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Absolute decay width measurements in ^{16}O

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Abstract. The reaction $^{12}\text{C}({}^6\text{Li}, d){}^{16}\text{O}^*$ at a ${}^6\text{Li}$ bombarding energy of 42 MeV has been used to populate excited states in ^{16}O . The deuteron ejectiles were measured using the high-resolution Munich Q3D spectrograph. A large-acceptance silicon-strip detector array was used to register the recoil and break-up products. This complete kinematic set-up has enabled absolute α -decay widths to be measured with high-resolution in the 13.9 to 15.9 MeV excitation energy regime in ^{16}O ; many for the first time. This energy region spans the 14.4 MeV four- α break-up threshold. Monte-Carlo simulations of the detector geometry and break-up processes yield detection efficiencies for the two dominant decay modes of 40% and 37% for the $\alpha+{}^{12}\text{C}(g.s.)$ and $\alpha+{}^{12}\text{C}(2_1^+)$ break-up channels respectively.

1. Introduction

Nuclear clustering and nuclear molecules [1] are well established phenomena that are manifest around the α -particle threshold energies in light nuclei. More recently, both theoretical [2, 3, 4] and experimental work [5] have hinted at the possible existence of condensed nuclear matter in the form of α -particles, forming close to the multi- α threshold energies. The Hoyle resonance [6] in ^{12}C , important for the production of all heavier elements in stellar nucleosynthesis is one such potential “condensate” [7]. Searches for analogues of this state have been made in heavier $N\alpha$ nuclei, with ^{16}O being the next candidate nucleus. However, the high-density of states around the multi- α threshold energies make high-resolution paramount for studying the properties of states in this energy regime. One candidate “condensate” in ^{16}O is the 15.1 MeV 0_6^+ level [8] ($S_{4\alpha}=14.437$ MeV). To highlight the complexity of these measurements, this state lies within 100 keV of an $I^\pi = 2^-$ resonance. Here, results from a newly developed set-up at the Maier

Leibnitz Laboratory (MLL), Munich are reported for which absolute α -decay widths between 13.9 and 15.9 MeV have been unambiguously measured with high-resolution.

2. Experimental Method

A self-supporting, $100 \mu\text{g cm}^{-2}$ target of ^{nat}C was bombarded by a 42 MeV ^6Li beam provided by the 15 MV tandem Van de Graaff accelerator at the MLL of the Technical University and Ludwig-Maximillan University, Munich. The energy-loss, energy and position of the ejectiles were detected at the focal plane of the high-resolution Q3D magnetic spectrograph [9]. The Q3D was centred at -21.5° with respect to the beam axis and had an acceptance of $\pm 3^\circ$ in the horizontal plane and $\pm 2^\circ$ in the vertical plane. On the opposite side of the beam axis, ≈ 70 mm from the target position, was the Birmingham silicon array comprised of four $50 \text{ mm} \times 50 \text{ mm}$ double-sided silicon-strip detectors in a 2×2 configuration. Each detector consisted of 16 horizontal and 16 vertical strips with the array covering $8.4^\circ \rightarrow 85.4^\circ$ and $-36.4^\circ \rightarrow 35.4^\circ$ in the horizontal and vertical planes respectively. The master trigger was set to any ‘good’ Q3D event (a coincidence between energy loss from a horizontal wire in the proportional counter and the residual energy, measured downstream in a plastic scintillator). (The focal-plane detector is described in detail in Refs. [10, 11].) The properties of the Q3D are such that ions of a given energy are focused to the same place on the focal plane, independent of angle. Therefore, deuteron position on the focal-plane corresponds to excitation energy in the ^{16}O recoil. Focal-plane position was calibrated using the published energies of peaks observed in ^{16}O [12] and covered the energy range 13.85 to 15.87 MeV.

