Characterization of a potential 4-α cluster state

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Abstract
The reaction ^{16}O(α,α') was studied at 0° at an incident energy of E$_{lab}$ = 200 MeV using the K600 magnetic spectrometer at iThemba LABS. Proton and α-decay from the natural parity states were observed in a large-acceptance silicon-strip detector array at backward angles. The coincident charged particle measurements were used to characterize the decay path of the 0_6^+ state in ^{16}O located at E$_x$ = 15.097 MeV. This state is identified by several theoretical cluster calculations to be a good candidate for the 4-α cluster state. Preliminary results indicate the possibility that the 0_6^+ state in ^{16}O is contaminated by the presence of an unresolved state that does not have a 0^+ character.

1. Introduction

Clustering phenomena in light nuclei, in particular α-clustering, have recently attracted much interest [1]. Light nuclei are expected to exhibit cluster-like properties in excited states with a low density structure. Such states should exist at excitation energies near the separation energies to these clusters, as described by the Ikeda diagram [2]. Aside from the interest in the nuclear structure of such states, they have astrophysical relevance as they can enhance element production in stars [3, 4]. The Hoyle state, the 0_2^+ state at 7.654 MeV in ^{12}C, may be considered the prototype of a state that exhibits α-particle condensation [5], i.e. it is considered to have a 3α gas-like structure similar to a Bose-Einstein condensate consisting of three α particles all occupying the lowest $0S$ state.

It is expected that equivalent Hoyle-like states should also exist in heavier Nα nuclei such as ^{16}O, ^{20}Ne, etc. [5]. Indeed a potential candidate in ^{16}O has been identified. Funaki *et al.* [6] solved a four-body equation of motion based on the Orthogonality Condition Model (OCM) that succeeded in reproducing the observed 0^+ spectrum in ^{16}O up to the 0_6^+ state. They showed that the 4α condensation state could be assigned to the 0_6^+ state located at 15.096 MeV. The 0_6^+ state obtained from the calculation is 2 MeV above the four α-particle breakup threshold (S$_{4\alpha}$=14.437 MeV) and has a large radius of 5 fm, indicating a dilute density structure. Ohkubo and Hirabayashi showed in a study of α+^{12}C elastic and inelastic scattering [7] that the moment of inertia of the 0_6^+ state is drastically reduced, which suggests that it is a good candidate for the 4α cluster condensate state. Calculations performed with the Tohsaki-Horiuchi-Schuck-Röpke (THSR) α-cluster wave function [8] also supports this notion, and yields a total width of 34 keV keV for the 0_6^+ state [9], much smaller than the experimentally determined value of 166±30 keV [10].

The measurement of particle decay widths of the 0_6^+ state in ^{16}O is required for a characterization of its structure. Recent attempts at such measurements highlighted the need for an experiment that com-

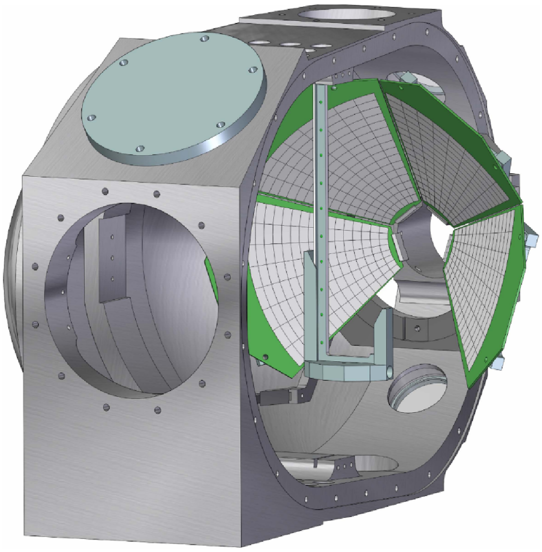

Fig. 1: The scattering chamber viewed from downstream with internal structure exposed, illustrating the target ladder and the lampshade configuration of the CAKE positioned at backward angles.

bines a high energy resolution experimental setup with a reaction capable of preferentially populating 0^+ states. Haigh *et al.* [11] used the ^{12}C(^{13}C,^{9}Be)^{16}O reaction at E_{lab} = 141 MeV to populate excited states in ^{16}O. The ^{9}Be ejectile was observed in a Q3D magnetic spectrometer in coincidence with ^{16}O decay products observed in an array of double-sided silicon strip detectors (DSSSD). An energy resolution of several hundred keV allowed only for the extraction of precise values for $\Gamma_{\alpha 0}/\Gamma_{tot}$ as well as limits for $\Gamma_{\alpha 1}/\Gamma_{tot}$ for the 5^- state at 14.66 MeV and the 6^+ state at 16.275 MeV. This was followed by a study of the ^{12}C(^{6}Li,d)^{16}O reaction, using a similar experimental setup but with an improved excitation energy resolution of 60 keV [12]. However, 0^+ states were not prominently excited due to momentum matching conditions not being fulfilled.

