A NEW STATE IN ^{6}He FOLLOWING THE ^{7}Li$(\gamma, p)^6$He REACTION

M. N. Thompson[1, †]
(For the Lund-Melbourne-Trent Collaboration)
M. J. Boland,[1] M. A. Garbutt,[1] R. P. Rassool,[1] A. J. Bennett,[1] J. W. Jury,[2] J.-O. Adler,[3] B. Schröder,[3] D. Nilsson,[3] K. Hansen,[3] M. Karlsson,[3] M. Lundin,[3] and I. J. D. MacGregor[4]
[1]*School of Physics, The University of Melbourne, Victoria 3010, Australia*
[2]*Trent University, Peterborough, Ontario, Canada K9J 7B8*
[3]*Department of Physics, University of Lund, P.O. Box 118, S-221 00 Lund, Sweden*
[4]*Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ, Scotland*

A broad excited state was observed in ^{6}He with energy $E_x = 5 \pm 1$ MeV and width $\Gamma = 3 \pm 1$ MeV, following the reaction ^{7}Li$(\gamma, p)^6$He. The state is consistent with a number of broad resonances predicted by recent cluster model calculations. The well-established reaction mechanism, combined with a simple and transparent analysis procedure confers considerable validity to this observation.

1. PREDICTED STRUCTURE FOR ^{6}HE

The physics of nuclei approaching the neutron drip-line is of interest as a means of further refining our understanding of the nucleon-nucleon potential. Amongst these so-called "halo" nuclei, ^{6}He has received considerable attention. The established level structure of ^{6}He [1] has been questioned for some years in a number of theoretical calculations. These considered extended neutron distributions by modeling ^{6}He as a ^{4}He+n+n three-body cluster.

A common feature of these calculations is low-lying structure, above the well known 2^+ first excited state. The nature of this structure was initially thought to be a soft dipole resonance [2, 3], with two halo neutrons oscillating against the core. However, more recent calculations refute this and postulate that it is caused by three-body dynamics [4–6]. This paper reports the unambiguous observation of a resonance in ^{6}He at an excitation energy of $E_x = 5 \pm 1$ MeV and width $\Gamma = 3 \pm 1$ MeV.

2. PREVIOUS EXPERIMENTS AND THEIR LIMITATIONS

Experimental measurements on the ^{6}He system have so far been concentrated on charge exchange reactions of the type ^{6}Li(^{7}Li,^{7}Be)^{6}He [7–10] and ^{6}Li(t,^{3}He)^{6}He [11]. All these results have reported low-lying strength in the reaction cross section at roughly the predicted energies by calculations, but none are able to determine the nature of the observed structure.

In each case the analysis of these experiments has involved several controversial assumptions in the background removal process. In particular, the non-resonant background in the (^{7}Li,^{7}Be) reaction was calculated but not measured. This process must include degrees of freedom due to the excited states of both the projectile and the ejectile. In one case [9], non-resonant background contributions to the cross section were not included at all.

Background subtraction is only one of the complications involved with heavy-ion reactions. Another difficulty is that many possible combinations of angular-momentum transfer exist between projectile and target. One of the simplest charge exchange reactions, namely (n, p), does not suffer the same problem. However, the poor resolution of these (n, p) experiments makes it difficult to see even the commonly resolved 2^+ state. Reactions of the type (t,^{3}He) also suffer from poor resolution, and use the same background removal process as the (^{7}Li,^{7}Be) reactions [11]. In contrast, tagged photon measurements have a relatively simple and unambiguous background removal procedure that is proven and well established [12–15] (and references therein). It is the results of the reaction ^{7}Li$(\gamma, p)^6$He that are reported here.

