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Absolute partial decay branching-ratios in ^{16}O

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Abstract. The α-transfer reaction $^{12}_{6}$C($^{6}_{3}$Li, d)$^{16}_{8}$O* has been performed at a ^{6}Li bombarding energy of 42 MeV to populate excited states in ^{13}C and ^{16}O. Absolute branching ratios have been unambiguously determined for states in the excitation energy range 13.85 to 15.87 MeV and reduced widths are extracted.

1. Introduction

Clustering is a well-established phenomenon in certain light nuclei [1], the most ubiquitous form of which is based on systems with at least one α-particle sub-unit. Precise measurements can be made to elucidate the underlying structure. One of the most useful properties in this regard is the reduced width for a particular state and decay branch. This enables the characterisation of the partial decay widths with the effect of barrier penetrabilities removed, allowing the degree of clustering to be quantified. In order to extract reduced widths a precise determination of the total width and the decay branching ratios is needed. This paper reports such measurements for excited states in ^{16}O.

2. Experimental Method

Beams of 42 MeV ^{6}Li^{3+} ions were provided by the 14 MV tandem accelerator of the Maier Leibnitz Laboratory of the Technical and Ludwig-Maximillian Universities, Munich. A self-supporting target of $^{nat.}$C (100 μg/cm^2) was bombarded at the centre of the target chamber and the deuteron ejectiles analysed by the Q3D high-resolution spectrograph [3] yielding focal-plane position (recoil excitation energy), energy-loss and energy [4, 5]. The operation of the spectrograph is such that ejectiles of a particular energy are focused to the same point on the focal plane, independent of angle. The recoils or the recoil break-up products were detected in a 2×2 array of 50×50 mm^2 double-sided silicon-strip detectors covering a large angular range: 8.4° to 84.5° and −35.4° to +36.4° in the horizontal and vertical planes respectively. The master trigger condition required one good event at the Q3D focal plane after which a 5 μs time window was opened for reading all ADC events.

Energy calibration of the focal-plane detector was done using known resonances in ^{16}O while a triple-α source (^{239}Pu, ^{241}Am and ^{244}Cm) provided the energy calibration for the silicon detectors. More details for this experiment can be found in Ref. [6]. The Q3D settings used for the experiment are as follows:

Q3D at 21.5°; Excitation energy settings: 6.23 MeV (5.20 to 7.95 MeV),
14.6 MeV (13.85 to 15.87 MeV).

3. Results

The analysis was performed by identifying the recoiling products, which for the main, 14.6 MeV setting was dominated by break-up particles. The method employed for this was Catania plots. This can be understood by examining the energy balance for the final-state particles. Briefly, for a reaction between a beam, b, and target, t, $m_b + m_t \rightarrow m_{eject.} + m_{rec.}$. If the recoiling nucleus subsequently undergoes the break-up, $m_{rec.} \rightarrow m_1 + m_2$, an overall three-body Q-value can be defined by combining the kinetic energies such that

$$Q_3 = E_d + E_1 + E_2 - E_b, \tag{1}$$

where E_d is the deuteron (ejectile) kinetic energy. The data recorded in the current work were dominated by multiplicity 1 events in the silicon array, corresponding to detection of only one of the two break-up particles. The assumption is made that particle 1 is detected and its energy is corrected for losses in the target ($E_{1corr.}$). Via conservation of momentum the total momentum of the undetected particle 2 is

