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The $^{12}C+^{12}C$ "6-α Chain State" Resonance

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Abstract

The inelastic scattering of ^{12}C+^{12}C to states above the decay threshold into 6 α-particles has been studied at center of mass energies in the range 25 to 40 MeV. We observe strong resonant behavior in the $0_2^+ + 3_1^-$ and $0_2^+ + 0_2^+$ channels around 32.5 MeV with strikingly enhanced cross sections at 90° in the center of mass. Further measurements suggest that the $0_2^+ + (0_3^+)$ channel also resonates in this energy region. These data are compared to recent band crossing model calculations and the shape eigenstate interpretation.

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I. INTRODUCTION

The myriad of resonances observed in ^{12}C+^{12}C scattering have attracted intensive investigation for over three decades [1]. Recently, observation [2] of a wide (Γ_{cm}=4.7 MeV), Breit-Wigner shaped, resonance at E_{cm}=32.5 MeV in the ^{12}C(^{12}C,^{12}C(0_2^+))^{12}C(0_2^+) inelastic scattering reaction has caused some difficulty in interpretation with conventional reaction models. The simple band-crossing model (BCM) [3,4] cannot account for such resonant behavior in the strongly angular-momentum-mismatched mutual 0_2^+ channel, since in general 0^+ bands do not cross. Furthermore, the angle-averaged on-resonance cross section σ_{av}, for 0_2^++0_2^+ (σ_{av}=15 μb) and 0_2^++0_1^+ (σ_{av}=100 μb) [4,5] does not correlate with the factor of 100 difference in their Coulomb penetrabilities. Wuosmaa *et al* [2] proposed an understanding of this structure through the formation of a 6-α linear chain configuration (LCC) at E_x=46.4 MeV in ^{24}Mg. The cranked cluster model (CCM) [6] predicts such a state some 15-20 MeV above the 6-α breakup threshold, with a band-head excitation of around 45.5 MeV [7]. This LCC is consistent with the large prolate deformations found in both Hartree-Fock [8] and Nilsson-Strutinsky [9] potential energy surface calculations. Taking the rotational spacing of the 6-α LCC as $\hbar^2/2\mathcal{J}$=22 keV (as predicted by the CCM) and that of two touching ^{12}C nuclei in the elastic band as 90 keV results in a band crossing at $E_x\simeq$50 MeV for L=16 [6], confirming observation of the L=14,16 dominant angular momenta [2].

An alternative explanation is offered by Satpathy and Sarangi, who have applied a dynamic bonding-potential model [10] to the 0_2^++0_2^+ channel [11], as an extension of their di-nucleus rotation-vibration picture of ^{12}C+^{12}C scattering resonances [12]. An increase in cross section at E_{cm}=33.09 MeV with L=14 is predicted, precluding the necessity for population of any compound state in ^{24}Mg. The apparent success of this unified approach to molecular resonances is, however, criticized [13] for inappropriate approximation of the centrifugal potential which can produce spurious results.

Most importantly, the above theoretical descriptions fail to reproduce the strikingly large enhancement in the angular distribution found at 90^o (c.m.) on resonance. Experimentally, this has been found to be the major source of resonant strength. An enhancement in such a restricted angular range requires a coherent contribution from many angular momentum waves in the scattering. Merchant and Rae [14] have, therefore, suggested a new type of mechanism whereby several degenerate l-states are excited in a cluster band, characterized by a fixed value of $2n + l$ (where n and l are the nodal and angular momentum quantum numbers, respectively), to form an approximate-shape-eigenstate [15] fixed in orientation with no definite angular momentum. Here the degeneracy is accounted for by an exotic structure with a very large moment of inertia (2R $\simeq$18 fm), consistent with a 6-α LCC, aligned with its long axis perpendicular to the beam direction.

The dominant decay mode of a 6-α LCC is expected to be through symmetric fission into two 3-α LCCs, where the ^{12}C(0_2^+) state at $E_x = 7.65$ MeV is often associated with such a configuration [16,17]. This identification, however, still remains a point of contention. The 7.65 MeV 0_2^+ state lies only 280 keV above the particle breakup threshold and in many generator coordinate model (GCM) calculations the first excited 0^+ state does not turn out to be a linear chain but a dominantly bent configuration [18]. Indeed a structure in which the 3 α-particles are loosely coupled, but not necessarily as a chain, must be used to account for the large α-decay width of the 0_2^+ level [19]. Furthermore an artificial mixing of Brink-style equilateral triangle and other bent 3-α geometries is required to describe the strong $0_2^+ \rightarrow 0_1^+$ monopole transition [17]. A true linear chain might be expected to lie at higher excitation energies. Using a recent model of ^{16}O [20], Rae and Merchant have speculated that the LCC may be formed when the ^{8}Be is in its 2^+ $M = 0$ state. Thus the linear chain might be some 3 MeV (viz the excitation of ^{8}Be(2^+)) above the bent chain. Simple GCM calculations [21] support this speculation. Hence, one may reasonably expect any symmetric 6-α LCC breakup to possibly include higher excitations in ^{12}C* with an LCC component. The rôle of the 10.3 MeV (0_3^+) state, first proposed by Morinaga [22] as the second level (2_2^+) of the 3-α rotational band, may therefore be important.