†Electronic address: max@physics.unimelb.edu.au;
URL: http://www.ph.unimelb.edu.au/photo

3. THE ^{7}LI$(\gamma, P)^6$HE EXPERIMENT

This paper reports the presence of a broad resonance at an excitation energy of 5 MeV in ^{6}He that has been observed following the ^{7}Li$(\gamma,p)^6$He photonuclear reaction. The measurement was made in the energy range of E_γ = 50–70 MeV, using the MAX-lab tagged photon facility [16] at Lund University. The protons and other charged particles were detected with solid-state spectrometers,

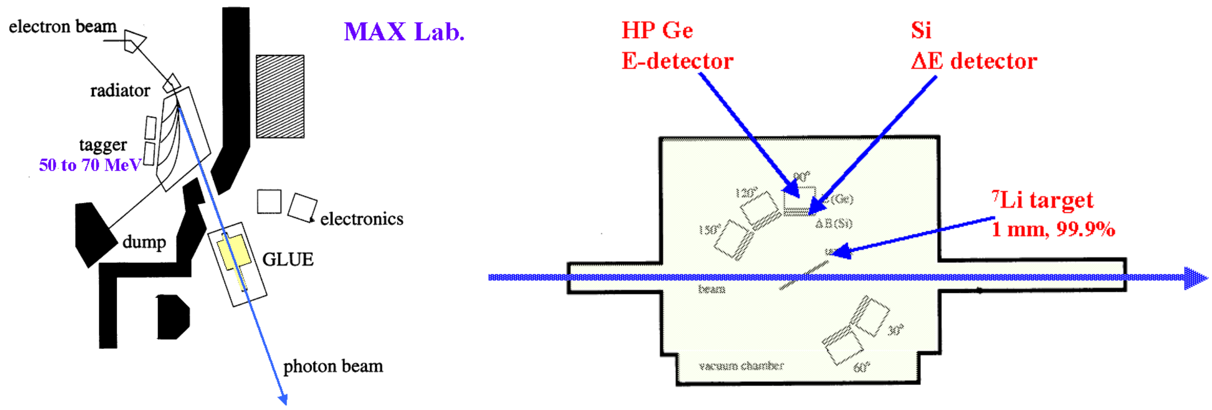

Fig. 1: Experimental arrangement, together with details of the detector location in the GLUE chamber.

each consisting of a thick HP-Ge E-detector and a thin Si ΔE-detector. These were placed at angles of θ = 30°, 60°, 90°, 120°, and 150° to the photon beam, similar to the configuration described in [17]. A 1 mm thick target of 99.9% pure ^{7}Li was placed at 60° to the photon beam. Protons were selected from other charged particle events by use of a particle-identification plot of the energy lost in the full-energy detector, versus that lost in the ΔE-detector.

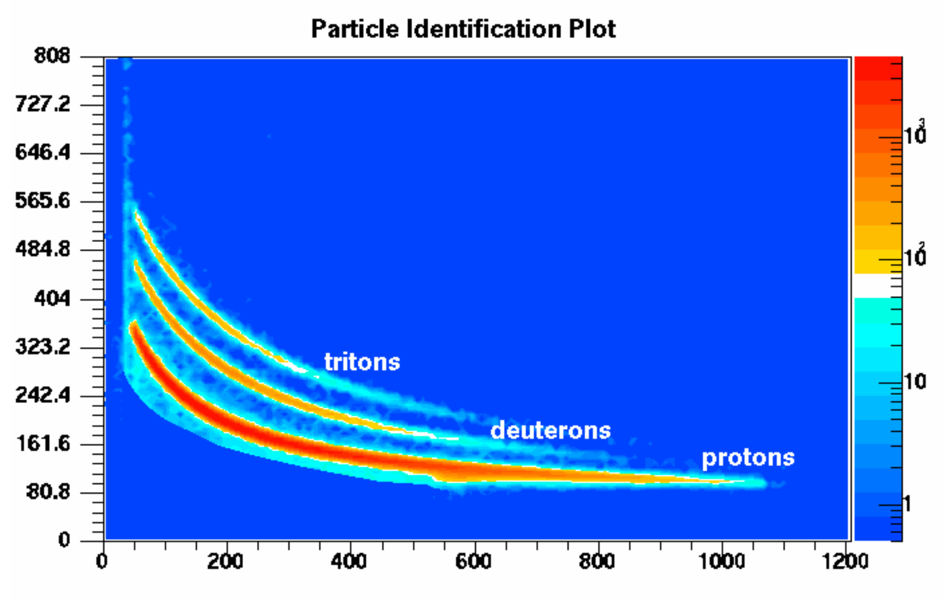

Fig. 2: The $\Delta E - E$ particle identification plot.

