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A newly observed state in ^{12}C – characterisation and consequences

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Abstract. Measurements of the ^{12}C(^{4}He,^{4}He)^{12}C* reaction at 40 MeV were performed using a charged-particle detector array composed of four double-sided silicon strip detectors. Resonances in ^{12}C were reconstructed with the requirement that the α-decay proceeded first via the ^{8}Be ground state. Of primary significance was the population of the 13.3 and 22.4 MeV resonances, the latter, observed for the first time in this measurement. By using the angular correlation technique the spins of the resonances, have been established as J^π=4$^+$ and J^π=5$^-$ respectively.

1. Introduction

Despite all the knowledge acquired over several decades, there are still important details that remain unexplained regarding the nature of the ^{12}C nucleus. Its second excited state at 7.654 MeV (0$^+$) was first proposed 61 years ago by Fred Hoyle in order to explain the abundance of ^{12}C in the universe [1]. Carbon-12 is of great importance for the creation of the elements key to organic life, as well as being the primary step in the synthesis of heavier nuclei in stars. The structure of the Hoyle state is a significant open question. It is known to be composed of three α-particles, but the precise arrangement remains unclear. *Ab initio* calculations suggest the state is configured as a bent-arm [2], in which the three α-particles are located at the vertices of an open triangle. The measurement reported here was motivated by the idea of measuring and characterising the 13.3 MeV excited state in ^{12}C which had previously been observed by members of the Charissa collaboration [3, 4], and which is thought to be a candidate member of the Hoyle-state band. Recent investigations show the existence of a 2$^+$ resonance, which could be a collective rotation or vibration of the Hoyle-state [5, 6]. The 13.3 MeV resonance may be one of these collective resonances. Ultimately, by making evermore precise measurements, the data may be sufficiently discriminating to refine current nuclear models. Some results from the present study have been published in [7].

2. Experimental Details

The measurements were performed at the University of Birmingham's MC40 cyclotron with a ^{4}He beam at an energy of 40 MeV incident on a 100 μgcm^{-2} ^{12}C target. The reaction of interest was ^{12}C(^{4}He,^{4}He+^{4}He+^{4}He)^{4}He which corresponds to the inelastic excitation of ^{12}C above the three α-decay threshold at 7.275 MeV. A bespoke charged-particle detector array of four double-sided silicon strip detectors (DSSSDs) was used. Each detector is subdivided by 16 vertical and 16 horizontal strips on the front and back faces respectively giving a 5 $\times$ 5 cm^2 surface with

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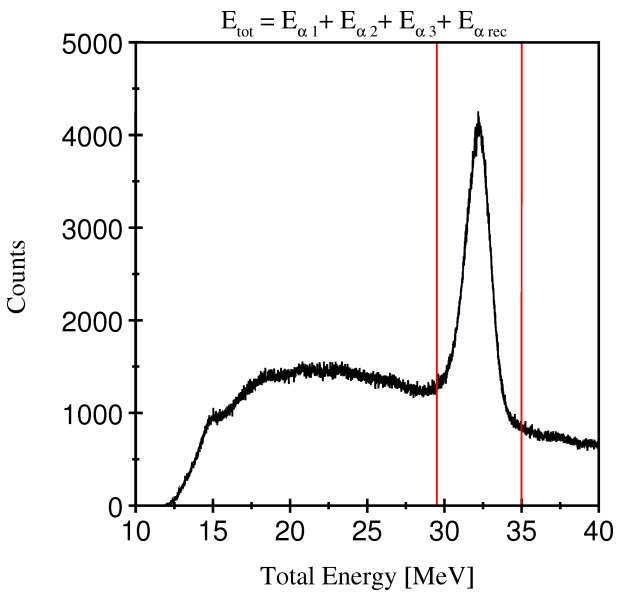

Figure 1. Total energy spectrum. The region between the two red lines was selected, as this corresponds to events proceeding from the ^{12}C(^{4}He,^{4}He+^{4}He+^{4}He)^{4}He reaction (Q=−7.275 MeV).