These unresolved issues have prompted us to perform detailed angular distribution measurements, over the energy region of this resonance, for ^{12}C(^{12}C,6α) reactions and study the formation of $^{12}C^*$ above the 3-α breakup threshold. Our results are compared with recent BCM calculations and the shape eigenstate interpretation.

II. EXPERIMENTAL METHOD

The data were taken at the Australian National University's 14UD tandem Van de Graaff facility using ^{12}C beams, accelerated over selected laboratory energies in the range 50 to 80 MeV. The target consisted of a self-supporting 90 μg cm^{-2} natural carbon foil. Three 25 cm^2, 500 μm thick position sensitive strip detectors (PSSDs) were arranged with their centers 12 cm from the target at $+25^o$, $+52^o$ and -32^o in the horizontal plane relative to the beam direction. The PSSDs were fabricated from a single wafer of n-type silicon implanted with boron ions to form a resistive p-type layer, that serves as the front anode of the detector and forms the p-n junction. Division of this electrode into 16 horizontally arranged 3 mm strips, with contacts made to either end of each strip, allows for the determination of position, energy and timing of up to 16 simultaneous hits in the detector, providing no two particles enter via the same strip. Thus the PSSDs were particularly suited to the study of the $^{12}C(^{12}C,6\alpha)$ reaction, in particular to the recording of all 6 α-particles in coincidence from the assumed sequential breakup of resonant states in $^{24}Mg^*$ through $^{12}C^*$ then $^8Be_{gs}$. The data acquisition system used, however, limited the maximum number of available ADC channels to 80. Hence, the single (-32^o) detector was operated in normal mode and the neighboring ($+25^o$ & $+52^o$) PSSDs were coupled into a novel "doubled" configuration. This was achieved by the electrical connection of adjacent strip ends between the PSSDs, so that charge collected at either of these ends passed to the same preamplifier-amplifier-ADC combination. These signals could then be determined as originating from one detector or the other by the application of suitable logic. For example, the true strip of any particular hit must have both signals from the coupled and uncoupled ends present above threshold. No explicit particle identification was made during the experiment, since over determination of the reaction kinematics allowed reconstruction of the data in terms of multiplicity with a low degree of background contamination. In this case, each hit in a 6-fold event could be unambiguously assigned to an α-particle on measurement of a total reaction Q-value $\simeq$-14.6 MeV. Only those events in which at least 5 PSSD strips fired above threshold, including a minimum of 2 in the double-detector, were recorded for detailed analysis.

For 6-α coincidences, occurring as 3-α hits either side of the beam, we calculate the excitation E_x and scattering angle of both decaying ^{12}C* nuclei from the momenta of the α-particles, viz

$$E_x = \sum_{i=1}^{3} E_{\alpha_i} - \frac{P^2}{2M} + Q_{thresh} \tag{2.1}$$

where the ^{12}C momentum,

$$P = \sqrt{(\sum_{i=1}^{3} P_{\alpha_i x})^2 + (\sum_{i=1}^{3} P_{\alpha_i y})^2 + (\sum_{i=1}^{3} P_{\alpha_i z})^2} \tag{2.2}$$

Q_{thresh} is the ^{12}C$\rightarrow$3α breakup threshold (7.27 MeV) and M is the mass of ^{12}C. The E_{α_i} and P_{α_i} are the measured α-particle energies and components of momentum respectively. This method of reconstruction is independent of the process by which the α-particles are formed, although here we consider only those 3-α events correlated as ^{8}Be$_{gs}$+α to originate from a ^{12}C nucleus. The accuracy of this reconstruction is dominated by the position response of the detection system, where the PSSDs localize incident events to within 200 μm and are linear to within a few percent.

Extensive Monte-Carlo simulations of the detection process have been performed for each of the 6-body final states discussed herein. The simulation assumes an isotropic center of mass angular distribution for the primary scattering with subsequent decays of the ^{12}C* nuclei having either isotropic or $1/sin(\theta)$ distributions for zero and non-zero spin states respectively. Detection of the α-particles is then modelled in detail, including energy threshold effects and rejection for multiple hits in a single strip. The resulting profiles then allow relative normalization of the data for variations in efficiency with respect to energy, angle and excitation of the reconstructed nuclei.

