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Exploring the excited structure of ^{11}Li through (t,p) reactions at the upgraded SEC Device

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Abstract. ^{11}Li is the best example of a two-neutron (2n) halo nucleus, a system where the last nucleons, due to the low binding energy and angular momentum, spend a large part of their time far from the core. Despite extensive experimental efforts, its excited structure remains a topic of debate. Experiment IS690 employs a novel approach to investigate the excited states of ^{11}Li, directly populating these states via the (t,p) reaction from the less exotic ^{9}Li nucleus. In this contribution the experimental setup and preliminar results are summarised.

1 Introduction

Halo nuclei are characterized by the low binding energy of their last nucleons, situated in low orbital momentum states; the combination of both results in a large spatial extension deviating from the standard $r = r_0 A^{1/3}$ relation. The first empirical observation of this special structure came from measurements of the interaction cross-section for light neutron-rich nuclei, among them the scattering cross-section of lithium (Li) isotopes. As the number of neutrons approached the dripline, the radius (proportional to the interaction cross section) deviated from theoretical predictions, with ^{11}Li being the main example [1]. The discovery was interpreted as a new nuclear structure [2], formed by a compact core and an external set of nucleons, this structure was confirmed a few years later in ^{11}Li break-up experiments [3].

^{11}Li is the archetype of a two-neutron halo: a three-body system formed by a ^{9}Li ground state (g.s.) core [4] and two weakly bound neutrons (S_{2n} = 369.3(6) keV) with a extended density distribution. After several experiments the wave funtion of the ^{11}Li g.s. has been established to be a mixture of p (59(1)%), s (35(4)%), and d (6(4)%) waves [5]; however, knowledge of the resonant excited states (only the g.s is bound in ^{11}Li) is not properly determined.

The low-lying continuum in ^{11}Li is dominated by a broad dipole structure, observed in several experiments, with narrower resonances proposed higher up until 6.2 MeV. Recent results on this low-lying continuum structure have been obtained from inelastic p- and d-scattering at TRIUMF [6, 7]. The elastic cross-sections obtained from both experiments are consistent; however, the inelastic p-scattering results indicate a resonant state at 0.80(4) MeV, Γ = 1.15(6) MeV [7], while the resonance was characterized to be at 1.03(4) MeV, Γ = 0.51(11) MeV by d-scattering [6]. A more relevant question concerns the population of these resonances: excitation to a resonance or direct excitation to the continuum?

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Most of the previous attempts to probe the resonant structure of ^{11}Li consisted of promoting a ^{11}Li g.s to the excited states through a reaction. The only exception being the rather complex reaction ^{14}C(π^-,p+d) [8], where the result was limited by low resolution.

2 Experiment IS690

Experiment IS690 was proposed [9] and performed in the Scattering Experimental Chamber (SEC) beam line at the ISOLDE-CERN facility, with the intent to clarify the excited structure of ^{11}Li by directly populating the resonant states through a two-neutron transfer reaction ^{9}Li(t,p)^{11}Li. The main argument behind this approach is the DBWA calculations [10] that indicate a possible L=0 transmission to the ^{11}Li g.s. or three L=1 excitations whose differential cross-section peaks for inverse kinematics at foward angles. Figure 1 shows the calculations for the cross-sections for the emitted proton performed by A. Moro [12].