Events for which single hits were registered in the silicon detectors were assumed to originate from the detection of one of the two break-up particles from the decay of ^{16}O into:

$$\begin{array}{ll} p + ^{15}\text{N} & (12.127 \text{ MeV}) \\ n + ^{15}\text{O} & (15.664 \text{ MeV}) \\ \alpha + ^{12}\text{C} & (7.162 \text{ MeV}) \\ ^8\text{Be} + ^8\text{Be} & (14.620 \text{ MeV}), \end{array}$$

where relevant threshold energies are given in parentheses. These single-hit events were incremented into four Catania plots [13] (one for each break-up channel), in which the reconstructed ‘missing’ energy and the square of the ‘missing’ momentum of the undetected particle were plotted on the vertical and horizontal axes respectively. The reconstruction was made by assuming that the heavier break-up particle was detected. This enabled the undetected particles to be identified, and, therefore, the break-up channel. In addition, the excitation energy in the break-up partners could also be extracted, allowing the states populated in the daughter nuclei to be established. Monte-Carlo Simulations using the RESOLUTION8 code [14, 15] were performed and included energy loss and energy and angular straggling in the target. An isotropic break-up distribution in the centre-of-mass frame was found to most closely match the data. The same analysis code was used to analyse both the simulated and experimental data. The Monte-Carlo-generated data were used to obtain the efficiency of the silicon detector array and the selection/gating criteria. For more details about this analysis technique and the experimental set-up see Ref. [13].

3. Results

The above analysis procedure has demonstrated that only the $\alpha + ^{12}\text{C}(g.s.)$ and $\alpha + ^{12}\text{C}(2_1^+)$ decay paths are observed for ^{16}O states populated in the present study. Figure 1(a) shows the Catania plot for the $\alpha + ^{12}\text{C}$ channel. Four straight lines can be clearly seen (labelled in Fig. 1(b)). These correspond to the carbon break-up fragments being detected in the ground and first excited states (lines with the steepest gradient) and α particles being detected for the same

two carbon states (lines with the shallowest gradient). Figure 1(b) shows the corresponding output from the Monte-Carlo generated events.

