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Does a 4-α linear chain exist in ^{16}O?

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Abstract. The ^{12}C(^{4}He,^{8}Be)^{8}Be reaction has been measured with a beam energy ranging from 12.2 to 20.0 MeV. The α-particles emitted in the decay of ^{8}Be were detected in an array of four double sided silicon strip detectors. The excitation function for events in which the ^{8}Be centre of mass angle $\theta_{\rm cm} = 90^\circ$ provides evidence that the previously observed 6^+ resonance at an excitation energy of 19.35 MeV in ^{16}O is a 6^+ doublet, with members at $\sim$ 19.30 and 19.37 MeV.

1. Introduction

In 1967 Chevallier *et al.* reported [1] on the results of a measurement of the ^{12}C(^{4}He,^{8}Be)^{8}Be reaction. A number of resonances were observed in the excitation function obtained for the ^{8}Be centre of mass angle $\theta_{\rm cm} = 90^\circ$, ranging from an excitation energy (E$_{\rm x}$) in ^{16}O of $\sim$ 16 to 21 MeV. A study of the angular distributions for the resonances allowed spin and parity (J^π) assignments to be made for the resonances at $E_{\rm x} = 16.95$, 17.15, 18.05 and 19.35 MeV, these being $J^\pi = 2^+$, 2^+, 4^+ and 6^+, respectively. The energy - spin systematics for these four resonances indicate that a rotational structure is populated in the ^{12}C(^{4}He,^{8}Be)^{8}Be reaction, the moment of inertia of which is approximately four times larger than that calculated classically for the spherical ^{16}O ground state. The conclusion of Chevallier et al. [1] is that the structure corresponds to a rigidly rotating linear arrangement of four α-particles in a string.

The idea that a structure exists in ^{16}O that corresponds to a four α-particle chain state is supported by theoretical work. For example, a rotational band is predicted in the Alpha Cluster Model (ACM) calculations of Bauhoff et al. [2], that has the same rotational parameter, $\hbar^2/2I$ (where I is the moment of inertia) = 64 keV, and a very similar band head energy, $E_0 = 16.3$ MeV, as the band seen in the Chevallier measurements ($\hbar^2/2I = 64$ keV and $E_0 = 16.7$ MeV). The density contour plot for the ACM band (Fig. 3 in Ref. [2]) quite clearly shows a linear arrangement of four α-particles.

In order to confirm the results of Chevallier *et al.* a new measurement of the ^{12}C(^{4}He,^{8}Be)^{8}Be excitation function has been performed. In addition to studying the four resonances observed by Chevallier *et al.* that form the chain state rotational band, the current work aims to obtain spin assignments for the other resonances reported in [1]. A search will also be made for the $J^{\pi} = 8^{+}$ member of the band, which, from the energy - spin systematics of the known band members, should lie at $E_x(^{16}O) \sim 21.3$ MeV.

2. Experimental Details

The experiment was performed using a ^{4}He beam provided by the University of Notre Dame FN tandem. A total of 344 unique beam energies were studied, ranging from 12.2 to 20.0 MeV. The energy ranges and step sizes used are listed in table 1. To provide a cross-check during the analysis, 40 beam energies were measured twice and 4 were measured three times. The average beam exposure was (3700 ± 1600) nC for each beam energy run.

Table 1. Measured beam energy ranges and step size.

Beam energy range (MeV)	Beam energy step (keV)	Beam energy range (MeV)	Beam energy step (keV)
12.50 - 20.00	100	18.21 - 18.60	30
18.25 - 19.35	100	12.20 - 13.69	10
13.72 - 13.90	30	16.24 - 16.28	10
14.21 - 14.80	30	18.10 - 18.67	10
15.99 - 16.50	30	19.25 - 19.45	10

Two carbon targets were used during the experiment, the thickness of each being obtained from measurements of the energy loss of α-particles emitted by a collimated α-source. The first target was measured to be ~ 46 μg/cm^2 at the start of the experiment and ~ 53 μg/cm^2 after exposure to the beam. The second target was initially ~ 40 μg/cm^2, increasing to ~ 51 μg/cm^2 after use. During the analysis the increase in thickness has been assumed to scale linearly with beam exposure, and a correction made for each individual run. The cross-sections obtained from the two different targets for runs at the same beam energies are consistent, supporting this analysis method.

