Exploring the ^{10}Li structure by the d(^{9}Li,p)^{10}Li transfer reaction

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Abstract. The ^{9}Li + ^{2}H reaction has been investigated at 11 AMeV incident energy at the ISAC II facility (TRIUMF). In the present paper we focus on the one-neutron transfer channel, which potentially holds spectroscopic information on the unbound nucleus ^{10}Li. The TUDA setup has been used in order to detect and identify the outgoing ^{9}Li at forward angles and the recoil protons at backward angles. This setup allows to study the ^{10}Li emitted in the crucial region at forward angles in the center of mass.

1. Introduction

Transfer reactions are essential tools to probe selected components of the nuclear wave functions. Thanks to that they have been used in the past and are still crucial for nuclear spectroscopy purposes. With the advent of radioactive beam facilities, the new opportunity to explore nuclear phenomena far from the stability valley has driven a renewed interest to transfer reactions, to be studied in inverse kinematics.

On one hand there is a specific attention to understand how the transfer mechanism is influenced by the reduction of the binding energy of the projectile [1]; on the other hand, the measured spectra could reveal unexpected features due to nucleon correlations which are beyond the mean field description of nuclear structure [2]. Examples of such phenomena have been recently found in light neutron rich nuclei such as the Li isotopes.

In particular, the study of the unbound system ^{10}Li is of great interest since the knowledge of its structure is a crucial ingredient in the description of the two-neutron halo nucleus ^{11}Li. Despite the significant amount of experimental information gathered during the last years, the properties of the ^{10}Li continuum remains unclear, to the extent that even the energy and the spin-parity of the ground state are still controversial [1-4].

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2. Past attempts to study the d(^{9}Li,p)^{10}Li reaction

Recently ^{10}Li has been the subject of different theoretical and challenging experimental studies [3-5], including two attempts to explore the resonant energy spectrum by the d(^{9}Li,p)^{10}Li transfer reaction at 2.35 AMeV incident energy at REX-ISOLDE and at 20 AMeV at NSCL-MSU, respectively.

In the experiment at 2.35 AMeV of Ref. [3], the energy spectrum of ^{10}Li has been measured up to about 1 MeV excitation energy in an angular range between 100° and 140° in the centre of mass. Due to the low beam intensity of ~5 × 10^4 pps, a relatively thick target of deuterated polyethylene CD2 (660 μg/cm^2 thick) was used in order to maximize the yields, which slightly exceeded 100 events in total. The recoiling protons were detected by large area telescopes of position sensitive silicon detectors located between 18° and 80° in the laboratory. At backward laboratory angles, the energy of the protons was too low to be detected, thus excluding in the collected data the crucial region corresponding to forward angles in the centre of mass. Despite the low statistics and the not optimal angular range explored, an excitation energy resolution of about 300 keV (FWHM) was obtained and the authors could draw some conclusions about the role of the $s_{1/2}$ and $p_{1/2}$ neutron orbitals in ^{10}Li around the neutron emission threshold.

In the NSCL-MSU experiment [4], a similar experimental technique was used but at higher incident energy (20 AMeV). The beam intensity was even lower than in the REX-ISOLDE experiment (~7 × 10^3 pps) and had considerably worse emittance. The CD2 target was about 2 mg/cm^2 thick. The recoiling protons were measured at backward angles by a series of large area silicon detectors in coincidence with the ^{9}Li detected by the S800 spectrometer at forward angles. The obtained energy resolution was about 700 keV and the reconstructed ^{10}Li spectra were measured up to about 4.5 MeV excitation energy. However, due to the poor statistics (less than 100 counts in total) and energy resolution, not much has been added to our understanding of ^{10}Li states.

In a recent theoretical study of the ^{10}Li low energy resonances [2], a state dependent treatment of the pairing interaction, beyond the usual BCS approximation, has proven to be necessary to reproduce the energy spectra measured in the REX-ISOLDE experiment. In addition it has been shown that, despite the complications due to the resonant structure of the final states, the cross sections can be accurately described within the DWBA.

