Evidence for Alpha-Particle Chain Configurations in ^{24}Mg

A. H. Wuosmaa, R. R. Betts, B. B. Back, M. Freer, B. G. Glagola, Th. Happ, D. J. Henderson, and P. Wilt

Physics Division, Argonne National Laboratory, Argonne, Illinois 60439

I. G. Bearden

Physics Department, Purdue University, West Lafayette, Indiana 47907

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We have observed a strong peak in the excitation function for the inelastic scattering reaction $^{12}C(^{12}C,^{12}C(0_2^+))^{12}C(0_2^+)$ at an energy of $E_{c.m.}=32.5$ MeV. A recoil coincidence arrangement between two double-sided silicon strip detectors was used to detect the α particles from the decaying ^{12}C nuclei, and the reconstructed reaction kinematics were used to calculate the two-body scattering Q value. This excitation-function structure may be interpreted as arising from very highly deformed α-particle chain configurations in the nucleus ^{24}Mg.

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A striking prediction of nearly all cluster models, as well as cranked Nilsson-Strutinsky calculations, is the existence, in light nuclei with even N and Z, of exotic structures corresponding to linear chains of α particles [1]. Pronounced minima at very large prolate deformations appear in potential-energy surfaces obtained using the cranked shell model [2] or Hartree-Fock calculations [3]; these correspond to the extended chain structures of the α-cluster model [4] and the cranked cluster model (CCM) [5]. These and other α-particle cluster structures in light nuclei result from the stabilizing effects of the symmetries in the α cluster itself, which take maximum advantage of the single-particle shell structure which occurs at very large deformations [6].

In the cluster model, the ground state of ^{8}Be corresponds to a two-α chain, and in ^{12}C, the three-α-particle linear cluster has been identified with the first excited 0^+ level (0_2^+) at an excitation energy of 7.65 MeV [7,8]. In ^{16}O, resonances in the $\alpha+{}^{12}C\rightarrow{}^8Be+{}^8Be$ reaction at energies from $E_x=16$ to 21 MeV have been associated with a rotational band built upon a linear configuration consisting of four α particles [9]. In the heavier nucleus ^{24}Mg, the CCM predicts the bandhead for this chain configuration to lie at approximately 42 MeV of excitation, well above the threshold for the decay $^{24}Mg\rightarrow 6\alpha$. The identification of such a decay through the unraveling of the resulting six-body final state thus presents an intriguing and difficult experimental challenge.

For ^{24}Mg, a decay channel of particular interest is $^{24}Mg^*\rightarrow{}^{12}C(0_2^+)+{}^{12}C(0_2^+)$. Since the 0_2^+ state of ^{12}C at 7.65 MeV is known to consist primarily of a linear three-α configuration, structural and phase-space considerations suggest that a six-α chain structure in ^{24}Mg should have a large decay branch for symmetric breakup into a final state consisting of two ^{12}C nuclei in the 0_2^+ level. The appearance of strong resonance behavior in the mutual inelastic scattering reaction $^{12}C+{}^{12}C\rightarrow{}^{12}C(0_2^+)+{}^{12}C(0_2^+)$ could then provide a signature for the existence of the elongated structure in ^{24}Mg. As a result of the mixing of cluster configurations in the ^{12}C ground state and 0_2^+, the entrance channel could directly populate the six-α chain in ^{24}Mg [5,6]. Also, due to the very large angular-momentum mismatch, the already weak direct processes populating this channel should be strongly suppressed.

At 7.65 MeV, the 0_2^+ state in ^{12}C lies 379 keV above the threshold for decay into three α particles. In order to study in detail the six-body final state of the 0_2^+-0_2^+ inelastic scattering reaction, we have used a recoil-coincidence setup with two large-area, double-sided silicon strip detectors (DSSD's) [10]. These devices are fabricated from 5×5 cm^2 silicon wafers [11], with the front and back sides of the detector divided into two crossed sets of sixteen strips, each of which provides energy and timing information. In this way, the detector is effectively segmented into 256 pixel regions. The redundant energy information obtained from the two sides of the detector can be used to provide the X and Y coordinates of each particle striking the detector, thus resolving the inherent position ambiguities in such a device for multiparticle events [12].

