Characterization of Cluster States in ^{16}O with the (p,t) Reaction

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Abstract.
Several theoretical cluster calculations predict the existence of the 0_6^+ state in ^{16}O, located at 15.1 MeV. This state is considered as a very good candidate for the equivalent of the Hoyle state in ^{12}C. In order to investigate this possibility a high energy resolution measurement of the ^{16}O spectrum in coincidence with the ^{16}O decay products was proposed, using a (p,t) reaction at zero degrees for a proton energy of 200 MeV.

1. PHYSICS MOTIVATION

The excited states of light nuclei lying near and above the particle-decay threshold play an important role in the nucleosynthesis in stars. In 1954, Hoyle showed that the observed amount of carbon in the cosmos could be made in stars only if there was an excited state in carbon with a particular spin and parity, 0^+, and a particular energy of about 7.65 MeV that enhances the fusion of three α-particles. This state was found experimentally [1] and lies just 375 keV above the three α-decay threshold. The energy of this state is not well reproduced by the no-core shell model [2]. However, many theoretical calculations that use microscopic α-cluster models indicate that the 0_2^+ state in ^{12}C has a loosely bound three-α cluster structure [3,4,5].

The ^{8}Be nucleus has the simplest form of α-particle clustering in nuclei that is found in its ground state [6]. Aside from this nucleus, there are many other light systems which are proposed to exhibit cluster-like properties most likely in excited states with a low density structure. The sixth 0^+ state in ^{16}O located 660 keV above the four-α decay threshold at E_x=15.1 MeV (Γ=166 keV) has been identified as the best candidate for the equivalent of the Hoyle state in ^{12}C [7]. This state should be found to have a well developed four-α substructure with a rather low density.

An experiment was recently proposed to populate the 15.1 MeV 0^+ state in ^{16}O using the ^{18}O$(p,t)^{16}$O reaction in order to study its decay properties. Due to the density of states in the region of excitation energy around 15 MeV in ^{16}O the triton measurement was performed with the high energy resolution K600 magnetic spectrometer. This paper reports on the preliminary analysis of data acquired with targets containing ^{6}Li, ^{7}Li, ^{12}C, ^{16}O and ^{18}O. At incident energies around 200 MeV, very little is known about the behaviour of (p,t) cross sections across this target mass range. An investigation was therefore carried out to verify whether the distorted-wave Born approximation (DWBA) approach, which works moderately well at lower energies for these targets,

can be extended to higher energies.

2. EXPERIMENTAL PROCEDURE

The measurements were performed with a 10-13 nA beam of 200 MeV protons provided by the separated sector cyclotron (SSC) accelerator at iThemba LABS. The beam impinged on various metallic oxide targets that were composed of different combinations ^{6}Li, ^{7}Li, ^{12}C, ^{16}O and ^{18}O. The decay products of the excited recoil nuclei were detected at angles close to 180 degrees by means of two 50 mm $\times$ 50 mm double sided silicon-strip detectors (DSSSD), each approximately 300 μm thick. The outgoing tritons emitted at zero degrees were identified in the K600 magnetic spectrometer focal plane detector system, which consists of vertical drift chambers (VDC). Each VDC has two wireplanes, a U- and X wireplane, both with a 4 mm wire pitch that allows the determination of horizontal and vertical positions and angles in the focal plane. Two plastic scintillators mounted behind the wire planes allowed particle identification and time of flight measurement. The beam was operated in the momentum dispersion matched mode and a typical energy resolution of about 45 keV was achieved. We have initially focused on precise measurement of ^{16}O energy spectrum using the K600 events as the master trigger. The segmented silicon detectors were used in slave mode in order to collect the decay products of different excited recoil nuclei. The measured triton energy spectrum is displayed in Fig.1. This spectrum was used to identify the different excited states of residual nuclei. The ^{14}O and ^{10}C excited states are strongly populated whereas ^{16}O excited states are weakly populated. However, the 15.1 MeV 0^+ is not clearly seen. This is due to the low grade ^{18}O enriched material used in the target manufacturing process and also to lower cross sections. Energy calibration was achieved by comparing the relative positions of known ^{10}C discrete states in the various targets. Absolute cross sections were extracted from measured yields, beam currents, target thicknesses, and defined spectrometer acceptance solid angle.