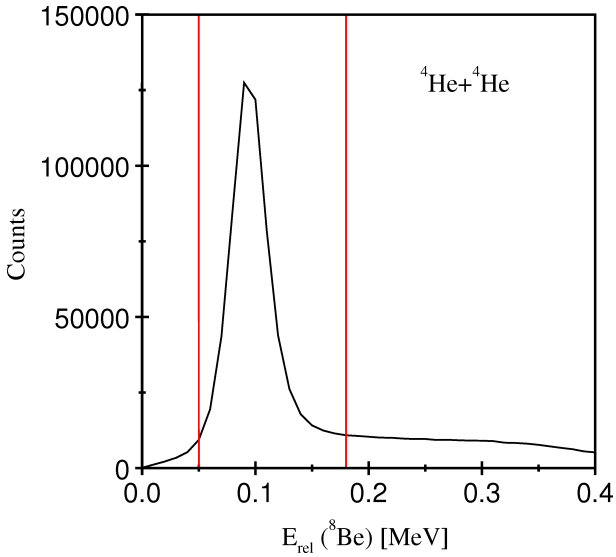

Figure 2. Peak associated with the decay from the ^{8}Be ground state at 92 keV. Data between the two red vertical lines were selected for further analysis.

a thickness of 500 μm. The master trigger was such that at least three of the four final-state particles were recorded via detectors placed at distances 13.0, 11.0, 11.0, 13.0 cm from the target at in-plane angles 62.0°, 32.0°, −32.0°, −62.0°, respectively (positive and negative values indicate opposite sides of the beam axis). The array covered an angular range of θ_{lab} = 20° to 75°. The detectors were calibrated with a triple α-particle source.

3. Analysis and Results

The DSSSDs do not have explicit particle identification so event selection was achieved through the full kinematic reconstruction allowing the energy and scattering angle of each particle to be determined and, therefore, the momentum. By conservation of momentum and energy the fourth, undetected α-particle was reconstructed. Using the information from all the products and the beam energy it was then possible to create the total energy spectrum for the reaction, as shown in figure 1. This allowed events from the reaction of interest to be selected, with Q= −7.275 MeV. A second filter, which gives an additional level of selectivity, required events originating only from the decay of the ^{8}Be nucleus in its ground state, reconstructed from pairs of detected α-particles for events within the peak of figure 1. The centroid of the peak of figure 2, at a relative energy, E_{rel} = 92 keV, clearly identifies the decay of the ^{8}Be ground state.

To visualise the event energy landscape, a Dalitz plot was generated as shown in figure 3. Excitation energies in ^{12}C were calculated for the case in which three α-particles from the decay from ^{12}C were detected (horizontal axis). For the vertical axis the excitation energies were calculated for events in which one of the ^{12}C break-up α-particles was undetected, *i.e.* the reconstructed particle; the scattered beam particle being one of the three hits. It is possible to observe features running parallel to the horizontal and the vertical axes, as well as diagonal ridges (with a gradient equal to -1). The horizontal and vertical features correspond to resonances in ^{12}C and the diagonal lines to states in ^{8}Be (from right to left the ground state is the first diagonal