The experiment was performed using a ^{12}C beam from the Argonne National Laboratory accelerator ATLAS to bombard a 50 μg/cm^2 ^{12}C target at laboratory energies ranging from 52 to 80 MeV, in steps of $\Delta E_{lab}=2$ MeV. The energy loss of the beam in the targets was ≈100 keV. The two DSSD's were positioned 15 cm from the target, at 35° on either side of the beam, corresponding to a center-of-mass angle range of $70°\leq\theta_{c.m.}\leq105°$ for the double 0_2^+ inelastic channel. Particle identification was achieved by measuring the time of flight relative to the beam. The time resolution ranged from 1.2 ns for particle energies of 12 MeV, to less than 400 ps for particle energies greater than 20 MeV. For each event in which there were at least three hits in one detector and at least one hit in the other detector, the energy and time of flight for all hit front and back strips were recorded. Two monitor detectors at $\pm10°$ relative to the beam axis were used to measure the elastic scattering yields in order to provide normalization information.

At the energies of interest, the α particles from the 0_2^+ level are confined to a cone of half-angle ranging from 5°

to 8° due to the small amount of breakup energy available. The relatively long lifetime of the $^{12}C(0_2^+)$ state (0.05 fs) [13] ensures that the decay can be treated as sequential and final-state interactions between α particles from the two different ^{12}C nuclei can be ignored.

We have used Monte Carlo simulations to determine the weakly energy-dependent relative detection efficiency for different N-body final states, defined as the number of events in which we detect N α particles divided by the number of events in which the primary $^{12}C+{}^{12}C$ two-body scattering satisfied the recoil coincidence. For the mutual 0_2^+ channel, the efficiency for detecting all six α particles is (8–9)%, and improves to (20–30)% for detecting all three α particles from one $^{12}C(0_2^+)$ and at least one α from the other, depending on the $^{12}C(0_2^+)$ recoil energies.

For each event in which three α particles were detected in one DSSD, their measured energies and angles were used to reconstruct the kinetic energy, scattering angle, and excitation energy of the decaying ^{12}C nucleus. Figure 1(a) shows a reconstructed ^{12}C excitation-energy spectrum obtained at a laboratory energy of 64 MeV. The 0_2^+ peak is clearly identified at 7.65 MeV. The resolution for this reconstructed excitation energy, dominated by the energy resolution of the strip detector and the noise contribution of the preamplifier, is 65 keV FWHM. The broader peak at $E_x=9.64$ MeV corresponds to the

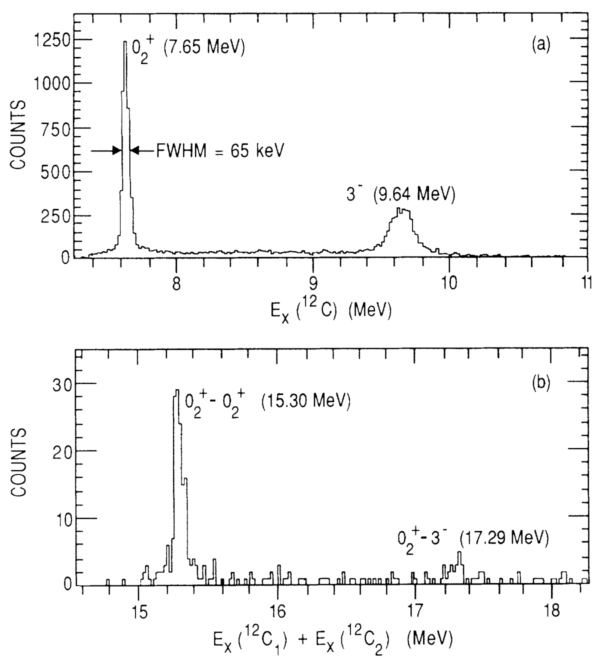

FIG. 1. (a) Spectrum of excitation energy for α-decaying ^{12}C nuclei, reconstructed from the measured momenta of three α particles detected in one DSSD. The peak at $E_x=7.65$ MeV corresponds to the excited 0_2^+ level in ^{12}C. (b) Total excitation energy of two α-decaying ^{12}C nuclei, from six-α-particle coincidence data at $E_{lab}=64$ MeV. The peak at $E_x=15.30$ MeV corresponds to the mutual 0_2^+-0_2^+ excitation.

