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Excitations in the halo nucleus ^{6}He following the ^{7}Li(γ,p)^{6}He reaction

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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(γ,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.

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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].

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 energies predicted 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 nonresonant 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], nonresonant 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).

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(γ,p)^{6}He photonuclear reaction. The measurement was made in the energy range of $E_\gamma = 50$–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, each consisting of a thick HP-Ge E detector and a thin Si ΔE detector. These

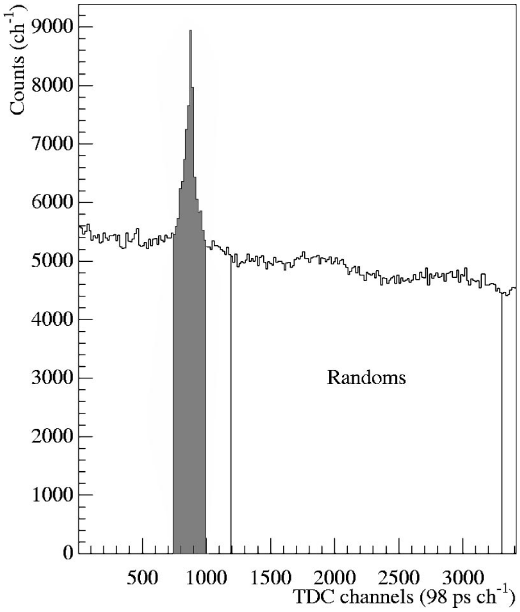

FIG. 1. The time correlation spectrum between protons and tagged photons for $\theta = 60°$. The 6 ns wide prompt peak (shaded) is clearly visible on top of a random background (labeled).

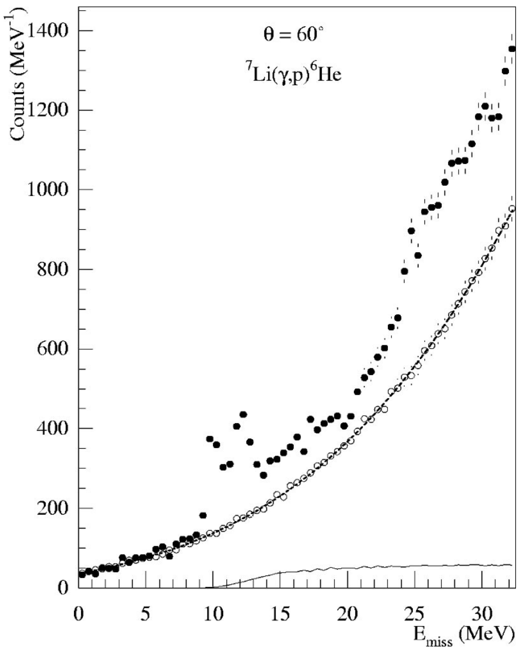

FIG. 2. Proton missing-energy spectrum at $\theta=60°$ showing (i) the random background (open dots) with a polynomial fit (dotted line), (ii) the calculated (γ,pn) background (solid line), and (iii) the prompt protons (filled dots).

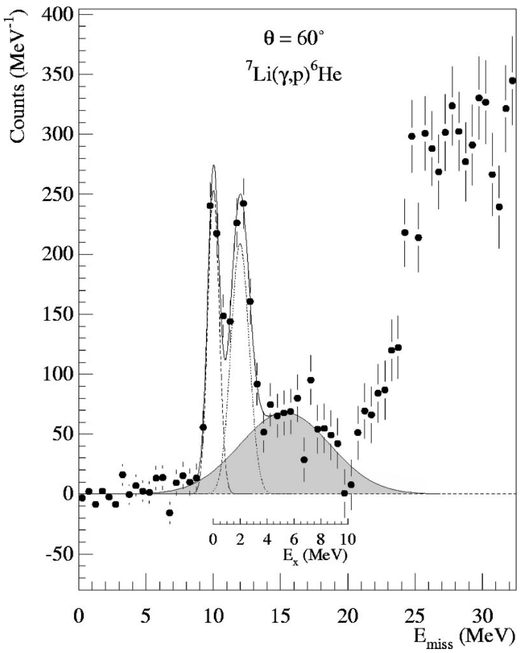

FIG. 3. Proton missing-energy spectrum at $\theta=60°$ following the reaction ^{7}Li$(\gamma,p)^6$He with the background contributions subtracted. The ^{6}He excitation energy scale is drawn for reference.

were placed at angles of $\theta=30°,60°,90°,120°$, 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. Protons correlated with tagged photons were located in a narrow *prompt* timing peak, shown shaded in Fig. 1, 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. 2). 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. 3, 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. 1). The resulting featureless background spectrum (open circles in Fig. 2) was normalized and fitted, before being subtracted from the spectrum of the prompt region.

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], which 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. 2) and as such cannot account for all the strength observed between $E_{miss}=13$–20 MeV. The pn background was normalized 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. 3.

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 $E_x\sim14$ 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 $E_x\sim3$–10 MeV. A fit of three Gaussians to the data in Fig. 3 gives a width of $\Gamma=3\pm1$ MeV and a centroid energy of $E_x=5\pm1$ MeV to the new structure, on the assumption that it is a single resonance.

The present experiment, like those using charge exchange reactions, is unable to define the exact nature of the observed resonance. The strongest candidates seem to be a 1^- soft dipole mode and a second 2^+ state, predicted by Suzuki [3] and others [19–22]. A calculation of 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}Li$(\gamma,p)^6$He cross section at 5 MeV is evidence of the 1^- dipole and the positive parity states, both of which were predicted by Danilin *et al.* [5]. 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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