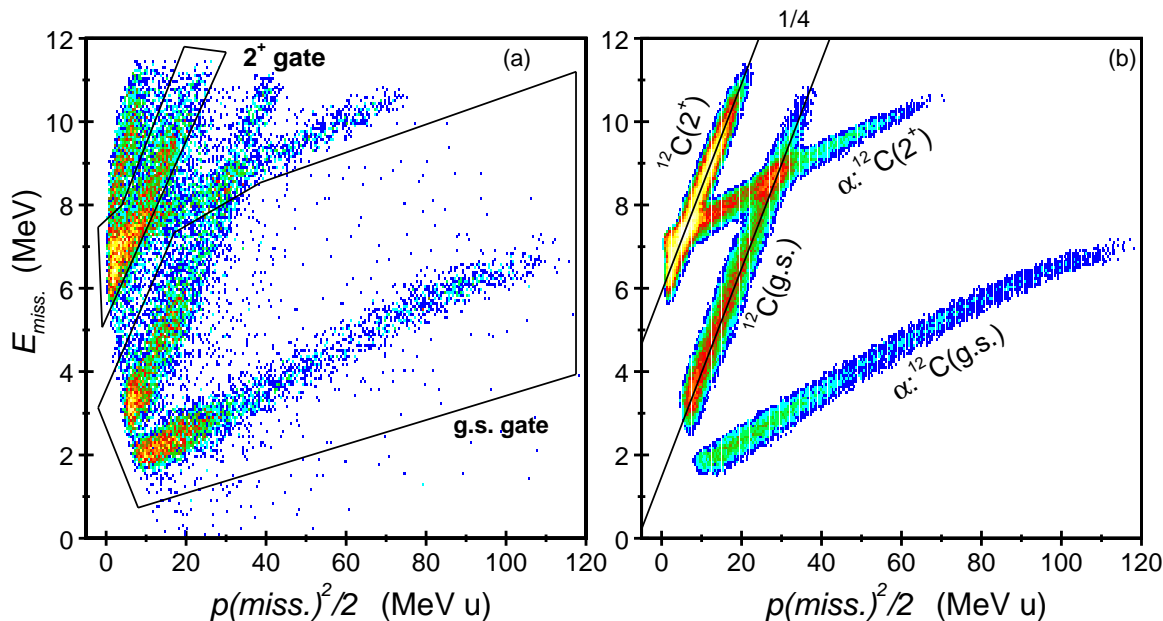


Figure 1. Catania plots adapted from Fig. 2 of Ref. [13]. The square of the ‘missing’ momentum is plotted on the horizontal axis against the ‘missing’ energy on the vertical axis. The ‘missing’ component is calculated assuming that the fragment registered in the silicon detectors is a ^{12}C nucleus. (a) Experimental data; the gates used to select the ground- and first excited state in ^{12}C are shown. (b) The corresponding plot for the Monte-Carlo generated events. The four distinct distributions are labelled first by the particle actually detected in the silicon array. The gradient of 1/4 shown above the top axis demonstrates that the ‘missing’ component in the $^{12}\text{C}(g.s.)$ and $^{12}\text{C}(2_1^+)$ distributions is from mass = 4 fragments *i.e.* α particles.

Following generation of the Catania plots (Fig. 1) the events associated with the $^{12}\text{C}(g.s.)$ and $^{12}\text{C}(2_1^+)$ were separated using the gates shown in Fig. 1(a). Projecting the resulting Q3D focal-plane spectra corresponding to these events yields the ^{16}O states, selected by decay path. The spectra are shown in Fig. 2. The absolute α -decay widths were obtained by taking the efficiency-corrected ratio of the Q3D events in coincidence with the above silicon-hit selection to the total population at the Q3D focal-plane, leading to:

$$\frac{\Gamma_{\alpha 0}}{\Gamma_{tot.}} = \frac{I(^{12}\text{C}(g.s.))}{I(tot.) \epsilon_{g.s.}} \quad \text{and} \quad \frac{\Gamma_{\alpha 1}}{\Gamma_{tot.}} = \frac{I(^{12}\text{C}^*(2_1^+))}{I(tot.) \epsilon_{2_1^+}} \quad (1)$$

where $I(tot.)$ is the total state population from the Q3D data, $I(^{12}\text{C}(g.s.))$ and $I(^{12}\text{C}^*(2_1^+))$ are the intensities gated by the ^{12}C ground and 2_1^+ states respectively. The associated efficiencies from the Monte-Carlo simulations are $\epsilon_{g.s.}=40\%$ and $\epsilon_{2_1^+}=37\%$. The results are shown in Table 1. Alpha-width measurements have been obtained for all of the levels populated, and, for all but the 14.66 and 14.91 MeV states, represent the first measurements for at least one of the decay paths. Where data exist from earlier studies, the α -width values are in good agreement to those obtained here. For example, for the 14.8 MeV state, $\Gamma_{\alpha 0}/\Gamma_{tot.}=0.46\pm 0.06$ compared to the literature value of 0.45 ± 0.05 [12]. Further consistency checks were made using a measurement

of the four bound excited states in ^{16}O at excitation energies of 6.049 (0^+), 6.130 (3^-), 6.917 (2^+) and 7.117 (1^-) MeV [12] for which decay widths to the ground-state consistent with 100% were obtained, as expected for internal decaying states. For the binary measurements the single silicon-hit events were the ^{16}O recoils. From these binary data the background from reactions on target contaminants was found to be negligible. Finally, it is noted that the α -decay widths obtained satisfy the angular momentum coupling condition, $\underline{I}_{16\text{O}^*} - \underline{l}_\alpha = \underline{I}_\alpha + \underline{I}_{12\text{C}^*}$, where \underline{l}_α is the orbital angular momentum of the α particle and $\underline{I}_\alpha = 0$. Unnatural parity states are forbidden from decaying to the ^{12}C ground state.

