Excitation function measurements of 12C(4He,8Be)8Be, 12C(4He,12C[7.65, 0+])4He, and 12C(4He,12C[9.64, 3−])4He reactions

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Excitation function measurements of $^{12}C(^4He,^8Be)^8Be$, $^{12}C(^4He,^{12}C[7.65, 0^+])^4He$, and $^{12}C(^4He,^{12}C[9.64, 3^-])^4He$ reactions

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In the present measurements a ^{12}C target was bombarded by a ^4He beam with energies from 14 to 21 MeV and the excitation function measurements for the reactions of the $^{12}C(^4He, ^8Be)^8Be$, $^{12}C(^4He, ^{12}C[7.65, 0^+])^4He$, and $^{12}C(^4He, ^{12}C[9.64, 3^-])^4He$ were obtained using an array of 6 double-sided silicon strip detectors. The excitation functions are used to gain an insight into possible α-cluster structures in ^{16}O.

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In recent times there has been renewed interest regarding the potential α-particle structure of light nuclei. It is known that both the ground-state of ^8Be and the second excited state of ^{12}C have a well-developed α-cluster structure. The latter state is the 7.65 MeV 0^+ Hoyle state which plays a crucial role in the synthesis of carbon in stars. Its properties are extremely hard to reproduce in models which do not explicitly contain clustering. For example, the no-core shell model [1] requires an extremely extended harmonic oscillator basis for the theoretical energy to even approach the experimental value. This has led to the description of such states in terms of a Bose gas of α particles, or even a Bose condensate [2].

Progress in identifying similar, highly clustered states in ^{16}O is less advanced. The structure of oxygen nuclei above the 4α decay threshold remains an open question. The evidence that there might be an extremely exotic structure in ^{16}O composed of a linear arrangement of 4α particles dates back to the 1960s. Chevalier and coworkers performed an excitation function measurement of the $^{12}C(^4He, ^8Be)^8Be$ reaction [3]. The data show a number of resonances above the 4α decay threshold (14.44 MeV), some of which are broad and some which were classified as narrow. The energy-spin systematics of the narrow states appeared to fall on a rotational $I(I+1)$ trajectory. The same reaction was also used by Brochard *et al.* to extend the measurements to higher energy [4]. Ames has also observed similar resonances in $\alpha + {}^{12}C$ scattering measurements [5], where the ^{12}C was excited to the $0_2{}^+$ state. Furthermore, a measurement of the $^{12}C(^{16}O, 4\alpha)^{12}C$ reaction was performed by Freer *et al.* [6]. Finally, the $^{12}C(^{12}C, ^8Be + ^8Be)^8Be$ reaction has been used to characterize ^{16}O excited states that decay to two ^8Be nuclei over the excitation energy region 19 to 40 MeV [7].

From a theoretical perspective, it has been speculated that the 0^+ excited state at 15.1 MeV may be a good candidate. One might expect that states with a well-developed cluster structure in ^{16}O decay to similar states in ^8Be and ^{12}C. This feature is illustrated in the case of the $0_6{}^+$ 15.1 MeV state in Ref. [8], and this will be exploited in the current measurements.

In the present measurement we repeat the measurements of Chevallier *et al.* using the $^4He + {}^{12}C$ reaction and simultaneously examine the $^8Be + {}^8Be$, $^{12}C(7.65\text{ MeV}, 0^+) + \alpha$, and $^{12}C(9.64\text{ MeV}, 3^-) + \alpha$ decay channels.

The experiment was performed at the Orsay Tandem Accelerator in Paris, France. A ^4He beam was used to bombard a 100 $\mu g/cm^2$ carbon foil. The excitation functions were measured over the energy range $E_{lab} = 14$ to 21 MeV, with steps, $\Delta E \approx 100$ keV.