Charged particles from breakup nuclei were successfully detected in coincidence with the ejectile tritons. In Fig. 2, correlated structures are observed with the ^{14}O$^* \rightarrow$p+^{13}N binary breakup identified in the two clear loci.
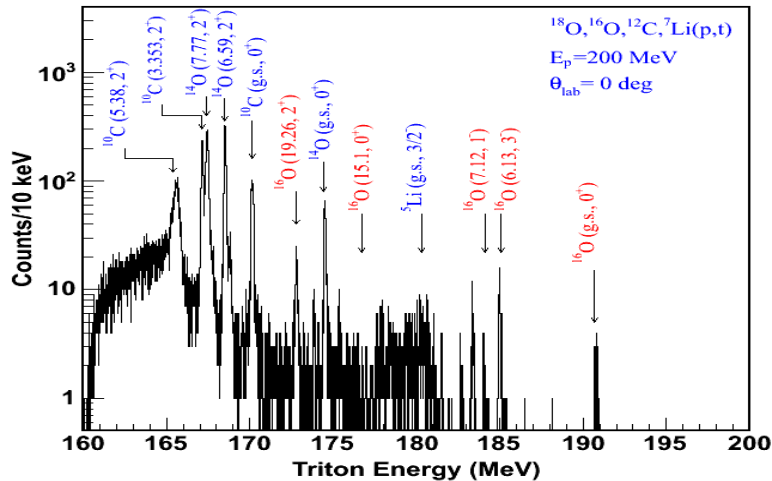

Figure 1. *Measured triton energy spectrum at E_{lab}=200 MeV and θ=0°. The excitation energies of the levels together with their corresponding spins and parities for the different residual nuclei are labelled. The expected position of the 15 MeV 0^+ state is also indicated.*

3. PRELIMINARY RESULTS AND OUTLOOK

Theoretical cross sections were calculated in the framework of a zero-range distorted-wave Born approximation (DWBA), which was successfully used in (p,t) reaction studies on ^{208}Pb and
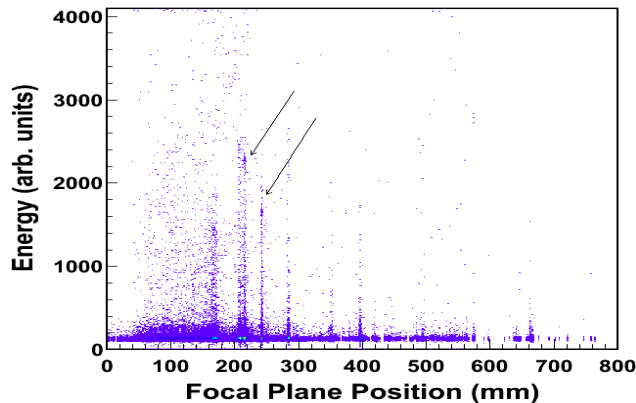
Figure 2. *A two-dimensional plot showing correlation of the light charged particles with the tritons from excited states in ^{14}O. The arrows indicate the $^{14}O^* \rightarrow p + {}^{13}N$ binary breakup loci.*

^{116}Sn nuclei at an incident energy close to 200 MeV [8]. These calculations were performed by implementing the code DWUCK4 [9]. Microscopic form factors, built up from the single-neutron form factors generated in a standard Woods-Saxon potential, were used by the code. The Woods-Saxon potential was adjusted to give a binding energy equal to one half two-neutron separation energy.