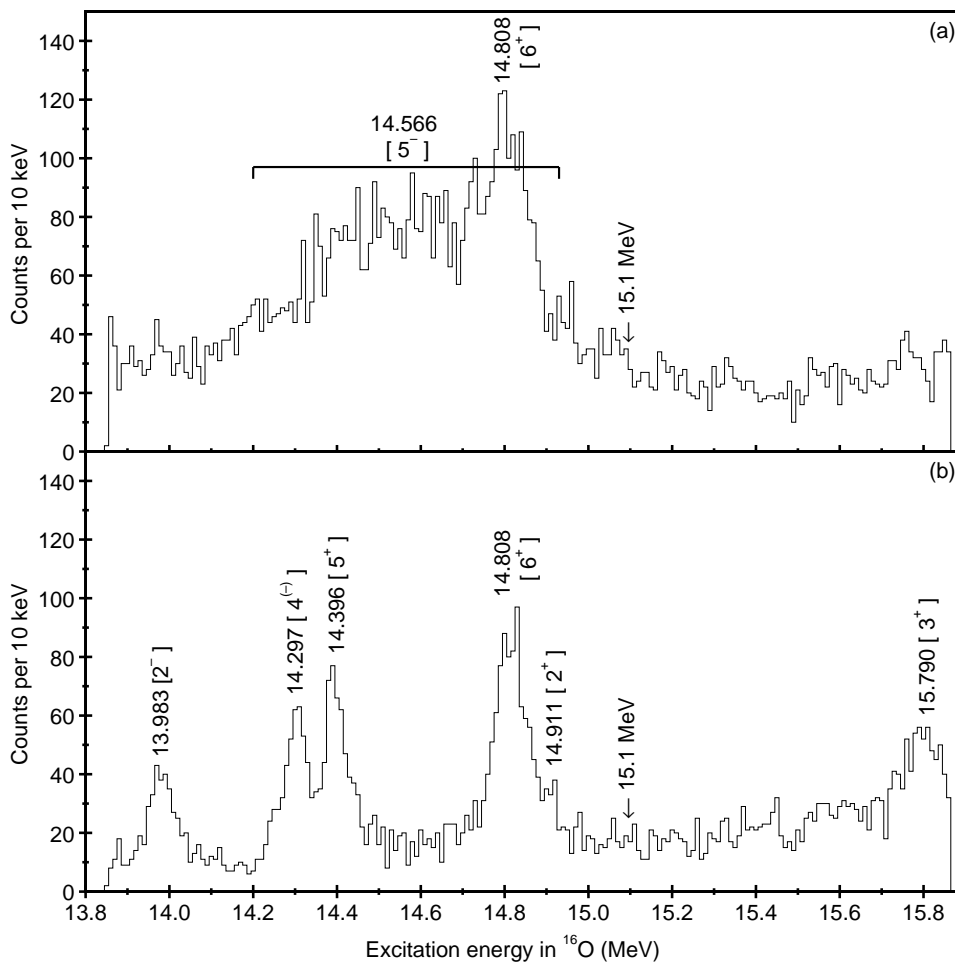


Figure 2. Spectra showing excited states in ^{16}O at the Q3D focal-plane gated by: (a) the break-up into $\alpha+^{12}\text{C}(g.s)$; and (b) the break-up into $\alpha+^{12}\text{C}(2_1^+)$. The gates used are shown in Fig. 1(a). The same vertical scales are used in both (a) and (b). The position of the unobserved 15.1 MeV, 0_6^+ state is shown to aid the reader. See text for details.

4. Discussion

Two α -cluster bands with $K^\pi = 0^+$ and $K^\pi = 0^-$ are known in ^{16}O [12, 16], the 14.66 MeV $I^\pi = 5^-$ member of which has been observed here (see Table 1) with $\Gamma_{\alpha 0}/\Gamma_{tot.}=1.14\pm 0.08$. This is in good agreement with the literature value of 0.94 [12]. Taking the combined weighted average of the new measurement and the average quoted in Ref. [16], yields $\Gamma_{\alpha 0}/\Gamma_{tot.}=1.002\pm 0.042$. This

Table 1. Known members of the $K^\pi = 0^+$ and 0^- α -cluster bands in ^{16}O [12], together with the states populated in the current work. The 14.66 MeV cluster state populated here is indicated in bold. Absolute α -decay widths are given.