The α-particles emitted in the ^{12}C(^{4}He,^{8}Be $\rightarrow \alpha+\alpha$)^{8}Be $\rightarrow \alpha+\alpha$ reaction were detected in an array of four double sided silicon strip detectors (DSSD). Each DSSD was (5×5) cm in active area and 500 microns thick. The front face of each detector was segmented into 16 horizontal strips, and the back face into 16 vertical strips, each strip being 3 mm wide. The four detectors were placed at the same height within the scattering chamber, such that each was centred vertically with the beam axis. Two DSSD's were positioned on either side of the beam. The target to detector distances and centre angles were 10.0 cm and $+50.9^{\circ}$, 13.8 cm and $+23.0^{\circ}$, 13.6 cm and -28.3° and 10.5 cm and -54.5°. The detectors were calibrated using a 2-line (^{148}Gd and ^{241}Am) α-source and the elastic scattering of a ^{4}He beam from Pb, Al and C targets. The energy resolution of the detectors, as measured with the 2-line α-source, was $\sim$ 80 keV.

3. Analysis and Results

In order to study the ^{12}C(^{4}He,^{8}Be $\rightarrow \alpha+\alpha$)^{8}Be $\rightarrow \alpha+\alpha$ reaction, events are first selected based on the number of detected particles in the DSSD array. The results presented below correspond to a detected multiplicity of M = 2, where both particles were detected on the same side of the beam. The detector array used in the experiment did not provide particle identification, so in the analysis described both hits are assumed to be α-particles.

If the two detected α-particles have energies E_1 and E_2 and momenta $\mathbf{P}_1$ and $\mathbf{P}_2$, the decay energy (E_{decay}) of the parent ^{8}Be may be obtained from $E_{decay} = E_1 + E_2 - E_{Be}$. Here $E_{Be} = \mathbf{P}_{Be}^2/2m$, where m is the mass of ^{8}Be and $\mathbf{P}_{Be} = \mathbf{P}_1 + \mathbf{P}_2$. An example ^{8}Be decay energy spectrum, obtained at a beam energy of 19.0 MeV, is shown in Fig. 1. A peak is seen at an energy equal to the Q-value of the α-decay of the ^{8}Be ground state (^{8}Be$_{gs}$), Q_2 = 93 keV. The background corresponds to either events in which the two hits have been incorrectly identified as α-particles, or in which the two α-particles did not arise from the decay of a ^{8}Be$_{gs}$.

After gating on the peak observed in Fig. 1 to select ^{8}Be$_{gs}$ events, the Q-value is reconstructed in order to distinguish between the ^{12}C(^{4}He,^{8}Be$_{gs}$)^{8}Be$_{gs}$ and ^{12}C(^{4}He,^{12}C$^* \rightarrow$ ^{8}Be$_{gs}$ + α)^{4}He reactions. The Q-value is equal to the difference between the beam energy (E_{beam}) and the sum of the α-particle and recoil (E_{rec}) energies, $Q = E_1 + E_2 + E_{rec} - E_{beam}$. The recoil energy is determined by applying momentum conservation between the beam and two detected α-particles and by assuming the recoil mass. In this analysis the recoil is assumed to be a single, mass 8, particle. Events from the ^{12}C(^{4}He,^{12}C$^* \rightarrow$ ^{8}Be$_{gs}$ + α)^{4}He reaction should not be reconstructed within the Q-value peak for the ^{12}C(^{4}He,^{8}Be$_{gs}$)^{8}Be$_{gs}$ channel, as in this case there will be two undetected, mass 4, particles. The Q-value spectrum for a beam energy of 19.0 MeV is shown in Fig. 2. A sharp peak can be observed at an energy equal to the Q-value for the ^{12}C(^{4}He,^{8}Be$_{gs}$)^{8}Be$_{gs}$ channel, $Q_3 = -$ 7.365 MeV.