The experimental (p, t) cross section $(d\sigma/d\Omega)_{exp}$ is related to that calculated by the DWUCK4 code $(d\sigma/d\Omega)_{DWUCK}$ by the the expression

$$(d\sigma/d\Omega)_{exp} = \frac{9.72 D_0^2 C^2 S}{2J + 1} \left[(d\sigma/d\Omega)_{DWUCK}\right] \varepsilon \ ,$$

where C is the Clebsch-Gordan coefficient that accounts for the isospin coupling of the residual nucleus to that of the transferred neutron pair to yield the isospin of the target nucleus. For the (p, t) reaction, C^2 is equal to unity. The S factor represents the two-neutron spectroscopic factor and is set to $(2J + 1)$ for neutron closed-shell nuclei. For partially filled subshells, the S factor is equal to $(2J + 1)V_{j1}^2 V_{j2}^2$, where V_{j1}^2 and V_{j2}^2 are the occupation probabilities for each neutron (j_1, j_2). These two quantities are taken from one-neutron pickup experiments [10,11,12] and shell-model calculations [13]. The ε parameter is called the enhancement factor which characterizes the ratio of experimental to DWBA cross sections. It measures the relative strenghts of various (p, t) transitions. D_0^2 is the zero-range normalization constant related to the normalization of the triton wave function. The value of 6.6 in 10^4 fm^3 MeV^2 units was adopted as in Ref. [8]. Global proton and triton optical model potential parameters were used in DWBA analysis [14,15]. The experimental cross sections along with the theoretical cross sections and the enhancement factors are listed in Table 1.

The enhancement factors (ε) extracted from data are typically less than the ideal value of unity. DWBA calculations consistently overpredict the magnitude of the cross sections. This discrepancy can be ascribed to a bad choice of optical potential parameters or to inconsistent spectroscopic factors. The finite-range effect that arises from an increase of the momentum transfer to the triton at higher bombarding energies may also be of importance. Further theoretical investigation remains the object of a future study.

This collaboration will, within a few months, repeat the measurement with a better ^{18}O target, i.e. made from higher grade ^{18}O enriched material. As a consequence of the improved target and the allocation of more beam time, we will be able to collect more statistics in the excitation energy region of interest. This will hopefully allow the measurement of breakup particles emanating from the 0_6^+ state in ^{16}O.

Table 1. *Extracted cross section values of strongly populated states compared with theoretical predictions. The errors on the extracted cross section values are based primarily on statistics while the uncertainty on the target thicknesses was estimated to be less than 15 %.*

Levels of ^{16}O

$E_x(MeV)$	J^π	$\sigma_{exp}(\mu b/sr)$	$\sigma_{DWBA}(\mu b/sr)$	C^2S	ε	Pickup configuration
0	0^+	1.6±0.6	54.18	0.68	0.01	$(1d_{5/2})^2$
6.13	3^-	6.5±1.2	10.59	0.41	0.61	$(1p_{1/2} \times 1d_{5/2})$
7.12	1^-	1.8±0.7	10.20	0.44	0.18	$(1p_{1/2} \times 2s_{1/2})$
19.26	2^+	14.0±1.7	41.28	0.25	0.34	$(1d_{5/2})^2$

Levels of ^{14}O

$E_x(MeV)$	J^π	$\sigma_{exp}(\mu b/sr)$	$\sigma_{DWBA}(\mu b/sr)$	C^2S	ε	Pickup configuration
0	0^+	3.0±0.3	26.14	1	0.11	$(1p_{1/2})^2$
6.59	2^+	15.9±0.7	64.88	1	0.25	$(1p_{3/2} \times 1p_{1/2})$
7.77	2^+	22.7±0.9	75.62	1	0.30	$(1p_{3/2} \times 1p_{1/2})$

Levels of ^{10}C

$E_x(MeV)$	J^π	$\sigma_{exp}(\mu b/sr)$	$\sigma_{DWBA}(\mu b/sr)$	C^2S	ε	Pickup configuration
0	0^+	17.1±0.9	64.70	0.39	0.26	$(1p_{3/2})^2$
3.353	2^+	28.2±1.1	169.7	1.95	0.17	$(1p_{3/2})^2$
5.38	2^+	41.9±1.3	205.6	1.95	0.20	$(1p_{3/2})^2$

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