Inelastic α-particle scattering at zero degrees has the advantage that it only excites natural parity states, and particularly the 0^+ states. A measurement of the $^{16}\mathrm{O}(\alpha,\alpha')$ reaction at zero degrees, coupled with coincident observations of the ^{16}O decay products, is therefore an ideal tool to measure particle decay widths of the 0_6^+ state in ^{16}O, provided the experimental energy resolution is adequate. The results of such a measurement performed at the iThemba Laboratory for Accelerator Based Sciences (iThemba LABS) in South Africa are reported.

2. Experimental method

A 200 MeV dispersion matched α-beam was provided by the separated sector cyclotron at iThemba LABS. Inelastically scattered α-particles from a $^{nat}\mathrm{Li_2CO_3}$ target were momentum analyzed with the K600 magnetic spectrometer positioned at zero degrees [13]. The 510 μg·cm^{-2} thick $^{nat}\mathrm{Li_2CO_3}$ target was prepared on a 50 μg·cm^{-2} thick ^{12}C backing [14]. The solid angle acceptance of the spectrometer (3.83 msr) was defined by a circular collimator with horizontal and vertical acceptance of ±2°. The focal-plane detectors of the spectrometer consisted of two multiwire drift chambers, followed by a 6.35 mm thick plastic scintillator. The scintillator provided the master trigger signal for the VME-based MIDAS data acquisition (DAQ) system [15], and also aided with particle identification by providing energy loss and time-of-flight (TOF) information, measured as the time difference between scintillator signals and the RF signal for the pulsed beam.

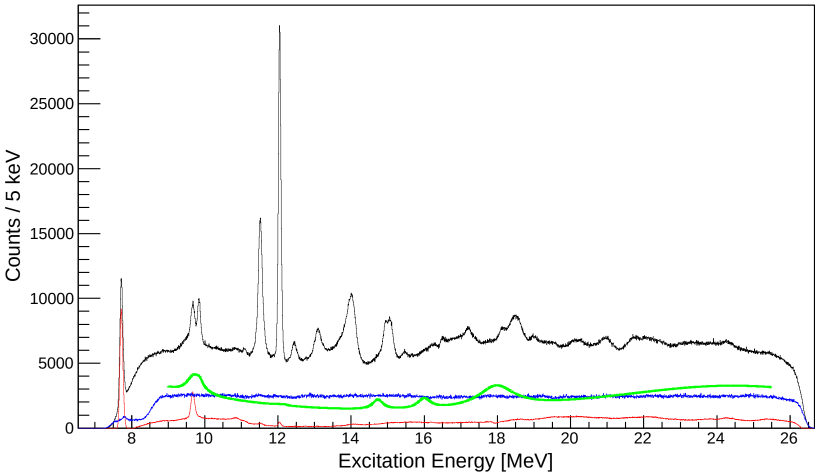

Fig. 2: The Li_2CO_3 excitation energy spectrum obtained from inelastic alpha particle scattering (black line), compared to the fitted contributions from ^{nat}Li (green line), the measured ^{12}C spectrum (red line) as well as the measured instrumental background (blue line).

The decay products were observed with the Coincidence Array for K600 Experiments (CAKE), consisting of four TIARA HYBALL MMM-400 double sided silicon strip detectors (DSSSDs) as shown in Fig. 1. Each of the 400 μm thick wedge-shaped DSSSDs consists of 16 rings and 8 sectors, and were positioned at backward angles with the rings covering the polar angle range $114° < \theta_{lab} < 166°$, resulting in coverage of 21% of the decay particle solid angle. The target-detector separation was ∼ 100 mm which is sufficient for identification of protons and α's through TOF measurements. This was however not required due to the well separated kinematic loci of the different decay channels. For each focal-plane event all signals from CAKE within a time window of six μs were digitized, yielding both K600 singles as well as K600 + CAKE coincidence events. A beam pulse selector at the entrance of the cyclotron was employed to ensure a sufficient time window (273 ns) for coincidence measurements.

3. Results

The ^{16}O excitation energy spectrum obtained from inelastic alpha particle scattering is shown in Fig. 2. An energy resolution of ∼85 keV (FWHM) was achieved, sufficient to allow for a deconvolution of the strength around 15 MeV into the 14.926 MeV 2^+ and 15.097 MeV 0^+ states. There are various background components to the spectrum due to the presence of ^{nat}Li and ^{12}C on the target. Fortunately these components have little influence on the data extracted for the ^{16}O states of interest due to the flat or slow varying nature of these background components. For the same reason, the unavoidable instrumental background contribution inherent to inelastic scattering measurements at zero degrees [13] is not a concern.