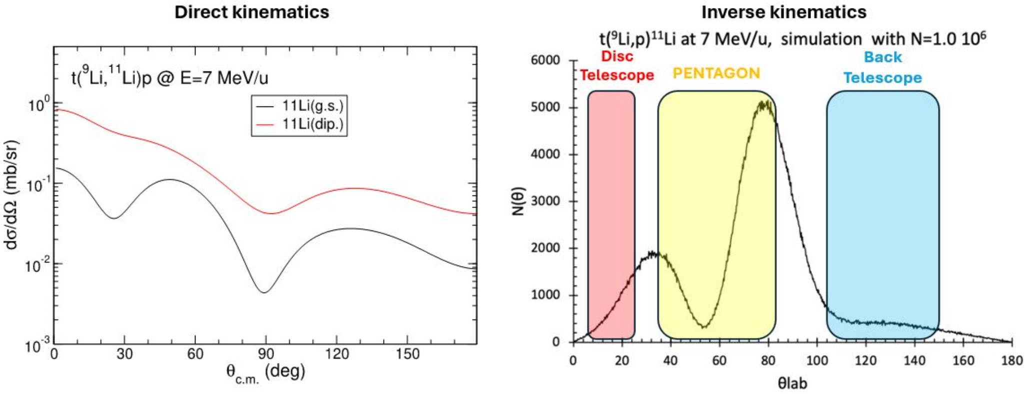

Figure 1. Left: Diferential cross section (mb/sr) for the ^{9}Li(t,p)^{11}Li reaction to the g.s (black) and first excited state (red). **Right:** Emitted proton distribution from populating the ^{11}Li g.s using the ^{9}Li(t,p)^{11}Li reaction in inverse kinematics. Angular coverge of the IS690 setup is overlaped.

The momentum and energy distribution of the residual protons gives information about the resonant states, while the elastic scattering cross-section is useful to fix optical potential models. This approach complements the ^{11}Li(p,t)^{9}Li experiment carried out at TRIUMF [11].

Production of ^{9}Li ($T_{1/2}$=178,2(4) ms) is hampered by the release time of the target. To enhance production, a new target material, TaCx, was implemented, Ta was substituted for Re in the transfer line, and the proton energy was increased from 1,4 GeV to 1,7 GeV, currently the highest energy for protons used at ISOLDE. These advancements led to a production rate of 1,27 (21) × 10^6 ions/μC at the ISOLDE tape station. The ^{9}Li^{+1} ion beam entered REX-trap before being transfered to the Electron Beam Ion Source (EBIS), and charge-bred to 3^+ to obtain an $A/Q = 3$ for the injection into HIE-ISOLDE where it is accelerated to 7 MeV/nucleon with an average intensity of 12.500 ^{9}Li ions/s at our setup.

The post-accelerated ^{9}Li beam is let to impinge on a ^{3}H target (^{3}H absorbed in a 1 μm Ti-foil with a 0,47/1 ratio). The energy of the ^{9}Li beam is chosen to realise the 2n transfer while reducing the number of additional open channels. Identifying the influence of background reactions, especially the ^{9}Li(p,d)^{10}Li, elastic, and fusion evaporation channels, constitutes the hardest part for the analysis. For this experiment to be successful, the setup must offer optimal angular coverage while enabling differentiation between very similar reaction products.

The detector setup was prepared as an upgrade of the one employed by the MAGISOL collaboration in its previous (d,p) experiments [13] and optimized with Geant4 simulations of the Si detectors to fine-tune the thickness and positions of the detectors, optimizing angular resolution and coverage and modelling the effect of the background channels.

Setup consists of different combinations of Si detectors from Micron Semiconductor Ltd, each part covering a specific region of the cross-section as shown in Figure 1.

1. Five particle telescopes formed by W1-60 μm DSSDs backed by MSX25-1500 μm Si-PADs, arranged in a pentagon covering angles from 37° to 84°.
2. Two Silicon Circular Detectors (CDs), each S3-1000 μm, forming a telescope and covering the forward direction from 6° to 32°.
3. An additional CD (S5-300 μm) covering the backward direction from 100° to 145°.

The target is placed between the pentagon and the backward CD detector; the incoming ^{9}Li beam enters through the central hole of the S5 detector via a 8 mm collimator. Since the reaction is done in inverse kinematics, the heavy reaction products will move in the forward direction, while the lighter ones will be detected by the surrounding detectors. Additionally, a collimator is placed at the entrance setup; this collimator is equipped with four particle detectors that can be used to center the beam. After the setup, a beam dump equipped with a particle telescope is used to monitor the beam intensity. All detectors were calibrated using a 4α (^{148}Gd, ^{239}Pu, ^{241}Am, ^{244}Cu covering 3.1-5.8 MeV) source. Figure 2 shows the CAD design of the setup and a photo of the final setup.

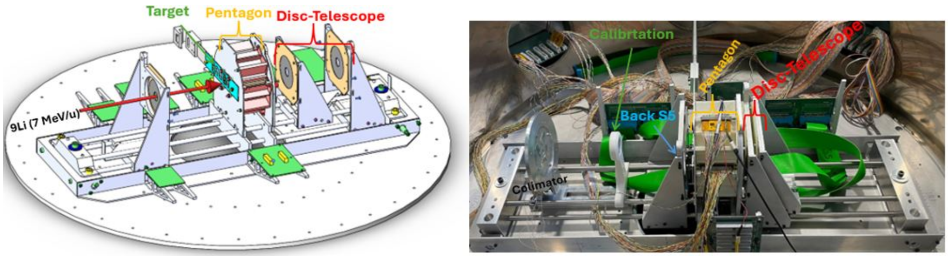

Figure 2. Right: CAD design of the IS690 setup with the different components indicated. Left: Photo of the final setup used in the IS690 setup including the calibration source.