The aim of the measurement was to populate resonances in ^{16}O which decay via ^8Be emission to states in ^8Be or α decay to states in ^{12}C above the 3α decay threshold. The ^8Be nucleus is unbound to decay with respect to two α particles by 92 keV and the $^{12}C[0^+]$ and $^{12}C[3^-]$ excited states are unbound to decay with respect to $^8Be + \alpha$ threshold by 283 keV and 2.27 MeV respectively. The measurement of the $^8Be + {}^8Be$ decay channel involves the detection of two α particles from the ^8Be decay. The measurement of the $^{12}C^* + {}^4He$ channel involves the detection of three α particles with the first α particle resulting from the decay to ^8Be and then two more from the decay of ^8Be. To reconstruct these complex final states, an array of six double-sided silicon strip detectors (DSSSDs), each 50×50 mm^2 in area and 500 μm thick, was used for the experiment. All detector faces possessed 16 strips, each $\sim$3 mm wide, with the direction of the strips on the front and back faces mutually perpendicular. Such detectors are ideal

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TABLE I. Distances of detectors from the target position and the central angles of detectors measured with respect to the beam direction.

Detector	Distance from target (mm)	Center of detectors (Degrees)
1	158 (2)	−16.7 (2)
2	155 (2)	−16.7 (2)
3	160 (2)	−39.7 (2)
4	157 (2)	−39.7 (2)
5	151 (2)	22.5 (2)
6	155 (2)	22.5 (2)

for breakup reactions, as the detection of multiparticle events within a single detector as well as between different detectors is possible [9]. Table I shows the distances of the detectors from the target and their angles measured with respect to the beam direction. All the detectors lay with their centers in a single horizontal plane. The energy calibration of the detectors was performed using alpha sources (^{239}Pu, ^{241}Am, and ^{244}Cm) and elastic scattering of the ^{4}He beam from a ^{197}Au target.

Analysis was performed for events in which there were two hits corresponding to ^{8}Be decay and three hits from ^{12}C* decay in the 6 detectors. For these multiplicity-2 and -3 events it was assumed that each hit corresponded to an α particle and the momentum of each particle was deduced from the recorded energy and position.

For the multiplicity-2 events which were ascribed to the ^{12}C(^{4}He, ^{8}Be)^{8}Be reaction, the momentum of the ^{8}Be nucleus can be written as

$$\mathbf{P}_{^8\mathrm{Be}} = \mathbf{P}_{\alpha_1} + \mathbf{P}_{\alpha_2}, \tag{1}$$

where $\mathbf{P}_{\alpha_i}$ is the momentum of the ith α particle. The energy of the ^{8}Be nucleus is then given by

$$E_{^8\mathrm{Be}} = \frac{(\mathbf{P}_{\alpha_1} + \mathbf{P}_{\alpha_2})^2}{2m(^8\mathrm{Be})}, \tag{2}$$

where $m(^8\mathrm{Be})$ is the mass of the ^{8}Be nucleus and the decay energy of ^{8}Be to two α particles is then given by

$$E_{\mathrm{d}}(^8\mathrm{Be}) = \sum_{i=1}^{2} E_{\alpha_i} - E_{^8\mathrm{Be}}, \tag{3}$$

where E_{α_i} is the kinetic energy of ith alpha particle.

The Q value for the ^{12}C(^{4}He, ^{8}Be)^{8}Be reaction is then given by

$$Q_{^8\mathrm{Be}} = E_{\mathrm{tot}} - E_{\mathrm{beam}}, \tag{4}$$

where

$$E_{\mathrm{tot}} = \sum_{i=1}^{2} E_{\alpha_i} + E_{\mathrm{rec}}. \tag{5}$$

Here E_{rec} is the kinetic energy of the undetected ^{8}Be recoil nucleus. This was calculated from conservation of momentum

$$\mathbf{P}_{\mathrm{rec}} = \mathbf{P}_{\mathrm{beam}} - (\mathbf{P}_{\alpha_1} + \mathbf{P}_{\alpha_2}), \tag{6}$$