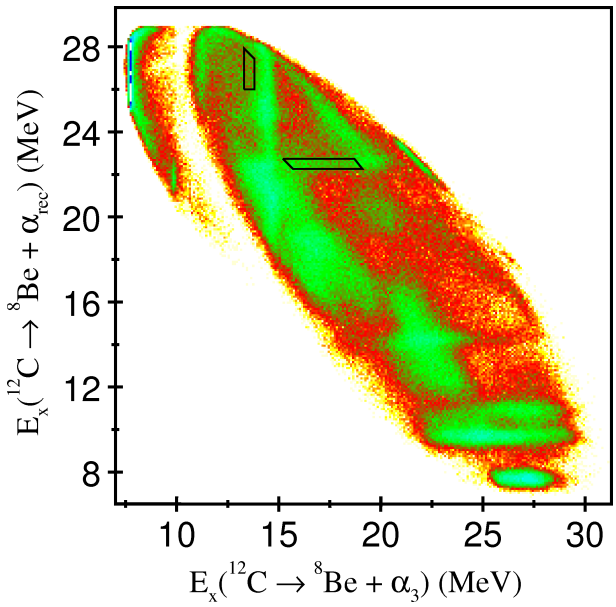

Figure 3. Dalitz plot of the $^{12}C(^4He,^4He)^{12}C^*$ reaction measured at a beam energy of 40 MeV. The solid boxes shows the region selected for the angular correlation analysis.

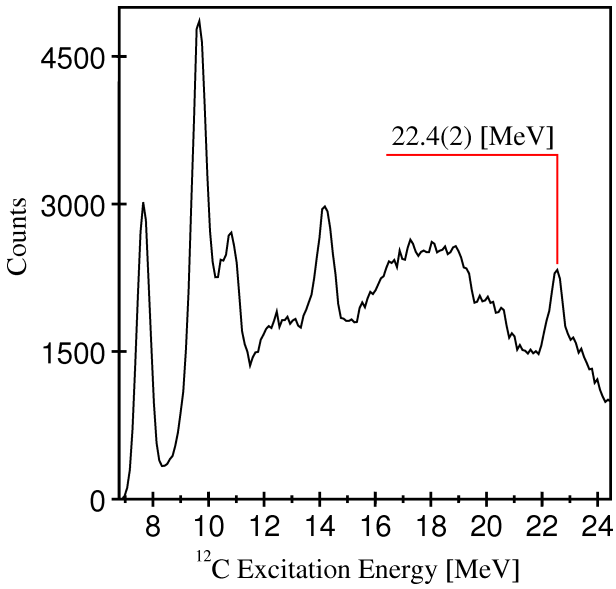

Figure 4. Projection onto the vertical axis of the Dalitz plot of figure 3. Different known resonances are shown as well as the newly observed state at a 22.4(2) MeV.

line). The projection of the Dalitz plot is shown in figure 4, in which excited states at 7.654 (0^+), 9.641 (3^-), 10.844 (1^-), 14.083 (4^+) MeV are observed. Additionally, the presence of a resonance at 22.4(2) MeV is observed for the first time.

3.1. Angular Correlations

With the aim of gaining an insight into the nature of the newly observed state in ^{12}C the distribution pattern of the final products (α-particles) in the decay has been analysed. This analysis method is formally known as angular correlations and is model independent when the initial and final particles all have spin zero, as here. A more detailed explanation of this method can be found in [8]. For this correlation analysis it is necessary to define the centre-of-mass emission angle θ^* of the ^{12}C nucleus with respect to the beam axis, and the emission angle Ψ of the first α-particle from the decay of the resonance in ^{12}C, also with respect with the beam axis, and within the ^{12}C centre-of-mass frame. Using the Dalitz plot of figure 3 it was possible to select a specific excitation energy to be examined. The event selection windows are shown by the solid rectangular boxes in figure 3, for the 13.3 and 22.4 MeV states, determining both the excitation energy and the origin of the particles detected, and therefore, enabling the angular correlation plots for the selected data to be produced. This procedure was first applied to well known resonances, 7.654 (0^+), 9.641 (3^-), 10.844 (1^-) and 14.083 (4^+) MeV, with the aim of demonstrating the effectiveness of the procedure. Subsequently, this method was applied to the 13.3 MeV and the newly observed 22.4 MeV states. The angular correlation plots for the 13.3 MeV and the newly observed resonance are shown in figure 5, demonstrating the key features in which the structure in the θ^*-Ψ plane are dependent on