Protons correlated with tagged photons were located in a narrow *prompt* timing peak, shown shaded in Fig. 3, sitting on a timing spectrum of random events. Missing-energy spectra were produced from a cut on the prompt peak at each angle (filled dots in Fig. 4). The missing energy is defined as $E_{miss} = E_\gamma - T_p - T_R$, where T_R is the kinetic energy of the ^{6}He nucleus, and T_p is the kinetic energy of the emitted proton. The excitation energy, shown in Fig. 5 is related to E_{miss} by $E_x = E_{miss} - Q$, where Q is the proton separation energy, and for the reaction ^{7}Li$(\gamma,p)^6$He,

$Q = 10.0$ MeV. The contribution of random proton events in the prompt region, was measured by making a cut on the random background region (labeled in Fig. 3). The resulting featureless background spectrum (open circles in Fig. 4) was normalised and fitted, before being subtracted from the spectrum of the prompt region.

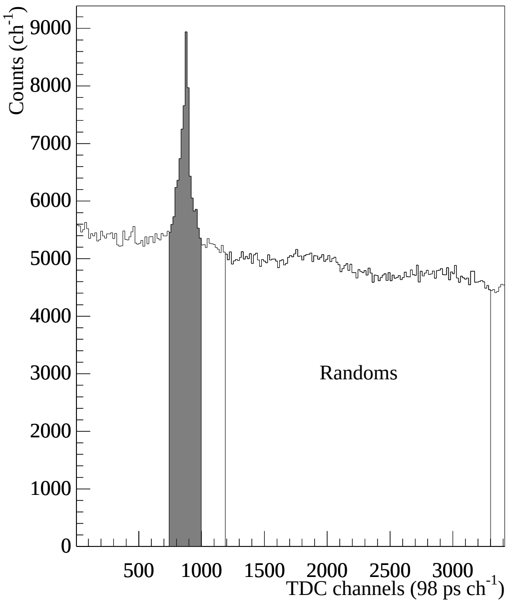

Fig. 3: The time correlation spectrum between protons and tagged photons for $\theta = 60°$. The 6 ns wide prompt peak (shaded) is clearly visible on top of a random background (labeled).

The contribution due to the (γ, pn) reaction (threshold $E_{miss} = 11.9$ MeV) also needed to be considered. The momentum distribution of this background channel was calculated using a Monte-Carlo model of direct two-nucleon emission [18], that included all the experimental parameters, and covered the full phase-space of the experiment. The peak of the (γ, pn) missing-energy distribution is located at $E_{miss} = 29$ MeV (see Fig. 4) and as such cannot account for all the strength observed

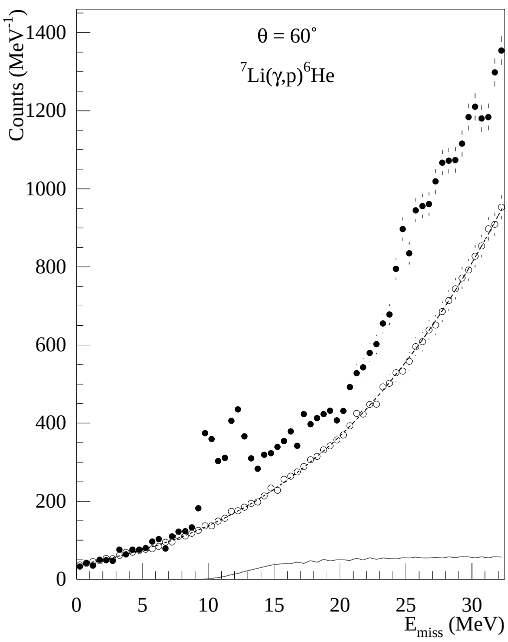

Fig. 4: Proton missing-energy spectrum at $\theta = 60°$ showing (i) the random background (open dots) with a polynomial fit (dotted line) (ii) the calculated (γ, pn) background (solid line) and (iii) the prompt protons (filled dots).

between $E_{miss} = 3$–10 MeV. The pn-background was normalised in a consistent manner for all angles, then subtracted such that the net missing-energy spectrum was positive at all energies. The resulting missing-energy spectrum of protons emitted at $\theta = 60°$ is shown in Fig. 5.