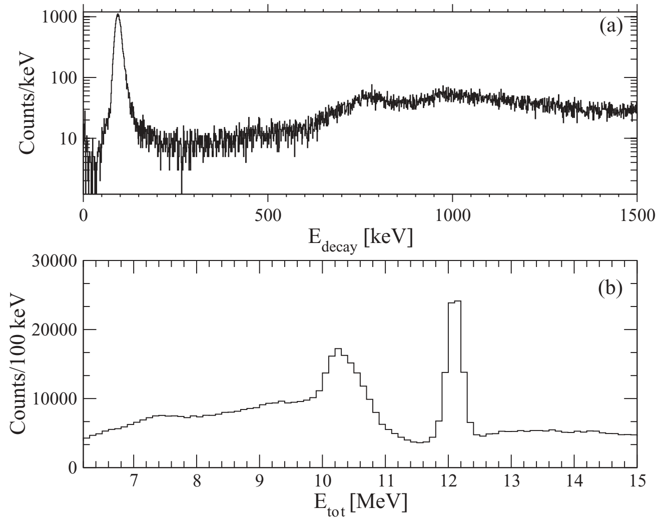

FIG. 1. (a) The decay-energy spectrum for multiplicity two events at $E_{\mathrm{beam}} = 19.6$ MeV. The peak close to 92 keV corresponds to the decay of the ^{8}Be ground state. (b) The total energy spectrum for ^{12}C(^{4}He, ^{4}He + ^{4}He)^{8}Be reaction and $E_{\mathrm{beam}} = 19.6$ MeV.

$$E_{\mathrm{rec}} = \frac{\mathbf{P}_{\mathrm{rec}}^2}{2m(^8\mathrm{Be})}. \tag{7}$$

Similar expressions can be obtained for carbon channels, but with there being three detected particles rather than two.

For the events in which two particles were detected the ^{8}Be decay-energy spectrum was reconstructed [see Fig. 1(a)]. There is a clear peak close to 92 keV associated with the decay of the ^{8}Be ground state. The total energy spectrum for the ^{12}C(^{4}He, ^{4}He + ^{4}He)^{8}Be reaction is shown in Fig. 1(b) for the beam energy of 19.6 MeV. There is a strong peak close to 12.2 MeV ($E_{\mathrm{beam}} + Q$) associated with the ^{12}C(^{4}He, ^{4}He + ^{4}He)^{8}Be$_{\mathrm{g.s.}}$ reaction. The peaks at lower energies correspond to the formation of excited states in the second (undetected) ^{8}Be and contributions from the ^{12}C(^{4}He, ^{12}C*(^{4}He + ^{8}Be))^{4}He reaction which contaminate the spectrum. The resolution of the peak in the ^{8}Be decay spectrum is 20 keV [[full width at half maximum (FWHM)] and the resolution in total energy is 270 keV. In order to evaluate the yield for the ^{12}C(^{4}He, ^{8}Be$_{\mathrm{g.s.}}$)^{8}Be$_{\mathrm{g.s.}}$ reaction the number of events which simultaneously fell within the 92 keV and 12.1 MeV peaks in the Figs. 1(a) and 1(b) were evaluated as a function beam energy (see Sec. C).

Figure 2 shows the equivalent analysis for the detection of three particles in the array. The reconstructed ^{12}C excitation energy spectrum is shown in Fig. 2(a). The peaks associated with the 7.65 MeV, 0^+ and 9.64 MeV, 3^- states are clearly observed. The corresponding resolutions (FWHM) are 55 and 180 keV, respectively. The total energy spectrum corresponding to the ^{12}C(^{4}He, ^{4}He + ^{4}He + ^{4}He)^{4}He reaction is shown in Fig. 2(b). The peak at 12.1 MeV (FWMH = 630 keV) corresponds to the reaction leading to the 4α final state. Again events associated with the ^{12}C(7.65, 0^+) + α and ^{12}C(9.64, 3^-) + α final states were selected by gating on the peak in Fig. 2(b) and then integrating the number of counts in the 7.65 and 9.64 MeV peaks in Fig. 2(a).