Good coincidence data were extracted by gating on the prompt peak in the coincidence time spectrum, which yielded a random-to-real coincidence ratio of $\frac{1}{50}$. The coincidence matrix for all events with the target excitation energy as measured by the K600 on the horizontal axis and the energy of the charged particle decay as measured in CAKE on the vertical axis is shown in Fig. 3. The resolution of CAKE is dependent on the MMM detector ring number due to target attenuation effects, and was found to vary between 60 keV and 90 keV at ∼5 MeV. Several ^{16}O decay modes (α_0,α_1 and p_0) were clearly observed. For each of these decay channels the region around the 0_6^+ state was found to be free from target or instrumental background. The excitation energy spectra for each of these decay channels,

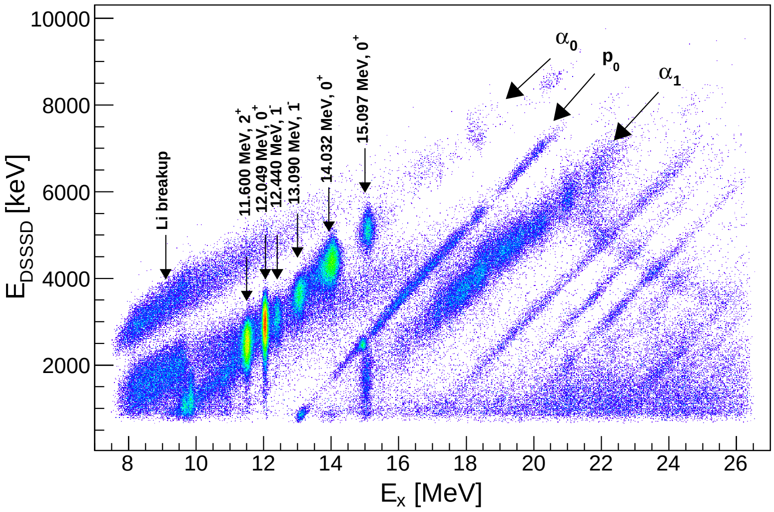

Fig. 3: Two-dimensional coincidence matrix for inelastically scattered α-particles from a ${}^{nat}Li_2CO_3$ target summed over all CAKE channels. Three ${}^{16}O$ decay channels (α_0, α_1, p_0) are indicated, as well as prominent low spin states in ${}^{16}O$. A display threshold of >3 was used in plotting the data.

selected by applying appropriate software gates to the coincidence matrix, are shown in Figs. 4(b)-(d).

In order to determine the branching ratios of the different decay channels of a particular state/resonance it is necessary to reliably extract the state population in the singles and coincidence datasets. The different excitation energy spectra were fitted with R-matrix Voigt lineshapes for all the natural parity states in ${}^{12}C$ and ${}^{16}O$ as well as states allowed by angular selection rules in ${}^{6,7}Li$. The results of the fitting procedure, together with the experimental excitation spectra, are shown in Fig. 4 for the singles results and various decay channels. The spectra for the decay channels represent data summed over all CAKE channels. The resonance energies were constrained to be within 2σ of the value known from literature, where σ represents the error from literature [16]. The Wigner limit was imposed as the upper limit of the reduced width parameter. The reduced chi-squared values obtained for the fits are 0.9, 1.37, 1.10 and 1.30 for the singles, α_0-, α_1- and p_0-decay channels, respectively. A complicated fit of this nature across a wide excitation energy range, while not absolutely essential in order to extract the strength of the 0_6^+ state at 15.097, does instill confidence in the treatment of the background under the state.

The angular distributions of decay modes from resonances in ${}^{16}O$ were extracted after a similar fitting procedure was applied to data from individual CAKE rings. The resonance widths and energies were fixed by the results of the fitting procedure to all CAKE channels. The angular distribution of the α_0 decay channel of the 11.520 MeV 2^+ and 12.049 MeV 0^+ states are shown in Fig. 5.

4. Discussion and summary

In order to assess the validity of the experimental method, the results of known states are considered first. From Fig. 5 it is clear that the angular distribution of the α_0 decay channel of the 11.520 MeV 2^+ and 12.049 MeV 0^+ states display the characteristic distributions associated with 2^+ and 0^+ states respectively. Also encouraging is the extracted branching ratio of 95.3± 0.5% for the α_0 decay channel of the 12.049 MeV 0^+ state, known from literature to be 100% [10]. The branching ratio for the 11.520 MeV 2^+ state will only be extracted at a later stage upon the completion of detailed angular correlation