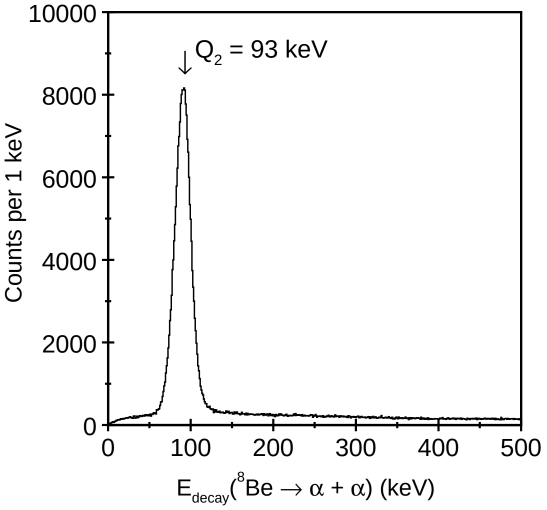

Figure 1. E_{decay}(^{8}Be) at a beam energy of 19.0 MeV. The arrow indicates the Q-value for the α-decay of ^{8}Be.

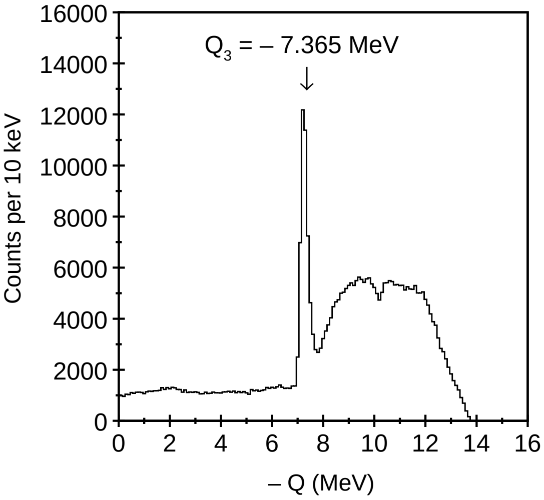

Figure 2. Q-value spectrum at a beam energy of 19.0 MeV. The arrow indicates the Q-value for the ^{12}C(^{4}He,^{8}Be$_{gs}$)^{8}Be$_{gs}$ reaction.

The cross-section for the ^{12}C(^{4}He,^{8}Be$_{gs}$)^{8}Be$_{gs}$ reaction is obtained from the yield in the Q-value peak, after corrections have been applied for the beam exposure, target thickness and detection efficiency. The detection efficiency was obtained from Monte Carlo simulations of the reaction, in which the production and decay of the two ^{8}Be nuclei was assumed to be isotropic. The simulations reproduce the angles covered by the DSSD array, as well as the detection energy thresholds. The predicted efficiency for simulated events with a ^{8}Be centre of mass angle of θ_{cm} = (90 ± 10)° is (0.784 ± 0.002) % at E_x(^{16}O) = 16.304 MeV (E_{beam} = 12.2 MeV), falling to (0.534 ± 0.002) % at E_x(^{16}O) = 22.164 MeV (E_{beam} = 20.0 MeV). The simulations indicate background from the ^{12}C(^{4}He,^{12}C$^* \rightarrow$ ^{8}Be$_{gs}$ + α)^{4}He reaction, integrated into the yield in the ^{12}C(^{4}He,^{8}Be$_{gs}$)^{8}Be$_{gs}$ Q-value peak, is only possible from the decay of ^{12}C via the 7.65 MeV, 0_2^+, state. The efficiency for such background is (0.192 ± 0.001) % at E_x(^{16}O) = 16.304 MeV, falling to zero at $E_x(^{16}O) = 17.280$ MeV ($E_{beam} = 13.5$ MeV). Such background is therefore not possible above this limit.