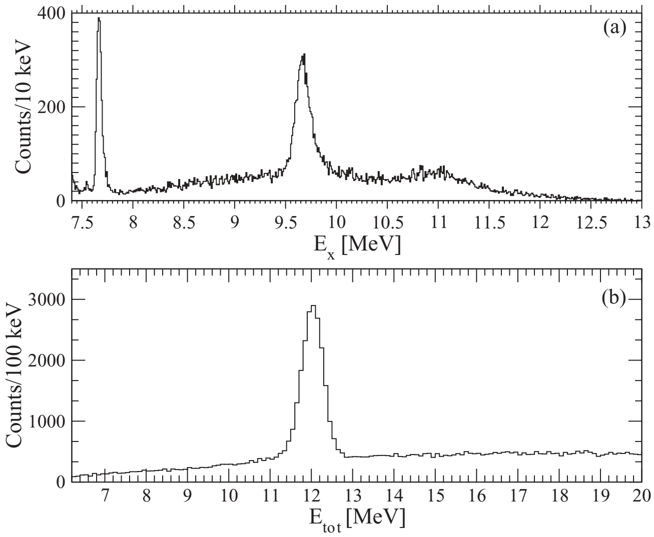

FIG. 2. (a) The ^{12}C excitation energy spectrum for multiplicity three events at $E_{\text{beam}} = 19.6$ MeV. The peaks close to 7.65 and 9.64 MeV correspond to the decay of the 0^+ and 3^- states, respectively. (b) The total energy spectrum for ^{12}C(^{4}He, ^{4}He + ^{4}He + ^{4}He)^{4}He reaction and $E_{\text{beam}} = 19.6$ MeV.

The yields extracted from the integration of the peaks were normalized by the integrated beam exposure for each energy and then plotted in Fig. 3. It should be noted that the data have not been corrected for detection efficiency since to do so would require a detailed understanding of the angular distributions for the various reaction channels. The threshold for the ^{8}Be + ^{8}Be and ^{12}C(0^+) + α decay channels are 14.62 and 14.81 MeV and that for the ^{12}C(3^-) + α channel lies nearly 2 MeV higher (16.80 MeV). The yields in the first two channels extend down to $E_x = 16.5$ MeV and the latter starts close to 18.5 MeV. At these low energies, the yields are dominated by the Coulomb barrier. The excitation function from the previous measurements of Chevallier *et al.* [3] which corresponds to the $\theta_{\text{c.m.}} = 90^\circ$ component is presented in Fig. 3(a). The present data correspond to $\theta_{\text{c.m.}} = 20^\circ$ to 80° (or equivalently $\theta_{\text{c.m.}} = 100^\circ$ to 160°) and so does not overlap completely with the previous measurements. The current data therefore represent more closely the total yield—which will contain both resonant and transfer components. Nevertheless, a comparison with the angular distributions in the present measurements and those in Ref. [3] show good agreement over the angular range which the data-set overlap. It is possible to correlate some of the structures in both measurements. For example, between $E_x = 16.5$ and 17.5 MeV, the two spectra have peaks close to 17.0 and 17.3 MeV. Between 17.5 and 18.0 MeV there are additional peaks in the present data which are broadly not found in the earlier measurements which were limited to 90°. The strong peaks in the Chevallier data close to 18.1 MeV are found to have reduced strength in the angle integrated yield. The peak close to 18.6 MeV in the present data is shifted to slightly higher energies in the 90° yield. Finally, the broad bump between 19.5 and 21 MeV is shifted slightly higher in energy in the earlier measurements [3].

The comparison with the ^{12}C(0^+) and ^{12}C(3^-) channels is interesting. For the ^{12}C(0^+) + α decay channel it is possible that resonances with negative parity (1^-, 3^-, 5^-, ...)

