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Excited states of ^{12}C above the alpha-decay threshold

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Abstract. The excitation energy spectrum of ^{12}C is important for both structural and astrophysical reasons; here we present evidence for a new state in ^{12}C. The two reactions ^{12}C(^{4}He,^{4}He+^{4}He+^{4}He)^{4}He and ^{9}Be(^{4}He,^{4}He+^{4}He+^{4}He)n were measured using an array of four double sided strip detectors. Excited states in ^{12}C were reconstructed filtered by the condition that the alpha-decay proceeded via the ^{8}Be ground-state. In both measurements evidence was found for a new state at 13.3(0.2) MeV with a width 1.7(0.2) MeV. Angular correlation measurements from the ^{12}C(^{4}He,^{4}He+^{4}He+^{4}He)^{4}He reaction indicates that the state may have $J^{\pi} = 4^+$.

1. Introduction

Pinning down the structure of light nuclei is a rather important task as it provides the anchor-points for our understanding of the nucleon-nucleon interaction which governs their detailed properties. Such measurements constrain ab initio calculations whereby nuclear properties are calculated from the starting point of the nucleon-nucleon interaction. Correlations between the nucleons have important contributions to the nuclear binding and in light systems can effects which dominate structurally. One manifestation of such correlations is the appearance of clustering. The ^{4}He nucleus is a maximally correlated system, possessing two protons and two neutrons in the $0s_{1/2}$ orbit, which is responsible for the very high binding energy and a first excited state in excess of 20 MeV. The intriguing possibility is that such correlations persist across the spectrum of light nuclei. The nucleus ^{8}Be is well within the reach of ab initio calculations and its properties have been calculated within a number of different frameworks. The Antisymmetrized Molecular Dynamics (AMD) approach[1] which simulates the interaction of nucleons from the starting point of 8 Gaussian wave-packets and an effective interaction clearly indicates that the nuclear density separates out into one which reflects the presence of two alpha-clusters in the ground-state. Here the clusters are not explicitly entered into the calculations, but rather grow from the details of the interaction used. The Greens Function Monte Carlo (GFMC) calculations have a starting point of a parameterized two body nucleon-nucleon interaction and a fitted 3-body component [2]. In this way the interaction is not an effective interaction as appears in the AMD approach. Remarkably, the GFMC approach also reveals a 2α cluster structure in the ground-state. This result is an impressive demonstration of what was already known for many years experimentally – that the ^{8}Be ground-state is highly clustered. The ground-state is unbound to alpha-decay and has a width which indicates strong preformation of the alpha-particles. Further, the

rotational band associated with the ground-state has a moment of inertia commensurate with such a cluster structure.

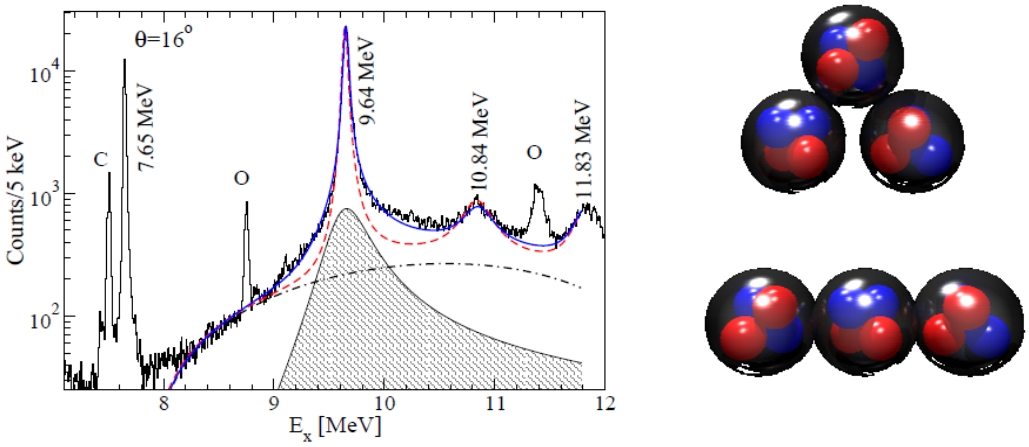

Fig. 1. Left-hand-side. ^{12}C excitation energy spectrum showing the broad 2^+ state required to reproduce the shape of the experimental spectrum, from Ref. 8. Right-hand-side. Possible arrangements of the alpha-clusters in either a triangle (top) or chain (bottom). The experimental data indicate that the triangular structure is preferred.

