Physics Letters B 718 (2012) 441–446

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

New excited states in the halo nucleus ^{6}He

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ARTICLE INFO

Article history:
Received 7 March 2012
Received in revised form 21 September 2012
Accepted 7 October 2012
Available online 24 October 2012
Editor: V. Metag

Keywords:
^{8}He(p, t)
Transfer reaction
Borromean nucleus
Resonant states

ABSTRACT

The low-lying spectroscopy of ^{6}He was investigated via the 2-neutron transfer reaction p(^{8}He, t) with the ^{8}He beam delivered by the SPIRAL facility at 15.4 *A* MeV. The light charged particles produced by the direct reactions were measured using the MUST2 Si-strip telescope array. Above the known 2^+ state, two new resonances were observed: at $E^* = 2.6 \pm 0.3$ MeV (width $\Gamma = 1.6 \pm 0.4$ MeV) and at 5.3 ± 0.3 MeV with $\Gamma = 2 \pm 1$ MeV. Through the analysis of the angular distributions, they correspond to a 2^+ state and to an $L = 1$ state, respectively. These new states, challenging the nuclear theories, could be used as benchmarks for checking the microscopic inputs of the newly improved structure models, and should trigger development of models including the treatments of both core excitation and continuum coupling effects.

These last 30 years, the use of radioactive beams to produce nuclei far from the valley of stability has led to the discovery of a large variety of new phenomena, which were not expected in the nuclear structure theories tested on the stable nuclei: alpha-cluster like, halo or neutron-skin structures, low-lying resonant states have been observed in the light nuclei close to the neutron drip-line [1,2]. The shell structure has also been found deeply modified from the picture established close to the β-stability line, with the apparition of new magic numbers [3]. These new features have been triggering intensive theoretical developments to explain the change in our usual nuclear structure conceptions. The recent highlights in our field have been the findings of the role played by the three-nucleon interaction (TNI) in the nuclear spectra of the light nuclei [4] and in the drip-line location [6,5] as well as the influence of the spin–isospin tensor term in the shell level ordering of the states [3] and the effects of the continuum-coupling (CC) between bound, resonant and scattering states in the low-lying spectra of the weakly-bound nuclei [7]. To understand the weak binding features of the light nuclei close to the drip-line, these CC effects have been investigated within various frameworks, the Gamow Shell Model (GSM) [7–9], the Continuum Shell Model CSM [10] or the Complex Scaled Cluster Orbital Shell Model (COSM) [11]. However, if these nuclear models are successful in predicting the characteristics of the ground or first well-studied excited states of the p-shell exotic nuclei, they disagree for the predictions of the other low-lying excited states. The discrepancies between theories question the validity of the microscopic inputs used for the description of the nuclear interactions, the various techniques adopted for the treatment of the many-body correlations, and their interplay with the CC effects.

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0370-2693/$ – see front matter
http://dx.doi.org/10.1016/j.physletb.2012.10.054