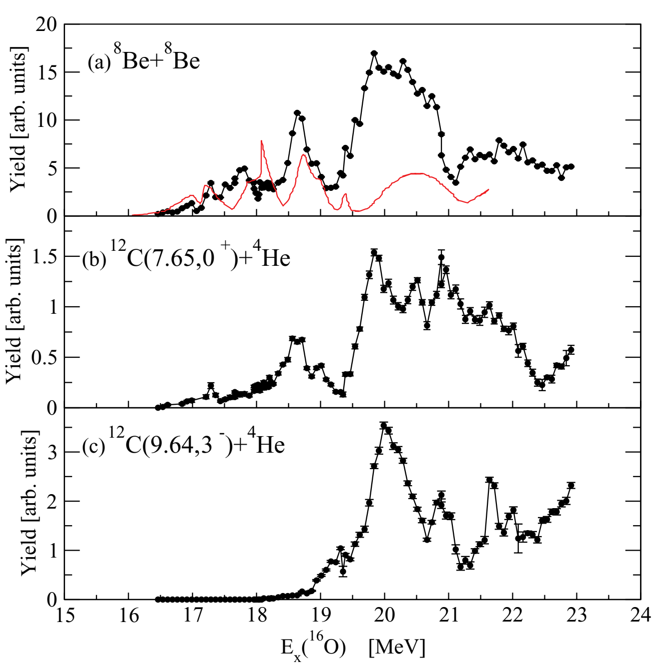

FIG. 3. (Color online) Excitation functions for (a) ^{8}Be + ^{8}Be, (b) ^{12}C(0^+) + α and (c) ^{12}C(3^-) + α final states. The solid (red) line in (a) corresponds to the measurements of Chevallier *et al.* [3]. Error bars reflect the statistical uncertainties.

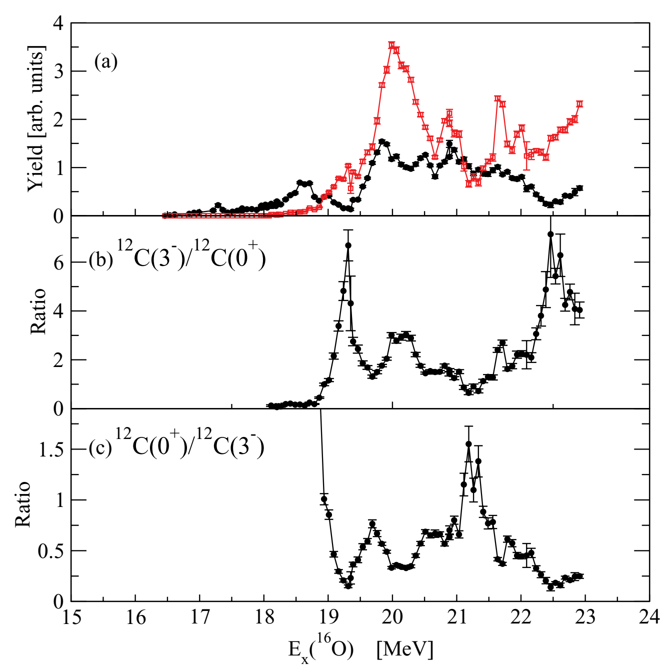

FIG. 4. (Color online) (a) Comparison between the ^{12}C(0^+) + α (black) and ^{12}C(3^-) + α (red) decay channels. (b) The ratio of the normalized yield in the ^{12}C(3^-) channel to that in ^{12}C(0^+) and (c) the yield associated with the ^{12}C(0^+) final state divided by that in ^{12}C(3^-).

contribute, whereas due to the decay to identical spin-zero bosons only even spin and parity states may contribute to the ^{8}Be spectrum. The peaks at $E_x = 17.28\,(5)$, 18.65 (5) MeV are found in both the ^{8}Be and ^{12}C(0^+) final states, where as the structure at 19.00 (5) MeV only appears in the spectrum associated with the ^{12}C(0^+) final state. It is possible that this indicates an odd-spin, odd-parity state. At excitation energies above 19.5 MeV both spectra in Figs. 3(a) and 3(b) reveal broad structures. The ^{12}C(0^+) spectrum indicates that there are again additional components not distinguishable in the ^{8}Be spectrum. The ^{12}C(3^-) spectrum [Fig. 3(c)] shows some features which overlap with those in the ^{12}C(0^+) channel, but there are clear differences.