Nevertheless, due to the limitations of the existing data, many of the details predicted by the theory have not been tested. For example only a measurement of the angular distribution at forward angles in the centre of mass would disentangle contributions from *s*, *p* and *d* orbitals in different portions of the energy spectrum. Also the behavior of the observed $s_{1/2}$ and $p_{1/2}$ orbitals should be better addressed, since in both cases the coupling with the $p_{3/2}$ proton generates a doublet of ^{10}Li states, namely 1^-, 2^- for the $s_{1/2}$ and 1^+, 2^+ for the $p_{1/2}$, while experimentally there is no indication of such doublets. In addition, according to the theory, $p_{3/2}$ and $d_{5/2}$ orbitals should generate resonances above 1 MeV, but these have not been observed experimentally, since the MSU data are difficult to be reliably interpreted.

To summarize, many of the key points regarding the ^{10}Li spectrum are still very uncertain, especially from an experimental point of view. As a consequence the description of the ^{11}Li halo nucleus is quite deficient, since the binding energy strongly depends on the same n - ^{9}Li interaction responsible for the ^{10}Li structure.

3. The experiment

We have studied the d(^{9}Li,p)^{10}Li reaction at 11 AMeV incident energy at the TRIUMF laboratory. At this energy the recoiling protons can be detected at backward laboratory angles, thus allowing the exploration of the crucial region at forward angles in the centre of mass.

A ^{9}Li beam, produced by the ISAC-II facility, impinged on a CD2 target, 126 μg/cm2 thick, evaporated at the INFN-LNS laboratory (Catania). The recoiling protons were detected at backward angles 127° < θ_{LEDA} < 152° by the LEDA array of silicon strip detectors [6], thus allowing the study of the ^{10}Li emitted at forward angles. Protons are detected in coincidence with the ^{9}Li fragments produced from the breakup of the corresponding ^{10}Li. ^{9}Li fragments were detected and identified by a ΔE-E telescope of S2 annular Double Sided Silicon Detectors located downstream the target. Fig. 1 shows an example of ΔE-E identification plot where the ^{9}Li locus is well identified and contoured by a solid line.