$$W(\theta^*, \Psi) \propto \mid P_J[\cos(\Psi + \Delta\Psi)] \mid^2, \tag{1}$$

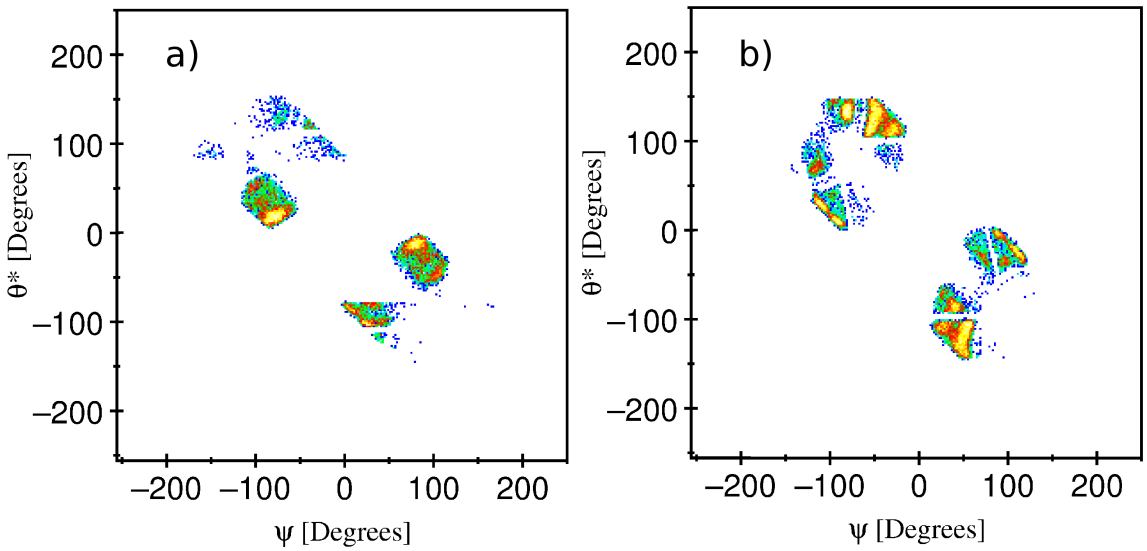

Figure 5. Angular correlation plot a) for the 13.3 MeV resonance and b) for the 22.4 MeV resonance in ^{12}C. The gradient of the angular correlation features increases as the spin increases.

to first order. A small change in Ψ, $\Delta\Psi$, is related to a small change in θ^*, $\Delta\theta^*$, through

$$\frac{\Delta\theta^*}{\Delta\Psi} = \frac{J}{l_{gr} - J}, \tag{2}$$

where l_{gr} is the grazing angular momentum J is the spin of the state and P_J are the Legendre polynomial of order J. Within the θ^*-Ψ plane, the formation of sloped features will appear with a specific gradient $\Delta\theta^*/\Delta\Psi$, given by equation 2 for which the periodicity reveals the spin of the resonance under analysis [8]. For the case of a spin-zero state the gradient will be zero, increasing as the spin increases, as shown in figure 5. In order to analyse the periodicity, the angular correlation plot is projected onto the Ψ axis at a specific angle $\Delta\theta^*/\Delta\Psi$, determined by the spin of the state. For the present reaction, the grazing angular momentum was estimated to be 9.8 $\hbar$ using r_0=1.2 fm, for which the optimum angles for the projection of the data for the 9.641 (3^-), 10.844 (1^-) and 14.083 (4^+) were found to be $\Delta\theta^*/\Delta\Psi$= 6.5°, 25.3° and 39.7° respectively. The known states all exhibit the correct periodicity for the published spin value. From figure 6 it is possible to observe that the 13.3 MeV data appear to best match the periodicity of the Legendre polynomial J=4 and for the case of figure 7 (22.4 MeV) the periodicity corresponds to order J=5. The associated angles are $\Delta\theta^*/\Delta\Psi$= 39.7° and 60.0° for 13.3 MeV and 22.4 MeV respectively. Recent measurements using ^{3}He projectiles observed a peak at 22.2(3) MeV, confirming this state [9].