The excitation function for ^{8}Be centre of mass angles $\theta_{cm} = (90 \pm 10)^\circ$ is shown in Fig. 3. The agreement with the previous results of Chevallier *et al.* [1] is generally excellent, with an exception in the region $E_x(^{16}O) = 19.2 - 19.5$ MeV (shown in the inset to Fig. 3). In the Chevallier work a single 6^+ resonance is observed at $E_x = 19.35$ MeV, whereas in the current data this peak is seen as a doublet with members at ∼ 19.30 and 19.37 MeV. It should be noted that the absolute cross-section scale in Fig. 3 is estimated to be 10 – 15 % too low, as it has not been possible to include a correction for the acquisition dead time. However, it is believed that such a correction would not effect the relative values for the individual data points by a large amount, as the shape of the excitation function agrees well with the Chevallier results. The error bars on the reaction cross-section in Fig. 3 result from a combination of the uncertainties in the beam exposure, target thickness, detection efficiency and statistical yield. The error bars on the ^{16}O excitation energy scale result mainly from the differential energy loss of the beam for reactions occurring at the front and back faces of the target. This leads to a variation in the centre of mass energy, and hence E_x. The contribution from the uncertainty in target thickness is also included, although this is small.

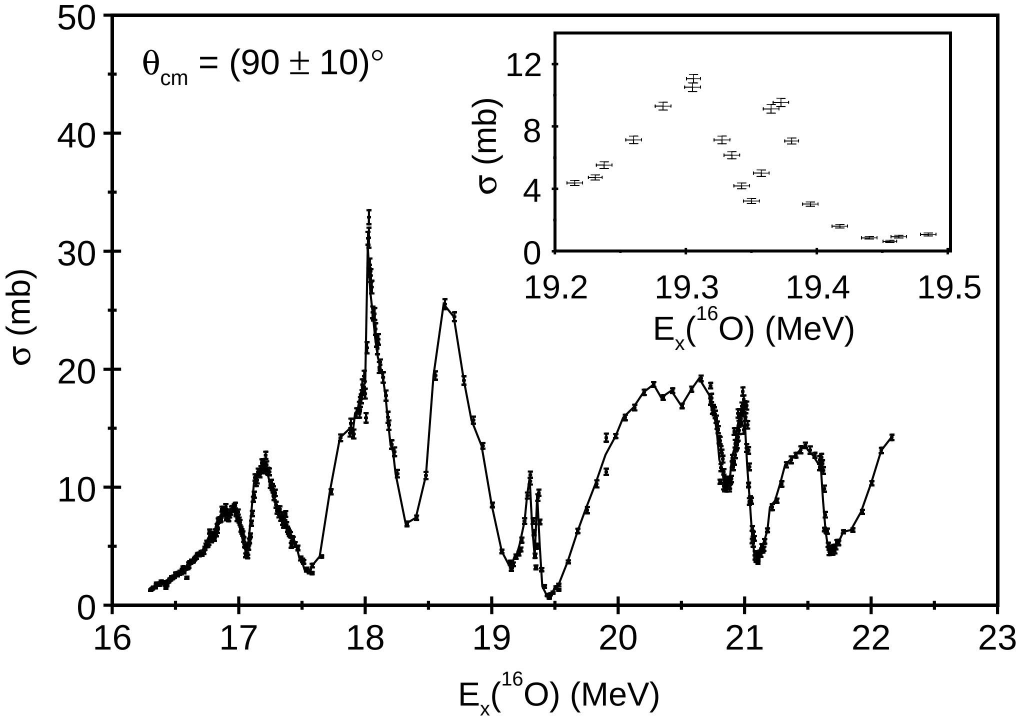

Figure 3. Excitation function for the $^{12}C(^4He,^8Be_{gs})^8Be_{gs}$ reaction for $\theta_{cm} = 90^\circ$. The line indicates the cross-section averaged in 20 keV wide bins. The region of the 6^+ doublet is shown in the inset.

The ^{8}Be centre of mass angular distributions for three points across the $E_x \sim 19.35$ MeV doublet are shown in Fig. 4. In Fig. 4(a) the angular distribution for the $E_x = 19.306$ MeV data point, the highest point of the left hand peak seen in the inset to Fig. 3, is shown. This exhibits a periodic structure that is well described by a squared Legendre polynomial of order 6, as is the $E_x = 19.373$ MeV point shown in Fig. 4(c) (in both Figs. 4(a) and (c) the polynomial has been arbitrarily scaled on the Y-axis). The $E_x = 19.373$ MeV data point corresponds to the highest point of the right hand peak in the inset to Fig. 3. In both cases the good agreement between the data and the polynomial suggests that the angular distributions are dominated by L = 6, indicating that both resonances are $J^{\pi} = 6^{+}$. The E_x = 19.350 MeV data point lies at the bottom of the valley between the two peaks seen in the inset to Fig. 3. The angular distribution (Fig. 4(b)) does not not have the periodic structure seen in Figs. 4(a) and (c), a result of destructive interference.