$$p_2(tot)^2 = \sum_{i=x,y,z} (p_{b\,i} - p_{1\,i} - p_{d\,i})^2. \tag{2}$$

Substituting into Eqn. 1 gives

$$E_b - E_d - E_{1corr.} = \frac{p_2(tot)^2}{2}\frac{1}{m_2} - Q_3. \tag{3}$$

Plotting the square of the 'missing' momentum $p_2(tot)^2/2$ on the abscissa and the 'missing' energy ($= E_b - E_d - E_{1corr.}$) on the ordinate yields the mass, m_2, of the undetected particle as the inverse gradient of the loci, and the intercept on the ordinate is minus the three-body Q-value. All that is required is an assumption of the mass of particle 1 to calculate its initial momentum ($p_1(tot) = \sqrt{2E_{1corr.}m_1}$). In the current analysis, for each pair of break-up particles, Catania plots were constructed assuming that the heavier particle was detected as particle 1. Figure 3a shows the Catania plot assuming the ^{16}O $\rightarrow$ p+^{15}N break-up channel. In the adjacent panel (Fig. 3b) Monte-Carlo simulations [7, 8] have been performed including the proton, α+^{12}C(g.s.) and α+^{12}C(2_1^+) break-up channels. Five loci can be clearly seen, four corresponding to the detection of the α and carbon nuclei for each channel respectively, and one representing detection of ^{15}N nuclei. The final locus would correspond to detection of the proton, which has a large spatial distribution and, therefore, is only very weakly present in Fig. 3. The particle identification is confirmed with a line of gradient 1 ($=1/m_p$) and intercept 6.439 MeV ($=-Q_3$) on Fig. 3b.

The Monte-Carlo simulations have been used to extract the geometrical efficiency for each gate/break-up channel. For the proton channel, $\epsilon_{N(g.s.)}$=0.41±0.01 and for the α channels $\epsilon_{C(g.s.)}$=0.40±0.01 and $\epsilon_{C(2_1^+)}$=0.37±0.01. Finally, the efficiency-corrected ratio of [counts detected at the focal plane in coincidence with a particle event in the silicon array] to [all events at the focal plane] yields the decay branching ratios,

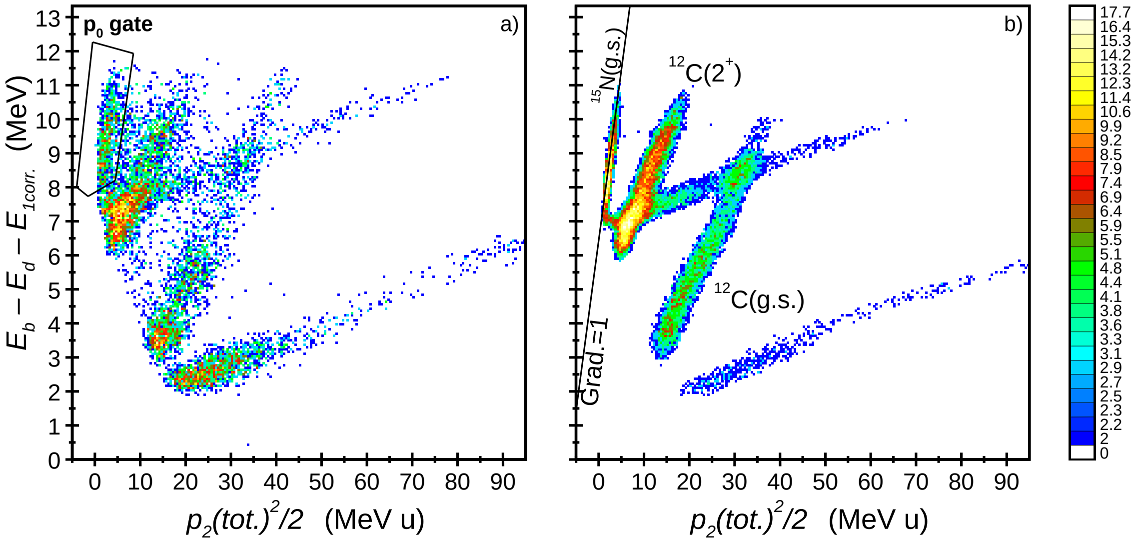

Figure 1. Catania plots constructed assuming the detected particle was ^{15}N. a) Data showing the proton, p_0 gate to the ^{15}N ground-state. b) Simulated events corresponding to $2{\times}10^4$ p+^{15}N events and $1{\times}10^5$ events for each of the α+^{12}C(g.s.) and α+^{12}C(2_1^+) channels. The verical scale has been normalised to match that of the data in panel a). For both panels a threshold of >1 has been used when plotting the data. See text for details.