III. RESULTS

The summed excitation energy for detected ^{12}C*+^{12}C* events at 32.5 MeV (c.m.) is given in figure 1, where the combinations of 0_2^+ and 3_1^- mutual excitations have been identified. Selection of ^{12}C(0_2^+) events in the single-PSSD enables states in ^{12}C* up to $\sim$12 MeV excitation to be studied in the larger area double-PSSD combination. Since the origin of 5 out of the 6 α-particles has been determined (i.e. ^{12}C+^{12}C$\rightarrow$^{12}C(0_2^+)+^{8}Be$_{gs}$+α), any background contamination is expected to be small. Figure 2 is an example of this measurement, again at 32.5 MeV. Note that the relative detection efficiency decreases by approximately 80% between E_x =7.65 and 12 MeV as the average breakup cone of ^{12}C*$\rightarrow$3α trajectories increases, from $\sim$13^o to $\sim$52^o, and considerably reduces any overlap with the double-PSSD's angular range. The 0_2^+ and 3_1^- states are clearly resolved in the efficiency corrected data, above an apparently structured background. Subtraction of these peaks via Gaussian fitting reveals two major structures comprising the remaining background: a wide peak at $E_x$$\simeq$9.9$\pm$0.5 MeV and a smaller contribution at $E_x$$\simeq$11 MeV. These are consistent with the (0_3^+) and 1^- cluster states in ^{12}C*, respectively. Integration of this background, between the limits given in Fig.2, then provides an estimate of the yield in the 0_2^++(0_3^+) and 0_2^++1^- channels. The relevant excitation functions, as extracted from Figs. 1 and 2 at each of the c.m. energies sampled, are presented in Fig.3. The large errors are representative of uncertainties in the correction for low efficiency. The 0_2^++0_2^+ and 0_2^++3_1^- channels are observed to resonate in the region of 32.5 MeV, along with the 0_2^++(0_3^+) background contribution. Efficiency corrected angular distributions, at selected energies, for the 0_2^++0_2^+, 0_2^++3_1^- and 3_1^-+3_1^- channels are shown in Figs. 4 to 6. A dramatic increase in cross section at 90^o, compared to the neighboring maxima, is a characteristic of resonance in the 0_2^++0_2^+ and 0_2^++3_1^-channels. Note that, the very small detection probability (< $\sim$0.1 %) and difficulty in accounting for the position dependent energy thresholds of the PSSDs makes the Monte-Carlo simulation for normalization of the low 3_1^-+3_1^- yield rather more inaccurate. This is reflected in the angular distributions presented for this channel, where symmetry about 90^o is not restored.

This demonstrates that any quantitative comparison to theory must accurately account for the phase space sampled in these multi-particle reactions and not rely on the simplified assumptions of Monte-Carlo codes for correction of the projected data.

IV. DISCUSSION

Returning to the theoretical interpretation of these data, the band crossing model of Abe *et al* [3] has recently been extended in calculations by Hirabayashi [23] *et al* to include realistic transition densities for ^{12}C. Since the 0_2^+ state in ^{12}C is highly deformed, in these new calculations the 0_2^+ bands have higher moments of inertia and thus cross the elastic band. These calculations appear to reproduce the angle integrated cross sections for both the 0_2^++0_1^+ and 0_2^++0_2^+ bands and also predict correlated enhancements in the 0_2^++3_1^- and 0_2^++0_3^+ channels roughly in line with our measurements. Reproduction of the 0_2^++0_2^+ angular distribution behavior about 90^o has also been achieved by Hirabayashi *et al*, but with a dominant partial wave (L=18) somewhat larger than those in the experimental data (L=14,16 [2]).

The observation of the 90^o enhanced resonance in the 0_2^++3_1^- channel appears to contradict the 6-α chain state interpretation, although not the shape eigenstate hypothesis which only requires a very large moment of inertia. In addition, there have been reports of this resonance being observed in other channels near 32.5 MeV with similar enhancements at 90^o in the angular distributions. Aliotta *et al* [25] and Freeman *et al* [26] have observed decay to ^{16}O$_{gs}$+^{8}Be, while Mirgule *et al* [27] have measured resonant cross sections for decay to the 13.9 MeV 6$^+$ and 20.5 MeV 8$^+$ states in ^{20}Ne. These data also appear to rule out the population of a LCC in ^{24}Mg, not least due to the fact that ^{16}O$_{gs}$ is spherical. However, Rae and Merchant [20,24] have proposed a mechanism which is consistent with both the 6-α chain state and shape eigenstate hypotheses and can explain the observed decay into these other channels.