3^- level in ^{12}C. The larger breakup cone for the 3^- state results in a substantially smaller efficiency for three α particles from this level, compared to the 0_2^+ state. The background observed in this spectrum corresponds primarily to misidentified α particles, as well as to three-α events from reactions that do not proceed through excited states in ^{12}C.

For six-α coincidence events, the total amount of excitation energy in the final state can be directly determined by summing the excitation energy of the two separate ^{12}C nuclei. Figure 1(b) shows a spectrum of total $^{12}C+{}^{12}C$ excitation energy thus obtained at a laboratory energy of $E_{lab}=64$ MeV, for final states above the $^{12}C+{}^{12}C\rightarrow 6\alpha$ threshold. The total-excitation-energy spectrum is extremely clean, and the mutual 0_2^+-0_2^+ excitation is clearly identified at $E_x(\mathrm{tot})=15.30$ MeV.

In order to take advantage of the greater efficiency for detecting four or five, rather than all six, α particles, the same information contained in Fig. 1(b), namely the two-body scattering Q value, can be obtained from the kinematic relationship between the reconstructed $^{12}C(0_2^+)$ kinetic energy and scattering angle. A spectrum of the reconstructed two-body Q value obtained at a laboratory energy of $E_{lab}=64$ MeV appears in Fig. 2, for coincidences between one $^{12}C(0_2^+)$ fragment and either an α particle or an intact ^{12}C nucleus in the other detector. Peaks corresponding to the 0_2^+-g.s. and 0_2^+-2^+ mutual excitations appear at Q values of -7.65 and -12.08 MeV, respectively, and correspond to final states in which only one of the two ^{12}C nuclei was excited above its α-particle decay threshold. The peaks at $Q=-15.30$ and -17.29 MeV represent the 0_2^+-0_2^+ and 0_2^+-3^- mutual excitations. Because of the greater sensitivity of the two-body kinematics to kinematic broadening from the detector segmentation of $\Delta\theta_{lab}=1.2°$, the resolution for the Q-value spectrum in Fig. 2 is somewhat worse than that for the reconstructed excitation energy (Fig. 1).

The integrated 0_2^+-0_2^+ peak yields were corrected for the recoil efficiency ($\epsilon_{recoil}\approx 100\%$ at $E_{lab}=70$ MeV) and 0_2^+ detection efficiency. The absolute normalizations were obtained by comparing the forward-angle elastic-scattering yields measured in the monitor counters to

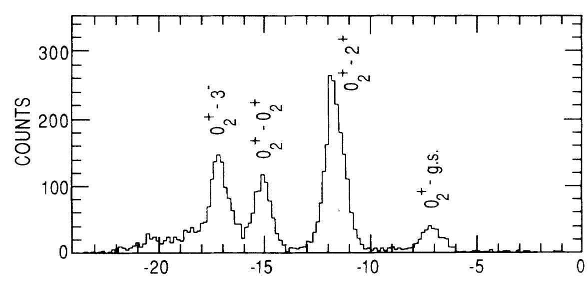

FIG. 2. Reconstructed two-body Q-value spectrum for $^{12}C(0_2^+)$-($^{12}C,\alpha$) coincidences. The mutual 0_2^+-0_2^+ excitation is at a Q value of -15.30 MeV.

cross sections calculated using the optical-model parameters of Reilly *et al.* [14]. The resulting excitation function for the 0_2^+-0_2^+ reaction channel appears in Fig. 3, where the differential cross section averaged over the angular acceptance of the recoil-coincidence setup, $70° \leq \theta_{\text{c.m.}} \leq 105°$, is plotted versus $E_{\text{c.m.}}$. We observe a prominent structure peaked at a center-of-mass energy of $E_{\text{c.m.}} = 32.5$ MeV, with a width, obtained from a Lorentzian fit to the data, of $\Gamma_{\text{c.m.}} = 4.7$ MeV.