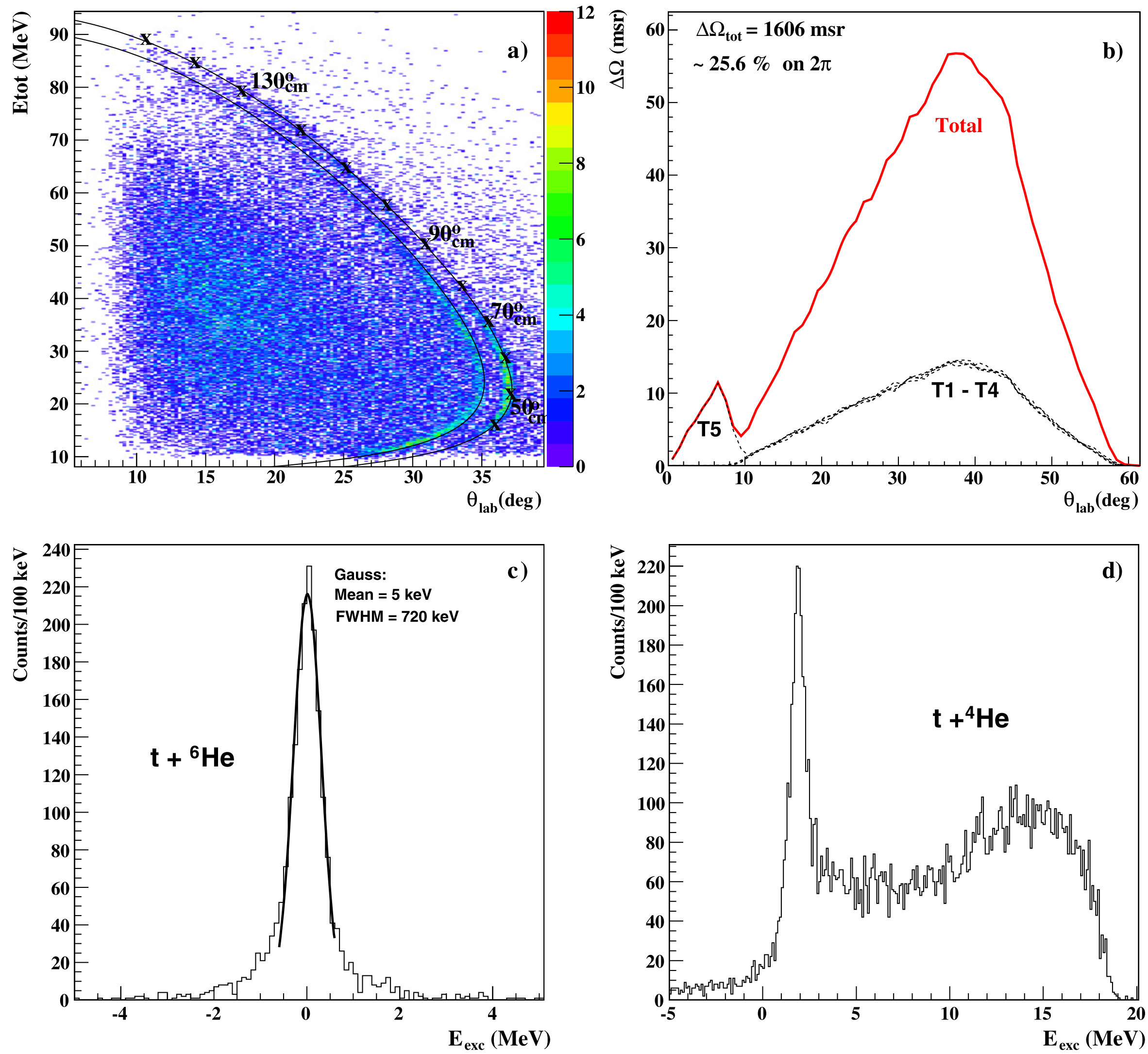

Fig. 1. a) Kinematics of the tritons produced by reactions of ^{8}He on proton at 15.4 A MeV; they are identified via E–ΔE and correlated with α or ^{6}He particles. The lines are the calculated kinematics for the (p,t) reaction to the ^{6}He gs and 2^+ state with crosses indicating the c.m. angles for the gs by steps of 10° and starting from 40° up to 150°. The total solid angle coverage of the set-up is shown in b). Panels c) and d) are the E_x spectra of ^{6}He obtained from the kinematics of the triton between 35 and $150^\circ_{\text{c.m.}}$ with different conditions applied for the coincidence of triton with c) ^{6}He or d) ^{4}He.

In this context, the low-lying spectroscopy of the light exotic nuclei represents a testing ground to constrain the models and to check their assumptions. It is the purpose of this Letter to present our experimental study of the low-lying positive parity excited states of the ^{6}He nucleus and to compare it to the predictions of the most recent nuclear theories. ^{6}He has neutron thresholds located at low energy ($S_n = 1.87$ and $S_{2n} = 0.97$ MeV) and no bound excited state. The first excited state is a 2^+ at 1.8 MeV ($\Gamma = 113$ keV) [12]. ^{6}He is now well known as a halo nucleus [13, 2] and the 2n-halo structure was intensively investigated within few-body models [14,2], but the positions, spin and parities of the resonant states above 1.8 MeV remained to be determined. On the theoretical side, various calculations [14,11,4] or No-Core Shell Model (NCSM) with TNI [15], indicated that a series of 2_2^+, 1_1^+, 0_1^+ states should exist above the 2_1^+ state and below the triton–triton threshold S_{t+t} at 12.3 MeV, but they disagree on the energies of these states. Experimentally, the main results were obtained via transfer reactions, which indicated resonances below S_{t+t} and broad resonances above. From the ^{7}Li(^{6}Li, ^{7}Be)^{6}He reaction [16], a 2^+ state was indicated at 5.6 MeV with a $\Gamma = 10.9$ MeV width and structures possibly $(1,2)^-$ at 14.6 ($\Gamma = 7.4$) MeV, and at 23.3 ($\Gamma = 14.8$) MeV; a broad one ($\Gamma = 4$) at 4 MeV was reported in Ref. [17], and at 18 MeV ($\Gamma = 7.7$) in Ref. [18]. From the ^{6}Li(t, ^{3}He)^{6}He reaction resonance-like structures were seen at 7.7, 9.9 MeV and at 5 ($\Delta L = 1$) and 15 MeV [19]. No resonance except the 2^+ was indicated from the ^{6}He(p, p′) scattering at 40.9 A MeV [13]. None of these experiments was successful to determine precisely the energy and width of the expected resonant states. In a recent experiment at the GANIL facility, the scattering and 1n-transfer reaction of the ^{8}He SPIRAL beam on proton [20] were studied. The (p,t) to the ^{6}He ground state (gs) and 2_1^+ excited state were also measured [21], with cross sections of the order of 1 mb/sr. This 2n transfer appeared to be a good probe to populate the possible excited states of ^{6}He with sufficient yields, taking advantage of the low energy and high intensity of the ^{8}He SPIRAL beam.

We report here the results of the (p,t) experiment carried out with the ^{8}He beam accelerated at 15.4 A MeV, and using an improved set-up to measure at forward angles the triton–particle correlations in the exit channel: triton with either ^{6}He in case of the $(p,t)^6$He$_{gs}$, or with the ^{4}He particle produced in the decay of the excited states of the ^{6}He nucleus into ^{4}He + 2n. The