicated.

Fig. 7. Projections of the $W(\phi_B^*, X)$ angular correlations at $E_{c.m.} = 37.5$ MeV in the ^{12}C(3_1^+)+^{12}C(3_1^+) channel for $k = k' = 3$ and the L' values indicated.

Fig. 8. Poor resolution in projections of the $W(\phi_B^*, X)$ angular correlations in the

^{12}C(3_1^+)+^{12}C(3_1^+) channel at $E_{c.m.} = 32.5$ MeV for $k = k' = 3$ and the L' values indicated.

Tables

Table 1. Crude estimates of the partial decay probability relative to the $0_2^+ + 0_2^+$ channel measured at each of the three resonant energies.

Table 1

A	$N_A/N_{0_2^+ + 0_2^+}$		
e	$E_{c.m.}$ (MeV)		
	32.5	37.5	43.0
$0_2^+ + 3_1^-$	11.3 ± 1.5	12.4 ± 1.7	5.3 ± 0.8
$3_1^- + 3_1^-$	141.0 ± 37.1	394.9 ± 79.1	164.7 ± 27.9
$0_2^+ + 0_1^+$	23.1 ± 1.9	35.1 ± 3.7	2.9 ± 0.3
$0_2^+ + 2_1^+$	6.3 ± 0.5	14.0 ± 1.5	5.7 ± 0.6
$3_1^- + 0_1^+$	304.8 ± 31.3	332.4 ± 33.7	145.6 ± 16.1
$3_1^- + 2_1^+$	65.3 ± 8.0	240.4 ± 29.3	44.6 ± 5.0