$$\frac{\Gamma_{p0}}{\Gamma_{tot.}} = \frac{I(^{15}N(g.s.))}{I(tot)\epsilon_{N(g.s.)}}, \quad \frac{\Gamma_{\alpha 0}}{\Gamma_{tot.}} = \frac{I(^{12}C(g.s.))}{I(tot)\epsilon_{C(g.s.)}} \quad \text{and} \quad \frac{\Gamma_{\alpha 1}}{\Gamma_{tot.}} = \frac{I(^{12}C(2_1^+))}{I(tot)\epsilon_{C(2_1^+)}}. \tag{4}$$

The results obtained from this analysis are summarised in Table 1. Due to the conservation of angular momentum, $I(^{16}\mathrm{O}^*) - l_\alpha = I(^{12}\mathrm{C}^*)$, only natural parity states can undergo α-decay to the ^{12}C ground state. The 14.6 MeV $I^\pi = 5^-$ level is the only state in this region to decay exclusively to the ^{12}C ground state. The only significant proton decay branch is observed for the 14.911 MeV level with a branching ratio obtained in the current work of $\Gamma_{p0}/\Gamma_{tot.}$=0.22±0.12. This is in agreement with the published value of $\Gamma_{p0}/\Gamma_{tot.}$=0.36±0.06 [9].

4. Discussion

In the preceding section precise measurements have been reported for all of the absolute partial decay branching ratios on a state-by-state basis. These can be used together with the total widths to extract the reduced widths, γ_i^2, with the effect of the Coulomb barrier (*i.e.* the barrier penetrabilities, P_i) removed;

$$\gamma_i^2 = \frac{\Gamma_i}{2P_i}. \tag{5}$$

Expressing the penetrabilities in terms of the Coulomb wavefunctions, $P_i = k_i r_i/[F_l^2(k_i r_i) + G_l^2(k_i r_i)]$ for the i^{th} decay channel, with wavenumber, k_i, and radius, $r_i = 1.4(A_1^{1/3} + A_2^{1/3})$ fm, dependent on the masses, 1 and 2, of the break-up fragments leads to

$$\gamma_i^2 = \Gamma_{tot.} \frac{\Gamma_i}{\Gamma_{tot.}} \frac{[F_l^2(k_i r_i) + G_l^2(k_i r_i)]}{2k_i r_i}. \tag{6}$$

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Table 1. Branching ratios, barrier penetrabilities and reduced widths for states observed in ^{16}O for each decay channel in turn. Where an energy level is not given, no decay strength has been observed in that channel.

E_{level} (MeV)	$\Gamma_{tot.}$ [a] (keV)	I^{π}	l	Branching ratios	Barrier penetrabilities [b]	Reduced widths [c]
$\boldsymbol{p0 + {}^{15}N(g.s.)}$			l_{p0}	$\Gamma_{p0}/\Gamma_{tot.}$	$P_{p0}/(k_{p0}r_{p0})$	θ^2_{p0}
14.911	84(37)	2^+	1	0.22(12)	0.402	0.005(3)
$\boldsymbol{\alpha 0 + {}^{12}C(g.s)}$			$l_{\alpha 0}$	$\Gamma_{\alpha 0}/\Gamma_{tot.}$	$P_{\alpha 0}/(k_{\alpha 0}r_{\alpha 0})$	$\theta^2_{\alpha 0}$
14.566	446(27)	5^-	5	1.14(8)	0.195	0.33(3)
14.808	71(9)	6^+	6	0.46(6)	0.0819	0.049(9)
15.790	122(15)	3^+	4	<0.3	0.457	$<9.350\times10^{-3}$
$\boldsymbol{\alpha 1 + {}^{12}C(2^+_1)}$			$l_{\alpha 1}$	$\Gamma_{\alpha 1}/\Gamma_{tot.}$	$P_{\alpha 1}/(k_{\alpha 1}r_{\alpha 1})$	$\theta^2_{\alpha 1}$
13.983	36(13)	2^-	1	0.87(11)	0.152	0.046(18)
14.297	27(19)	$4^{(-)}$	3	1.04(15)	0.0353	0.17(12)
14.396	22(18)	5^+	4	0.92(10)	0.00841	0.5(4)
14.808	71(9)	6^+	4	0.59(4)	0.0190	0.42(6)
14.911	84(37)	2^+	0	∼0.2	0.426	∼0.007
15.790	122(15)	3^+	2	0.88(18)	0.358	0.050(12)

[a] The experimental resolution of 60(4) keV has been removed from the widths measured in the current work.
[b] The quantity $P_i/(k_i r_i) = 1/[F_l^2(k_i r_i) + G_l^2(k_i r_i)]$.
[c] Calculated using excitation energies and $\Gamma_{tot.}$ measured in the current work; columns 1 and 2 respectively. See text for details.