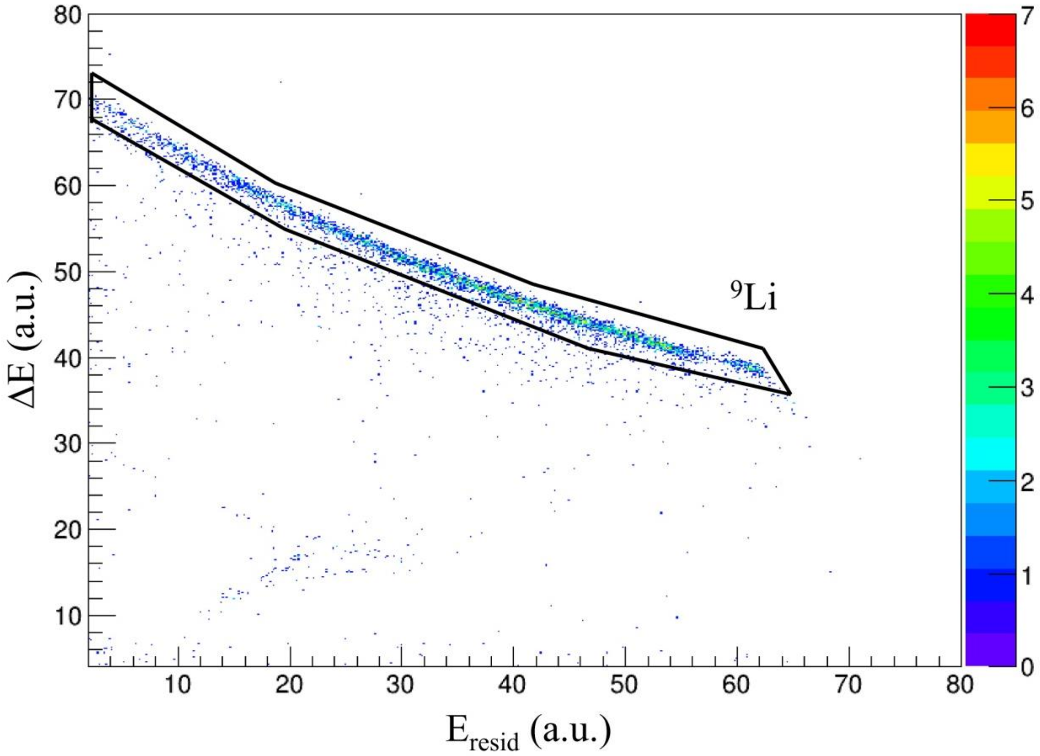

Figure 1. Energy loss (ΔE) measured by the first stage of the S2 telescope of annular silicon detectors as a function of the residual energy (E_{resid}). The graphical contour indicates the ^{9}Li events.

An additional benefit to placing the proton detectors at backward scattering angles is that no background was expected from other interactions between the beam and the target.

The ^{10}Li excitation energy was reconstructed with significant statistics, compared to the previous experiments of refs. [3] and [4], allowing to explore the ^{10}Li level structure at least in the low excitation energy region. Fig. 2 shows the excitation energy spectrum obtained up to 1.5 MeV in the angular region 8.3°< θ_{CM} < 16.2°. A centroid E_0 = 0.61 MeV and full width at half maximum Γ = 0.62 MeV were extracted for the unbound ground state by fitting the energy spectrum with a lorenzian shape and a background reproducing the three-body phase space. These values are consistent with the presence of a $p_{1/2}$ resonance predicted in the CCBA calculations performed in ref. [3]. Also the attempt to fit the experimental data of ref. [4] with two separate resonances, explored by the authors in the same paper, indicate the possible presence of a structure at that energy. In addition, the calculations of the angle integrated cross section reported in ref. [2], predict a resonance-like structure mainly determined by the $p_{1/2}$ contribution in the same energy region.

The highly segmented detection system available in the present experimental setup, also allowed to measure the angular distributions of the observed resonances at forward angles. The analysis of the angular distribution, which is still in progress, would give some indication about the controversial question of the spin-parity of the ^{10}Li unbound ground state.

Journal of Physics: Conference Series **590** (2015) 012037 doi:10.1088/1742-6596/590/1/012037

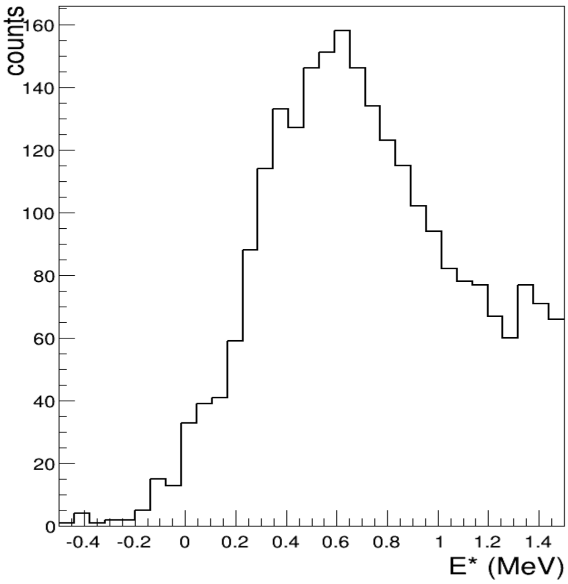

Figure 2. ^{10}Li reconstructed excitation energy from the $d(^{9}Li,p)^{10}Li$ reaction at 11 AMeV.

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