Figure 4 shows angular-distribution data obtained at two energies near the peak in the excitation function, $E_{\text{c.m.}} = 32$ and 33 MeV. The data are corrected for the angular dependence of the 0_2^+ detection efficiency. Both angular distributions are strongly oscillatory, with enhancements near 90° characteristic of interference between angular momenta. Superimposed on the data in Fig. 4 are Legendre polynomial curves corresponding to $P_{14}^2(\theta_{\text{c.m.}})$ (solid curve) and $P_{16}^2(\theta_{\text{c.m.}})$ (dashed curve). Both sets of curves reproduce the period of the oscillations in the angular distribution reasonably well, although $l = 14$ does slightly better at $E_{\text{c.m.}} = 32$ MeV, while at $E_{\text{c.m.}} = 33$ MeV, the agreement is slightly better for $l = 16$. These values are close to the suggested value of the elastic-scattering grazing angular momentum in this energy region [15]. In order to make definitive statements about the angular momenta involved, however, much more detailed angular-distribution data are required.

The present results are difficult to explain in the context of conventional reaction models of heavy-ion resonance behavior. The appearance of such a strong peak in the excitation function for the double 0_2^+-0_2^+ reaction channel, which is mismatched by more than six units of angular momentum, is inconsistent with resonancelike behavior described by, for instance, the simple band-crossing model (BCM) [16,17]. Also surprising is the rather large angle-averaged on-resonance cross section, $\langle\sigma\rangle \approx 15$ μb/sr at the peak of the excitation function, compared to a value of ≈ 100 μb/sr obtained at the peak of a resonance in the excitation function for the single 0_2^+-g.s. channel [16,18]. If we assume a dominant l value of 16 at $E_{\text{c.m.}} = 64$ MeV, the Coulomb penetrability, calculated assuming a channel radius of $1.4(A_1^{1/3} + A_2^{1/3})$, is smaller by a factor of approximately 100 for the mutual 0_2^+ channel than that of the 0_2^+-g.s. channel, whereas the angle-averaged differential cross sections differ by only a factor of 6.7.

Many of the present results can be understood by considering the linear six-α-particle chain configuration in ^{24}Mg. The rotational spacing for the chain configuration obtained from the CCM, $\hbar^2/2\mathcal{J} = 22$ keV, is dramatically smaller than that of the ^{12}C+^{12}C elastic band, $\hbar^2/2\mathcal{J} = 90$ keV [5]. As a result, the two bands, which would be parallel and separated by 15.3 MeV in the naive BCM, now have a well-defined crossing. In the CCM, this crossing is predicted to occur near $l = 16$ and an excitation energy of $E_x \approx 50$ MeV, very close to the energy and angular momentum at which we observe the structure in the 0_2^+-0_2^+ inelastic scattering cross section. Furthermore, if the 0_2^+-0_2^+ final state arises from the decay of the chain configuration, one expects the effective interaction radius to be substantially larger than for two ^{12}C nuclei in the ground-state cluster configuration, or for two ^{12}C in their 0_2^+ excited state, randomly oriented with respect to each other. This increased effective interaction radius can dramatically affect the values of the Coulomb penetrabilities and the angular-momentum matching properties for such a complex [19]. For example, an increase of 50% in r_{eff} increases the Coulomb penetrability

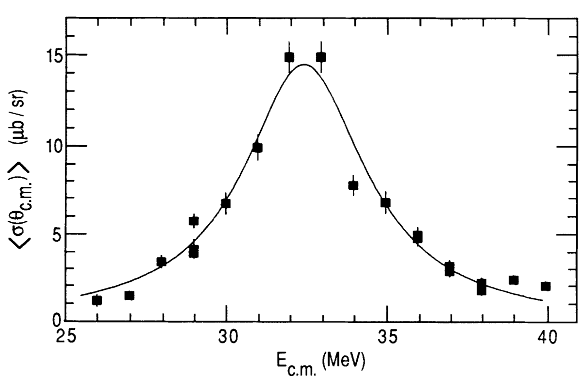

FIG. 3. Excitation function for the ^{12}C(^{12}C,^{12}C(0_2^+))-^{12}C(0_2^+) mutual inelastic scattering reaction. The cross sections are corrected for ^{12}C(0_2^+) detection efficiency and averaged over the angular range of the detector setup ($70° < \theta_{\text{c.m.}} < 105°$). The curve represents a Lorentzian fit to the data yielding a peak energy of $E_{\text{res}} = 32.5$ MeV and width $\Gamma_{\text{c.m.}} = 4.7$ MeV.