Rae and Merchant propose that there is considerable mixing of the chain state with other configurations in ^{24}Mg at this excitation energy. They suggest that the spreading width of this chain configuration is probably much larger than the escape (or fission) width. The mechanism of this mixing can be visualized in terms of an inelastic reorientation process. To describe a linear chain state composed of two ^{12}C α-chains the ^{12}C nuclei cannot have zero spin since then no orientation would be preferred and the structure would not be linear. Thus the 6-α LCC must involve $J = 2, 4$ and possibly higher ^{12}C spins. Also in order to have a linear structure with axial symmetry the ^{12}C nuclei must have $M = 0$ along the long axis of the chain state (both to preserve this as a symmetry axis and provide the alignment). Rae and Merchant propose that this wavefunction can decay in two ways: 1) by fission into two ^{12}C nuclei and 2) by reorientation of the ^{12}C spins from $M = 0$ to some other $M \neq 0$. This is essentially an inelastic scattering reorientation mechanism. After this reorientation the system no longer has the symmetry of a chain state and the ^{12}C nuclei are no longer aligned end to end. The state can then collapse inwards (this is essentially fusion) and change shape as it does so.

In this mechanism, since the 6-α chain state resonance is at a higher excitation energy than almost all other resonances in ^{12}C+^{12}C scattering, these shape changes could result in an excited configuration in any of the other possible local total energy minima. Thus we should expect to see all α-cluster model channels populated - possibly with an essentially statistical probability. This decay mechanism then automatically explains the formation of the chain state from the $^{12}\mathrm{C}_{gs}$+$^{12}\mathrm{C}_{gs}$ entrance channel, which is just the inverse of the decay process, viz that inelastic processes produce the alignment which results in the formation of the LCC.

This explanation suggests that the 32.5 MeV resonance should show structure if studied in finer energy steps. The widths of this finer structure should be comparable to the intermediate structure resonances observed in ^{12}C+^{12}C scattering, since to first order the chain state is mixing with other alpha cluster configurations which are thought to provide a consistent interpretation of the ^{12}C+^{12}C scattering resonances [28]. Thus it would be interesting to see if this prediction is borne out by experiment. Such a detailed excitation function measurement would be able to distinguish the band crossing model from the α-cluster model interpretation.

V. CONCLUSION

We have presented data which suggest that the resonance observed in the $^{12}C(0_2^+)+^{12}C(0_2^+)$ channel by Wuosmaa *et al* can also be observed in the $^{12}C(0_2^+)+^{12}C(0_3^+)$ channel, as predicted by Zhang and Rae, and in the $^{12}C(0_2^+)+^{12}C(3_1^-)$ channel. The latter observation presents a challenge to the original structural interpretation of the 32.5 MeV resonance as a 6-α LCC in ^{24}Mg. We have discussed two theoretical models which attempt to describe these data - a BCM calculation by Hirabayashi *et al* and a cluster model calculation by Rae and Merchant. The latter suggests that the chain state should be strongly mixed with other cluster configurations in ^{24}Mg at this excitation energy and thus should be observable in many decay channels. A more detailed analysis of the angular correlation data for the $^{12}C(0_2^+)+^{12}C(3_1^-)$ channel is underway. This should provide further information on the reaction mechanism and allow a more stringent test of the model calculations.

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FIGURES

FIG. 1. Summed excitation energy for $^{12}C^{*}+^{12}C^{*}$ events at E_{cm}=32.5 MeV. The excitation energies, E_x are reconstructed in both (s)ingle and (d)ouble PSSDs. The data has been normalized to beam exposure only.

FIG. 2. Excitation energy in $^{12}C^{*}$ for the $^{12}C(^{12}C,^{12}C^{*})^{12}C(0_2^+)$ reaction at E_{cm}=32.5 MeV. The data has been normalized to beam exposure (Raw) and detection efficiency (Corrected). The integration limits used for estimation of the (0_3^+) and (1^-) contributions are shown.

FIG. 3. Experimental excitation functions for selected channels in $^{12}C(^{12}C,^{12}C^{*})^{12}C^{*}$.

FIG. 4. $0_2^+ + 0_2^+$ angular distributions at the energies (c.m.) indicated in each frame.

FIG. 5. $0_2^+ + 3_1^-$ angular distributions at the energies (c.m.) indicated in each frame.

FIG. 6. $3_1^- + 3_1^-$ angular distributions at the energies (c.m.) indicated in each frame.