4. NEW EXCITATIONS

Protons leading to the ground state and the first excited state at $E_x = 1.8$ MeV can be clearly seen. Evidence for the known second excited state near $E_x \sim 14$ MeV can be distinguished at the onset of the high missing-energy region of the spectrum. Significantly, the evidence for a broad state can be seen in the region between $E_x \sim 3$–10 MeV. A fit of three Gaussians to the data in Fig. 5 gives a width of $\Gamma = 3 \pm 1$ MeV and a centroid energy of $E_x = 5 \pm 1$ MeV to the new structure, on the assumption that it is a single resonance.

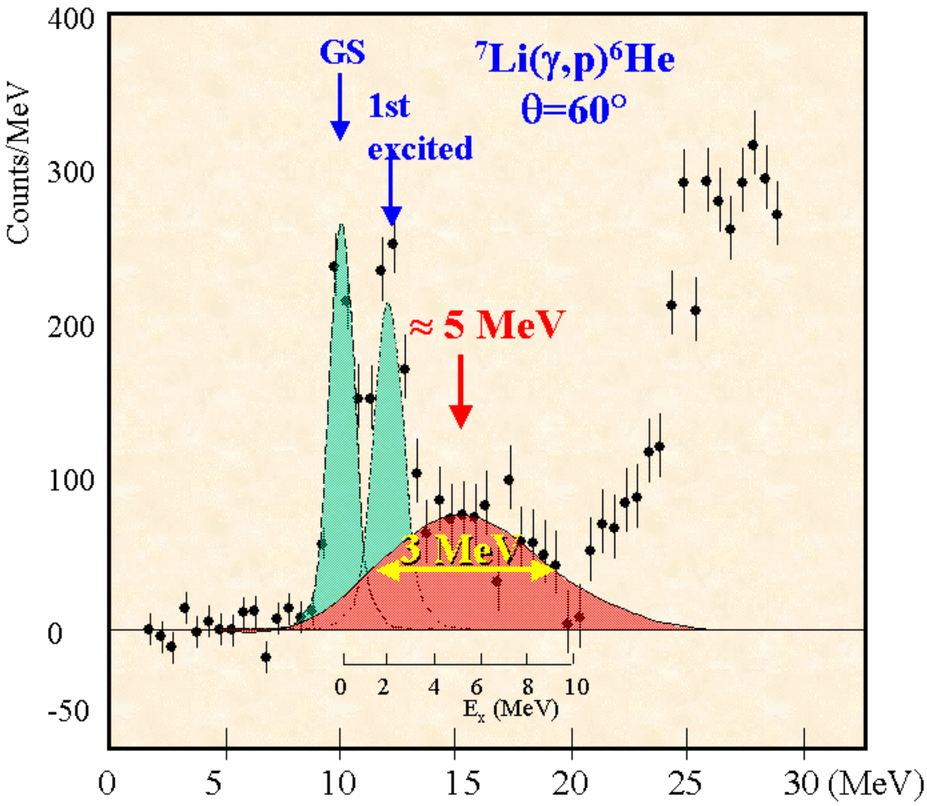

Fig. 5: Proton missing-energy spectrum at $\theta = 60°$ following the reaction $^7\text{Li}(\gamma, p)^6\text{He}$ with the background contributions subtracted. The ^{6}He excitation energy scale is drawn on for reference.

5. SUMMARY

The present experiment, like those using charge exchange reactions, is unable to define the exact nature of the observed resonance. In line with the results of recent experiments [7, 9, 23], the resonance is most probably 2^+ in nature, but consistent with the more recent calculations [5, 20, 24] may also contain 1^+ strength. The 1^- soft dipole mode also appears in calculations of ^{6}He by Suzuki [3] and others [5, 19–22] and is predicted to exist at low excitation energy. A calculation of the the $E1$ breakup of ^{6}He [6] shows an enhancement to the 1^- continuum at an energy consistent with the measurement presented here. It is possible that the strength we observe in the $^7\text{Li}(\gamma, p)^6\text{He}$ cross section at 5 MeV is evidence of the 1^- dipole, however the peak seen in Fig. 5 is much narrower than the predicted width of this multipole resonance. The structure is more likely to be the 2^+ state predicted by Danilin *et al.* [5], with small contributions from 0^+, 1^+ and 1^- unbound continuum states. A complete analysis of our data, including the angular distribution, may clarify the nature of the structure and thereby validate some of the model assumptions.

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