A five-slot target ladder is used to hold the target. One of the slots contains the tritium target; the others contain different targets used for other purposes:

1. A 15 μm thick Deuterated Polyethylen (DP) target, to compare with previous results of the (d,p) reaction [13].
2. The 0,1 μm thick ^{3}H/Ti target, (tritium embedded in a titanium foil to a ratio of 0,4/1)
3. A 0,1 μm thick titanium foil from the the same Ti sample, for measuring the background from the titanium in the tritium target.
4. An empty target frame to measure eventual scattering from the frame and let the beam pass to the beam dump telescope.
5. A gold target, to be used with the stable beam (^{12}C) for Rutherford scattering in order to obtain the exact angular position of each detector.

To change between targets, the ladder is connected to an external actuator that can be set to one of the five positions, each corresponding to a target.

For the electronic chain both Mesytec hardware and software were used. The two S3 CD-detectors, the S5 CD-detector, and two of the W1-DSSDs were connected via 5x MMR-64 digitizer cards, interfaced via optical cable to a VMMR-8 multiplexer module in the VME crate. The VMMR-8 supports up to eight MMR-64 cards, optimizing the setup by reducing the need for additional electronics.

The rest of the detectors were connected using more traditional electronics; the remaining 3x W1-DSSDs of the pentagon were connected via MPR-64 and MPR-32 preamplifiers to MDPP32 digitizers in the VME crate. While the 5x MSX25-PAD and the Beam Dump surface barrier Si-telescope detectors used the preamplifiers of a MSI-8, also connected to a MDPP32 digitizer. Both the VMMR-8 and MDPP32 modules were controlled via a Mesytec

MVLC module and via USB-3 cable to a computer running the Mesytec mvme daq software. In total, the setup comprises 3335 detector elements, read out by 327 electronic channels.

The Si-telescopes differentiates between proton, deuteron, triton and alpha particles. Once the protons are isolated, these are classified by the kinematic curves, which can be precisely determined due to the setup's good energy resolution (~ 100 keV) and good angular resolution (~ 6°).

3 Preliminary results

During experiment IS690 alternate runs of similar length were conducted with, Ti-target, the ^{3}H/Ti target, and with occasional runs using the empty target-frame, Au and DP targets. A preliminary analysis of the data from the particle telescopes reproduces reasonably well the MC simulations performed with LISE++, see figure 3. The comparasion of the Ti and ^{3}H targets, indicates a noticeable increase of proton counts in the ^{3}H/Ti data set, along with traces of tritium and deuterium that are not observed with the Ti target.

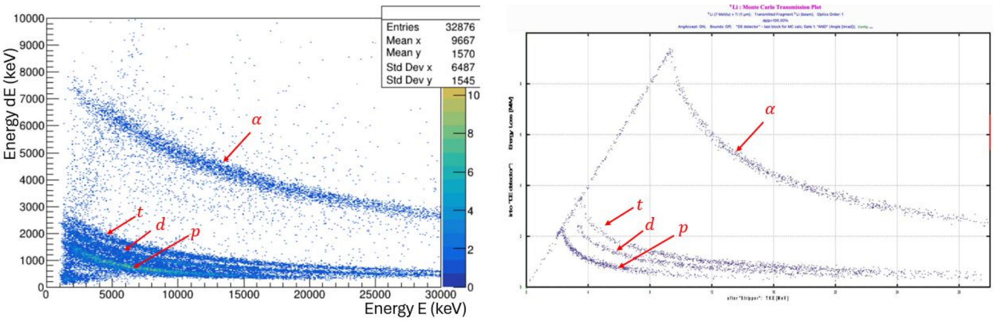

Figure 3. Comparison between online ΔE vs E plot obtained from particle telescopes using the ^{3}H target files (left) and a Montecarlo simulation produced with LISE++ (right). Presence of tritium, deuterium, protons, and alpha particles also observed.

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