2. Structure of ^{12}C

The complexity of the GFMC approach prohibits its extension currently to nuclei with A>12, and ^{12}C currently the focus of the calculations. In this nucleus it is excited states, as opposed to the ground-state, which is the focus in terms of alpha-cluster calculations. In fact, the state of interest is the 7.65 MeV, 0^+, Hoyle-state. The Hoyle-state because its existence was proposed by Sir Fred Hoyle some 50 years ago [3]. This state is the gateway through which carbon is synthesized via what is known as the triple-alpha process. Without this state there would be no organic life. Calculations of the properties of the Hoyle-state using the GFMC approach are still on-going. However, calculations using the AMD and its cousin the FMD approach (Fermionic Nuclear Dynamics) [4] reveal a highly clustered state. Its' very dilute nature, together with the 3alpha cluster structure has been interpreted in terms of an alpha-condensate by Peter Schuck and co-workers [5], this would be a new bosonic state of nuclear matter. Very recent calculations using the framework of chiral effective field theory have been able to closely reproduce the energy of the Hoyle-state [6]. Although they offer little detailed structural information they do suggest a larger charge radius than the ground-state, as observed experimentally. As with the ^{8}Be ground-state, the width of the 7.65 MeV state indicates a significant cluster structure and in agreement with theoretical predictions a large charge radius (see Ref. [4]) indicating a volume which is 3-4 times that of the ^{12}C ground state.

Revealing the collective excitations of such a state could have significant implications for understanding its structure. In the alpha-condensate model this would correspond to a 2^+ state which is associated with the conversion of one of the bosons from s-wave to d-wave. In a more traditional cluster model it would correspond to a collective rotation and the moment of inertia would then reveal the details of the cluster arrangement.

3. Experimental Measurements

Recent studies of the $^{12}C(\alpha,\alpha')$ [7] and $^{12}C(p,p')$ [8,9] (see Fig. 1) reactions indicate the presence of a 2^+ state close to 9.6-9.7 MeV with a width of 0.5 to 1 MeV. The state is only weakly populated in these reactions, presumably due to its underlying cluster structure, and is broad. Consequently, its distinction from other broad-states and dominant collective excitations (e.g. the 9.6 MeV, 3^-) makes its unambiguous identification challenging. Further evidence for such an excitation comes from measurements of the $^{12}C(\gamma,3\alpha)$ reaction performed at the HIGS facility, TUNL. Here a measurable cross section for this process was observed in the region of 9-10 MeV which cannot be attributed to known states in this region. Furthermore, the angular distributions of the alpha-particles are consistent with an L=2 pattern, indicating a dominant 2^+ component. Based on a rather simple description of this state in terms of three alpha-particles with radii given by the experimental charge radius, it is possible to use the 2 MeV separation between the Hoyle-state and the proposed 2^+ excitation to draw some conclusions as to the arrangements of the clusters (see Fig. 1). This would indicate that rather than a linear arrangement of the three clusters that a more appropriate description would be a loose arrangement of the alpha-particles in something approaching a triangular arrangement – i.e. the Hoyle-state would be a monopole excitation of the ground-state.