E_{level} [keV]	I^π	FWHM [keV]	$\Gamma_\alpha/\Gamma_{\text{tot.}}$ (<i>this work</i>)		$\Gamma_\alpha/\Gamma_{\text{tot.}}$ (<i>lit.</i>)	
			$^{12}\text{C}(g.s.)$	$^{12}\text{C}^*(2_1^+)$	$^{12}\text{C}(g.s.)$	$^{12}\text{C}^*(2_1^+)$
6049.4(10)	0^+	<i>bound</i>			—	—
6917.1(6)	2^+	<i>bound</i>			—	—
9585(11)	1^-	420(20)			~ 1	—
10356(3)	4^+	26(3)			0.86(9)	—
11600(20)	3^-	800(100)			1.00	—
<i>This work</i>						
13980(2)	2^-	70(6)	<0.09	0.87(11)	0	large
14302(3)	$4^{(-)}$	66(7)	<0.05	1.04(15)	—	—
14399(2)	5^+	64(5)	<0.05	0.92(10)	—	—
14660(20)	5^-	670(15)	1.14(8)	—	0.94	—
14815.3(16)	6^+	93(6)	0.46(6)	0.59(4)	0.45(5)	—
14926(2)	2^+	103(30)	—	$\sim 0.2^a$	0.027(2)	0.54(5)
15785(5)	3^+	136(13)	<0.3	0.88(18)	—	—
16275(7)	6^+	420(20)			0.982(48) ^b	—
20857(14)	7^-	900(60)			1.16(23)	—
22500(500)	$(8^+)^c$	—			—	—

^a Very weakly populated in the current work, ^b average from Ref. [16], ^c from Ref. [17].

level is the only natural parity state observed in the current study and has a 100% decay branch to the ^{12}C ground state. This follows the trend observed for the other α -cluster band members listed in Table 1 [12], implying that for this class of states, the angular momentum can be more easily accommodated as orbital motion of the emitted α -particle, rather than populating the $^{12}\text{C}(2_1^+)$ excitation. This feature of the decay process is consistent with an extended radius; expected for levels with an underlying α -cluster structure.

Finally, with reference to the search for an analogue of the Hoyle state in ^{16}O , the best candidate to date is the 15.096 MeV $I^\pi = 0_6^+$ state that has been proposed as a possible α condensate [3]. In the Q3D focal-plane spectra this state is absent, despite lying in a region of low background and away from neighbouring resonances (indicated by arrows in Fig. 2). The most plausible reason is due to the angular momentum matching conditions not being fulfilled at this excitation energy, as the 14.032 MeV $I^\pi = 0_5^+$ has also not been observed. However, the current work has demonstrated that the selectivity of the silicon detector array and the resolution of the Q3D spectrograph is able to unambiguously distinguish between states in this excitation region.

5. Summary

The $^{12}\text{C}(^6\text{Li}, d)^{16}\text{O}^*$ reaction, at a bombarding energy of 42 MeV, has been used to populate states around the 4α threshold energy in ^{16}O . A large angular acceptance, position-sensitive silicon detector array, in coincidence with the high-resolution Q3D spectrograph has been used to measure absolute α -decay widths without ambiguity, even at high level densities in the excitation energy range of 13.85 to 15.87 MeV. The results obtained are in good agreement with known

values where data exist. The α -decay widths: $\Gamma_{\alpha 1}/\Gamma_{tot.}=0.87\pm 0.11$ (13.980 MeV), 1.04 ± 0.15 (14.302 MeV), 0.92 ± 0.10 (14.399 MeV), 0.59 ± 0.04 (14.815 MeV) and 0.88 ± 0.18 (15.785 MeV) have been measured here for the first time.

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