Note that the orbital angular momentum carried by the decay particle is denoted by l. Taking the ratio of the reduced width to to the Wigner limit [10, 11] yields

$$\theta_i^2 = \frac{\gamma_i^2}{\gamma_{Wi}^2} = \Gamma_i \frac{2\mu_i r_i^2 \left[F_l^2(k_i r_i) + G_l^2(k_i r_i)\right]}{6\hbar^2 k_i r_i}, \tag{7}$$

[12], where μ_i is the reduced mass of the break-up particles. These reduced widths, θ_i^2, are tabulated (see Table 1) for each state and decay channel observed in the current work.

Examining the final column of Table 1 the majority of states exhibit relatively low reduced widths. The two exceptions are the 14.6 and 14.8 MeV level for the $\alpha 0$ and $\alpha 1$ channels respectively. The 14.6 MeV state is a strong candidate for the $I^{\pi} = 5^-$ member of the cluster band build on the 9.585 MeV 1^- bandhead. The current result demonstrates a significant degree of α clustering (33%) which is backed up by its exclusive decay to the ^{12}C ground state – implying a large radius compared to other states in this excitation energy range. The increased radius for the resonance makes it easier for the α particle to accommodate the orbital angular momentum. The large total width is also consistent with that of other members of the cluster band in ^{16}O [6].

For the 14.8 MeV level, the situation is less clear. With almost equal decay branches to both the ground state and first excited state of ^{12}C, it is only the latter that shows a large α-reduced width (42%), suggesting a configuration with smaller radius than the above mentioned 14.6

MeV state. The 14.8 MeV state is strongly populated in α-transfer reactions, but has yet to be assigned to a rotational band and more work is needed to unravel its associated structure.

5. Summary

A high resolution measurement has been made of the 14-16 MeV excitation region of ^{16}O using the Munich Q3D magnetic spectrograph coupled to the Birmingham large angular coverage silicon array. The break-up products for all decay channels have been unambiguously identified and the absolute branching ratios determined. States in this region are observed to decay via protons to the ^{15}N ground state and via α particles to the ^{12}C ground and first excited states. Reduced widths have been extracted, confirming the nature of the $I^{\pi} = 5^{-}$ level as an α+^{12}C cluster-band member.

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References

[1] Freer M 2007 *Rep. Prog. Ph.* **70** 2149
[2] von Oertzen W, Freer M and Kanada-En'yo Y 2006 *Phys. Rep.* **432** 43
[3] Löffler M, Scheerer H J and Vonach H, 1973 *Nucl. Instr. and Meth.* **111** 1
[4] Wirth H-F, Angerer H, von Egidy T, Eisermann Y, Graw G and Hertenberger R 2000 *Beschleunigerlaboratorium München, Annual Report* p71
[5] Wirth H-F 2001 Ph.D Thesis, Technical University, München, see *http://tumb1.biblio.tu-muenchen.de/publ/diss/ph/2001/wirth.html*
[6] Wheldon C *et al* 2011 *Phys. Rev.* C **83** 064324 and references therein
[7] Curtis N *et al* 1995 *Phys. Rev.* C **51** 1554
[8] Curtis N *et al* 1996 *Phys. Rev.* C **53** 1804
[9] Tilley D R, Weller H R and Cheves C M 1993 *Nucl. Phys.* A **565** 1
[10] Nilson R, Jentschke W K, Briggs G R, Kerman R O and Snyder J N 1958 *Phys. Rev.* **109** 850
[11] Teichmann T and Wigner E P 1952 *Phys. Rev.* **87**, 123
[12] Sanders S J, Martz L M and Parker P D 1979 *Phys. Rev.* C **20** 1743