4. Conclusions

The 13.3 MeV state must have natural parity as the decay involves only spin-zero nuclei, yielding a spin and parity of J^π= 4^+. Similarly for the 22.4 MeV level, the spin and parity are found to be J^π=5^-. The observation of a 5^- resonance at 22.4 MeV is strong evidence for triangular $\mathcal{D}_{3h}$ symmetry [10], based on the pattern of excited states 0^+, 2^+, 3^-, $4^\pm$ and 5^-, predicted by the algebraic cluster model [10], for an equilateral triangle structure. As a result, this symmetry is now established in nuclear physics [7]. The model also predicts additional states such as the 4^- state, degenerate with the 4^+ level; a strong signature of $\mathcal{D}_{3h}$ symmetry [3, 10]. The significance of this result is that the algebraic model also predicts the structure of the Hoyle

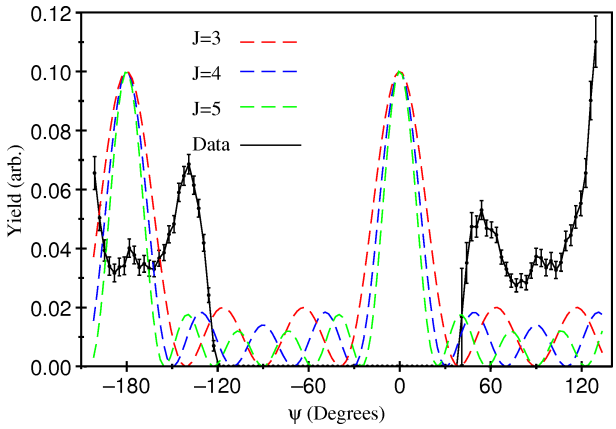

Figure 6. Projection of the angular correlation data for the 13.3 MeV resonance onto the Ψ axis at an angle of 39.7° (black line). The Legendre polynomials of order J=3, 4 and 5 are plotted for comparison (red, blue and green respectively).

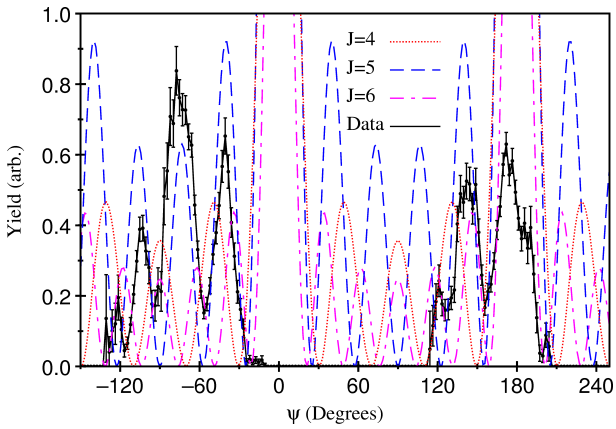

Figure 7. Projection of the angular correlation data for the 22.4 MeV resonance onto the Ψ axis at an angle of 60.0° (black line). The Legendre polynomials of order J=4, 5 and 6 are plotted for comparison (red, blue and magenta respectively), generated from [7].

state to correspond to an expanded equilateral triangle, the excitations of which are calculated to be 0^+, 2^+, 3^-, $4^\pm$, 5^-. The expanded structure means that the energy range is more compact, placing the calculated 5^- Hoyle resonance at around 17 MeV. Such concrete predictions offer a tangible challenge for future experiments.

5. Summary

A measurement of the ^{12}C(^{4}He,^{4}He)^{12}C* reaction establishes evidence for a newly observed resonance at 22.4(2) MeV for which an angular correlation analysis was performed. The spin and parity of the state was found to be J^π=5^- confirming the observation of a triangular oblate spinning top with $\mathcal{D}_{3h}$ symmetry for the first time in nuclear physics. The spin and parity of the 13.3 MeV Hoyle-band candidate has been measured unambiguously as J^π= 4^+.

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