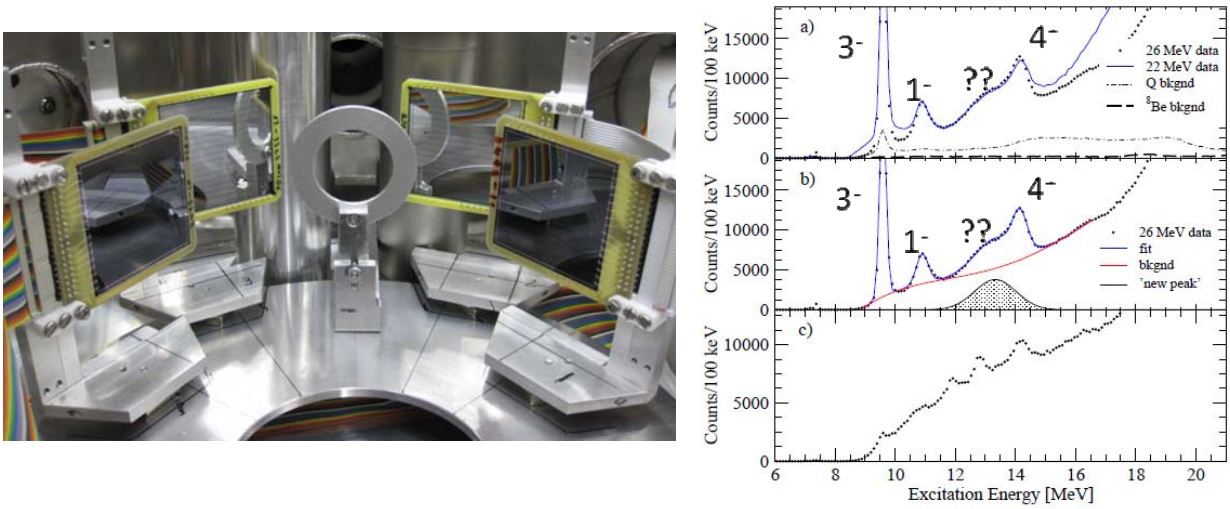

Fig. 2. Left-hand-side. Arrangement of the 4 silicon strip detectors used in the measurements in Ref. [11]. The beam passes from bottom to top in this picture. Right-hand-side. Carbon-12 excitation energy spectra. a) The blue line shows the measurement at 22 MeV. The spectrum corresponding to measurements at 26 MeV is shown by the dots. The backgrounds obtained by gating above the ^{8}Be peak (bold dashed line) and both above and below the Q-value peak (dot-dashed line) are both illustrated. b) Fit to the 26 MeV data is given by the blue solid line. The polynomial background (red-line) and line-shape for the new peak (shaded area) is shown. c) Excitation energy spectrum for events not proceeding via the decay to the ^{8}Be ground-state. The proposed new state is indicated by "??".

A natural extension of such a conclusion is that there should also be a collective 4^+ state. Using the simple $j(j+1)$ scaling, a 4^+ excitation close to $E_x(^{12}C)$ = 14 MeV would be expected. We have performed recent measurements of the two reactions $^9Be(\alpha,3\alpha)n$ and $^{12}C(\alpha,3\alpha)^4He$ [11]. In these measurements three alpha-particles were detected in an array of four silicon strip detectors (shown in Fig 2). The analysis required that two of the three alpha-particles came from the decay of the ground-state of ^{8}Be. For the decay of ^{12}C to ^{8}Be+α this ensures that the decay process can proceed through only natural parity states (i.e. 0^+,1^-, 2^+ ….). This restricts the complexity of the excitation energy spectrum. The measurements for both the ^{9}Be and ^{12}C targets reveal the known 3^-, 1^- and 4^+ states at

9.64, 10.84 and 14.08 MeV, respectively. However, there is an additional component to the spectrum close to 13.3 MeV with a width estimated to be 1.7 MeV (Fig. 2). It is believed that this is not a contaminant and is observed with similar properties in all spectra. Angular correlation measurements made using the ^{12}C target are not definitive, but indicate a 4^+ assignment.

Such measurements are challenging and it is difficult to be absolutely certain that the feature does not correspond to an experimental artifact. Nevertheless, the appearance of a 4^+ state close to the energy predicted based on the extension of the Hoyle-state and proposed 2^+ excitation. Such a feature is also observed in measurements of the neutron energy produced in the ^{9}Be(α,3α)n reaction [12]. However, it is clear that further measurements are required to confirm, or otherwise, this new state in ^{12}C. Moreover, analysis of beta-decay measurements populating alpha-decay states in ^{12}C indicate that there may be broad 2^+ strength in ^{12}C but at somewhat higher energies than suggested in the proton and alpha inelastic scattering measurements [13]. This contradiction between the two types of measurements remains to be reconciled and hence a firm conclusion regarding the excitation structure of ^{12}C above the alpha-decay threshold remains to be established.

It is abundantly clear that the resolution of the structure of the Hoyle-state and the nature of its excitations is of prime importance in nuclear physics as it is simultaneously central to both the understanding of clustering in light nuclear systems and testing ab initio models of nuclei. The renewed interest in this state has been driven by the authors of Reference [5] and in particular Peter Schuck, and the field owes them a great debt.

References

[1] Kanada En'yo Y, Horiuchi H 2001 *Prog. Theo. Phys. Suppl.* **142**, 205
[2] Wiringa R B, Pieper S C, Carlson J and Pandharipande V R 2000 *Phys. Rev.* C **62** 014001
[3] Hoyle F 1954 *The Astrophysical Journal, Supplement Series* Vol. 1 p. 12
[4] Chernykh M, et al. 2007 *Phys. Rev. Lett.* **98** 032501
[5] Tohsaki A, et al. 2001 *Phys. Rev. Lett.* **87** 192501
[6] Epelbaum E, Krebs H, Lee D and Meißner U-G 2011 *Phys. Rev. Lett.* **106** 192501
[7] Itoh M, et al. 2004 *Nucl. Phys.* A **738** 268
[8] Freer M, et al. 2009 *Phys. Rev.* C **80** 041303
[9] Gai M, et al. *submitted to Phys. Rev. C*
[10] Gai M for the UConn-Yale-Duke-Weizmann-PTB-UCL Collaboration 2011 *In press, APH Pol* B, March.
[11] Freer M, Almaraz-Calderon S, Aprahamian A, Ashwood N I, Barr M, Bucher B, Copp P, Couder M, Curtis N, Fang X, Jung F, Lesher S, Lu W, Malcolm J D, Roberts A, Tan W P, Wheldon C and Ziman V A 2011 *Phys. Rev.* C **83** 034314
[12] Aslanoglou X and Kemper K W 1986 Phys. Rev. C **34** 1649
[13] Hyldegaard S, et al. 2010 *Phys. Rev.* C **81** 024303