Figure 4 shows the comparison between the two ^{12}C decay channels. Figures 4(b) and 4(c) show the ratio of the two yields [^{12}C(3^-)/^{12}C(0^+) and ^{12}C(0^+)/^{12}C(3^-)]. In principle one would expect states with a well-developed cluster structure in ^{16}O to preferentially decay to the 7.65 MeV, 0^+ state in ^{12}C. It can be seen from Fig. 4(b) that there are structures at 19.30 (5), 20.14 (5), and 21.67 (5) MeV which might be associated with the ^{12}C(3^-) decay channel. Conversely, the structures at 19.70 (5) and 21.27 (5) MeV appear to be most strongly associated with decays to ^{12}C(0^+). There is some evidence that there are corresponding structures in the ^{8}Be + ^{8}Be decay channels at the same energy as those in the ^{12}C(0^+) channel.

The data for the ^{8}Be + ^{8}Be decay channel are compared in Fig. 5 with those previously from the ^{12}C(^{4}He, ^{8}Be)^{8}Be reaction [3] and the spectrum for the ^{12}C(^{12}C, ^{8}Be + ^{8}Be)^{8}Be measured at a beam energy of 84 MeV [7]. The resolution of the latter measurement is clearly not sufficient to resolve much of the structure in the excitation function measurement. Nevertheless, there is good agreement between the structure observed in all measurements at $E_x = 20.1\,(1)$ MeV. In the measurements of the ^{12}C(^{12}C, ^{8}Be + ^{8}Be)^{8}Be reaction, this state was found to have $J^\pi = 6^+$. However, the ^{12}C(^{12}C, ^{8}Be + ^{8}Be)^{8}Be reaction shows an additional component at 21.2 (1) MeV which is not found in the excitation function measurements. The ^{12}C + ^{4}He reaction would most strongly populate $4p$-$4h$ excitations; it is thus possible that this additional structure is associated with a more complex particle-hole structure.

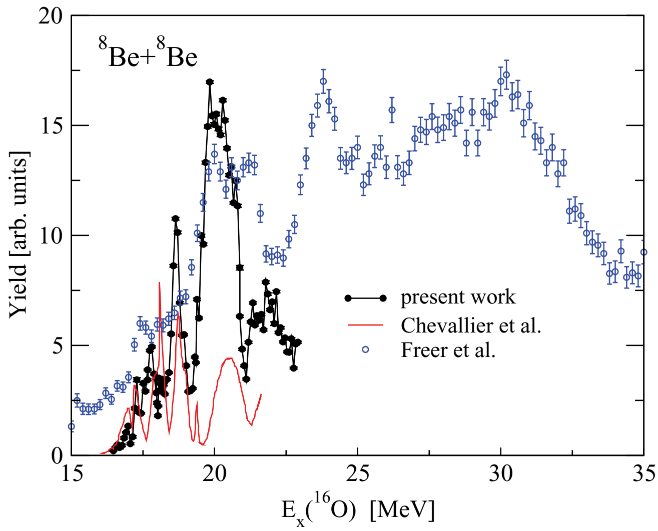

FIG. 5. (Color online) ^{16}O excitation energy spectra for the ^{8}Be + ^{8}Be decay channel. The data from the ^{12}C(^{4}He, ^{8}Be)^{8}Be reaction from the present measurements and those of Chevallier *et al.* [3] are compared with the spectrum for the ^{12}C(^{12}C, ^{8}Be + ^{8}Be)^{8}Be measured at a beam energy of 84 MeV [7].

Excitation function measurements of the ^{12}C(^{4}He, ^{8}Be)^{8}Be, ^{12}C(^{4}He, ^{12}C[7.65, 0^+])^{4}He and ^{12}C(^{4}He, ^{12}C[9.64, 3^-])^{4}He reactions have been performed, populating ^{16}O between excitation energies of 16.5 and 23 MeV. A comparison has been made between ^{12}C(7.65 MeV, 0^+) and ^{12}C(9.64 MeV, 3^-) final states which contain strongly developed α cluster and more compact structures respectively. There is some evidence for components in the ^{16}O excitation energy spectrum, at 19.70 (5) and 21.27 (5) MeV which mainly decay to ^{12}C(7.65 MeV, 0^+). Correspondingly, these may be associated with α-particle-like states in ^{16}O.

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