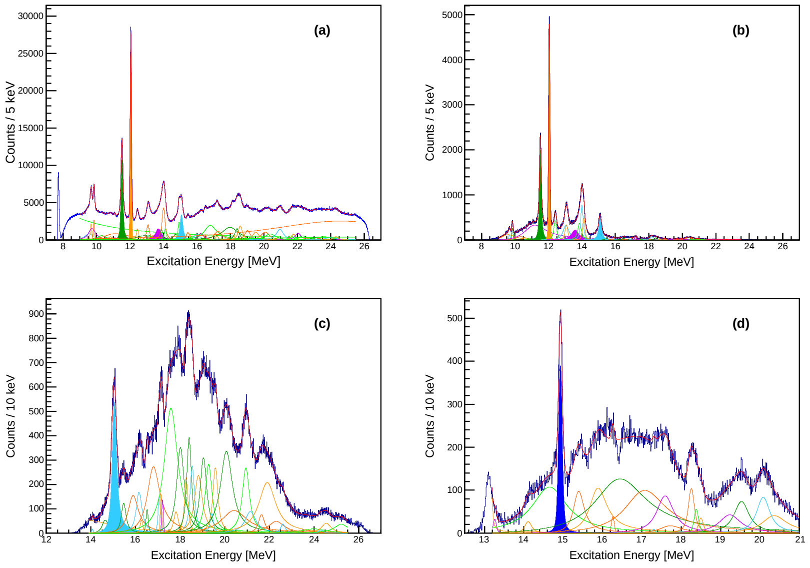

Fig. 4: Experimental and fitted excitation energy spectra for the singles dataset (panel a) as well as the various decay channels summed over all CAKE channels: α_0 (panel b), α_1 (panel c), and p_0 (panel d). Various prominent ^{16}O peaks are highlighted: 11.520 MeV (green), 12.049 MeV (orange), 14.926 MeV (dark blue) and 15.097 MeV (light blue). The red line represents the combined fit.

calculations for this particular experimental setup.

From literature the 15.097 MeV state in ^{16}O is known to have a width of 166±30 keV [10]. The total width extracted in this study from the singles spectrum is 162±4 keV. Assuming isotropic decay from the 0_6^+ state the branching ratios for the α_0 and α_1 decay channels were found to be 70 ±2% and 64 ±1% respectively. This problematic result follows from the seemingly incorrect assumption that the observed decays originate purely from a 0^+ state. Early indications are that while the angular distribution of the 15.097 MeV α_1 decay channel exhibits an isotropic nature, surprisingly the distribution for the 15.097 MeV α_0 decay channel does not.

It is therefore postulated that there are 2 unresolved states in the region of what is considered to be the 15.097 MeV state in ^{16}O. The angular distribution is indicative of the existence of a 0^+ state combined with a 2^+ state, although the exact nature can only be confirmed after the completion of angular correlation calculations for this experimental setup. The existence of two unresolved states could explain why the experimentally extracted width exceed that of theoretical calculations. Further analysis is underway to extract the angular distributions of the α_0, α_1, and p_0 decays in the region of the 15.097 MeV state, which will enable the extraction of accurate branching ratios and exact nature of the spin and parity of the resonances in the E_x = 15.097 MeV region.

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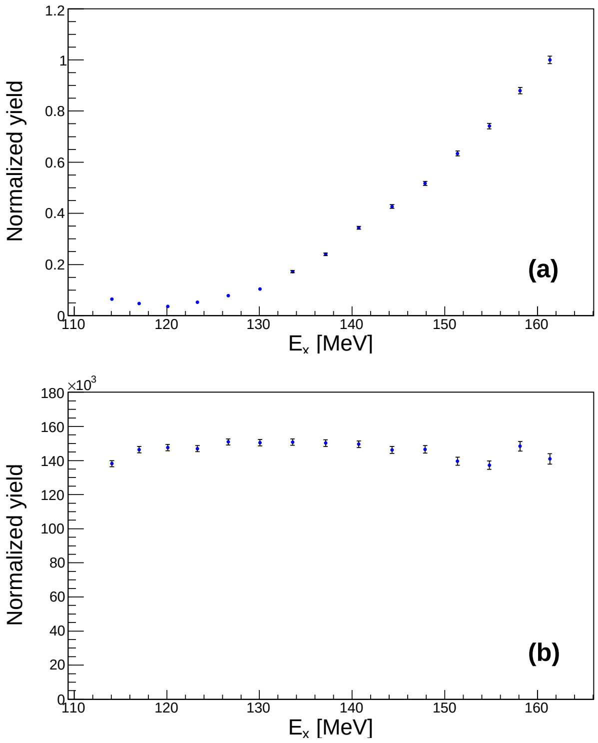

Fig. 5: The angular distribution of the α_0 decay channel of the 11.520 MeV 2^+ (panel a) and 12.049 MeV 0^+ (panel b) states.

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