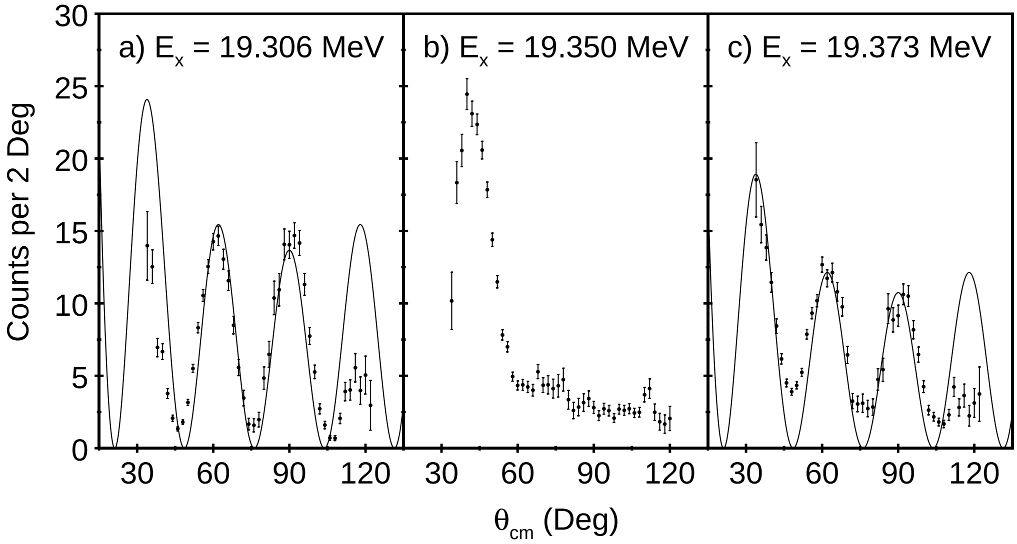

Figure 4. Angular distributions for $E_x(^{16}O)$ = a) 19.306, b) 19.350 and c) 19.373 MeV. The smooth line in a) and c) is a squared Legendre polynomial of order 6.

4. Summary and Future Work

The $^{12}C(^{4}He,^{8}Be_{gs})^{8}Be_{gs}$ reaction has been studied using a 12.2 – 20.0 MeV ^{4}He beam. The $\theta_{cm} = 90°$ excitation function is generally in excellent agreement with the results of Chevallier *et al.* [1]. Once exception is that the 6^{+} resonance previously observed at E_x = 19.35 MeV in ^{16}O is now seen to be a doublet, with both members appearing to be 6^{+}.

In order to study the spins of all of the resonances observed in Fig. 3 a phase shift analysis of the angular distributions will be performed. This will involve fitting the angular distributions with the function described by Chevallier *et al.* [1],

$$W(\theta) = |\sum_{L=0}^{L_{max}} \rho_L e^{i\varphi_L} P_L(cos\theta)|^2, \quad \varphi_0 = 0, \tag{1}$$

where $P_L(cos\theta)$ is a Legendre polynomial of order L, ρ_L the amplitude of the polynomial and φ_L the phase. A study of the systematics of the amplitudes and phases for each L value across the resonances will allow the dominant L, and hence spin, of the resonances to be determined.

The data will also be analysed to study the $^{12}C(^{4}He,^{12}C^{*}[7.65\text{ MeV}, 0_2^{+}] \rightarrow {}^{8}Be_{gs} + \alpha)^{4}He$ and $^{12}C(^{4}He,^{12}C^{*}[9.64\text{ MeV}, 3^{-}] \rightarrow {}^{8}Be_{gs} + \alpha)^{4}He$ reactions using multiplicity M = 3 events. A comparison of the $^{8}Be + {}^{8}Be$ and $^{12}C + {}^{4}He$ channels will provide information on the structure of the resonances, and help answer the question, does a 4-α linear chain exist in ^{16}O?

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