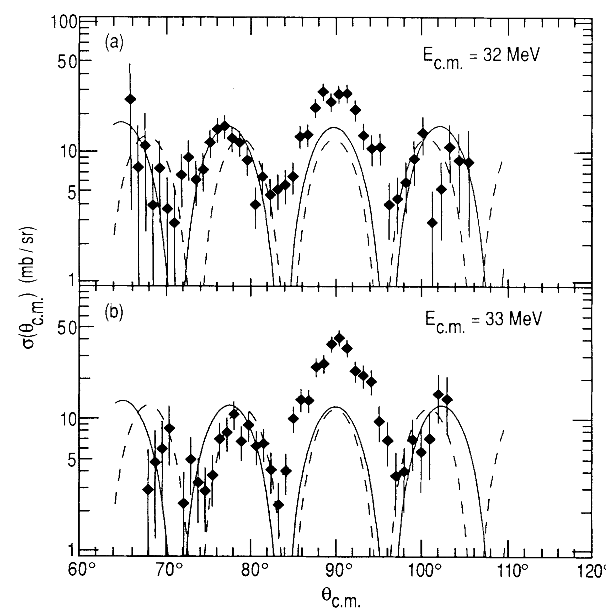

FIG. 4. Angular-distribution data obtained near the peak of the observed resonance, at (a) $E_{\text{c.m.}} = 32$ MeV and (b) $E_{\text{c.m.}} = 33$ MeV. The solid (dashed) curves represent pure squared Legendre polynomials of degree 14 (16).

for the 0_2^+-0_2^+ excitation at $E_{\rm lab}=64$ MeV and $l=16$ by more than a factor of 500. Such an effect could explain the large peak cross section observed in this channel.

While the present results suggest that coupling to a six-α-particle linear chain configuration could be responsible for the observed resonance behavior in this reaction, more experimental data are required to further support this conclusion. Extended angular-distribution data are necessary to characterize the contributing angular momenta. This characterization will in turn permit a detailed comparison between the experimental results and theoretical predictions for the six-α chain configuration. Also, the dramatically different slopes of the ^{12}C+^{12}C and 6α bands in the CCM calculations suggest a rather limited region of coupling between them. In this case, we expect that few other strong resonances should appear in this inelastic scattering channel. The range of the excitation function must be extended to higher energies in order to test this prediction. Finally, if populated, the six-α-chain configuration could decay into other final states involving chainlike structures, such as ^{8}Be$_{\rm g.s.}$+^{16}O(4α). The identification of such decay branches for this structure could provide important additional evidence for this exotic clustering behavior in ^{24}Mg.

In conclusion, we have used a recoil-coincidence experiment consisting of two highly segmented double-sided silicon strip detectors to study the inelastic scattering process ^{12}C(^{12}C,^{12}C(0_2^+))^{12}C(0_2^+). Detection of the three α particles from either one or both of the two decaying ^{12}C nuclei allow for complete kinematic reconstruction of the two-body scattering reaction. We observe a large peak in the cross section of this strongly angular-momentum mismatched exit channel at a center-of-mass energy of $E_{\rm c.m.}=32.5$ MeV, corresponding to an excitation energy of $E_x=46.4$ MeV in the nucleus ^{24}Mg. The limited angular-distribution data obtained in this experiment suggest dominant angular momenta in the range of $l=14$ to 16, placing this structure very near to the predicted crossing between the rotational bands arising from ^{12}C$_{\rm g.s.}$+^{12}C$_{\rm g.s.}$ and the predicted six-α-particle chain configuration obtained from the CCM calculations for ^{24}Mg. Comparison between the experimental results and theoretical calculations suggests that the structure observed in this reaction could represent the population of extremely prolate-deformed linear α-chain structures in ^{24}Mg.

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