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2015 J. Phys.: Conf. Ser. 630 012019

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# The $d(^9\text{Li},p)^{10}\text{Li}$ reaction as a tool to explore the $^{10}\text{Li}$ structure

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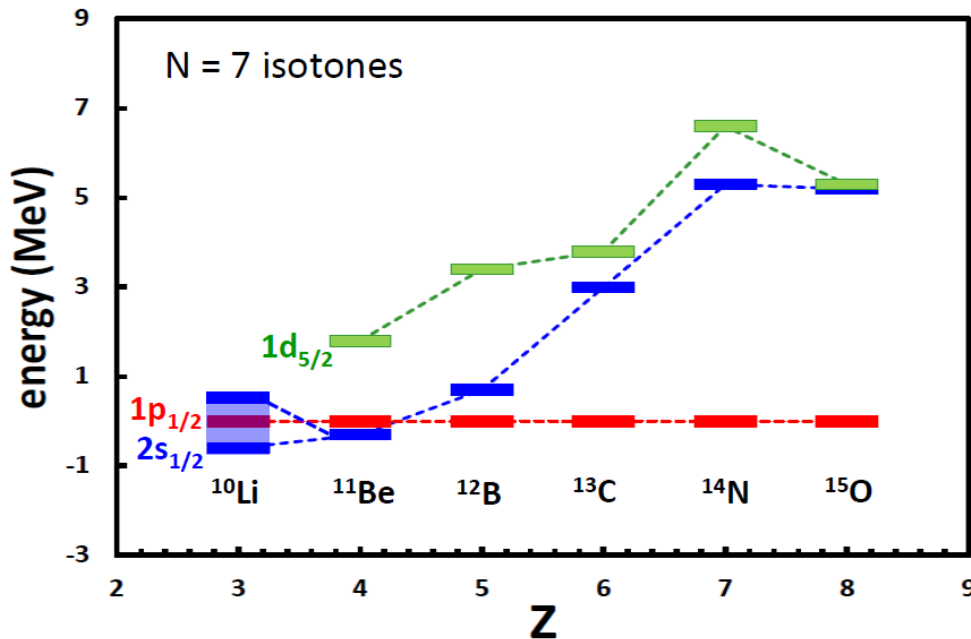
**Abstract.** The ground and low-lying states of the unbound nucleus  $^{10}\text{Li}$  were populated by the  $^9\text{Li} + ^2\text{H} \rightarrow ^{10}\text{Li} + ^1\text{H}$  reaction at 11 AMeV incident energy at the ISAC II facility (TRIUMF). In the experimental setup, the outgoing  $^9\text{Li}$  at forward angles and the recoil protons at backward angles were detected and identified. This setup allows to study the  $^{10}\text{Li}$  emitted in the crucial region at forward angles in the centre of mass.

## 1. Introduction

The study of the unbound system  $^{10}\text{Li}$  is of great interest since the knowledge of its structure is a crucial ingredient in the description of the two-neutron halo nucleus  $^{11}\text{Li}$  [1, 2]. Structure calculations for the weakly bound system  $^{11}\text{Li} = ^9\text{Li} + 2n$  either in the cluster model or in approaches based on the independent particle model require in fact the interaction between one neutron and the  $^9\text{Li}$  core as an important input quantity. This can be deduced directly from the binding energy and states of  $^{10}\text{Li}$ . Despite the significant amount of experimental information gathered during the last years, the properties of the  $^{10}\text{Li}$  continuum remain unclear, to the extent that even the energy and the spin-parity of the ground state are still controversial [4-9].

In the case of  $N = 7$  isotones, the energy and ordering of the  $2s_{1/2}$ ,  $1p_{1/2}$  and  $1d_{5/2}$  orbitals can be represented as in Fig. 1, according to the excitation energy of the known single particle states. In the case of  $^{15}\text{O}$ ,  $^{14}\text{N}$ ,  $^{13}\text{C}$  and  $^{12}\text{B}$  ground states, it is well known that the main component of the  $1d_{5/2}$  shell lies above the  $2s_{1/2}$ , which is in turn above the  $1p_{1/2}$ . In the  $^{11}\text{Be}$  ( $Z = 4$ ) ground state a shell inversion between  $2s_{1/2}$  and  $1p_{1/2}$  is known to appear [9,11]. If this anomaly is maintained also in the  $^{10}\text{Li}$  ( $Z = 3$ ) case, the lowest energy state in  $^{10}\text{Li}$  is expected to have a dominant configuration with one neutron in the  $2s_{1/2}$ . On the other hand, if one supposes that the presence of shell inversion in  $^{11}\text{Be}$  is related to the  $2\alpha$  cluster structure of Be isotopes, such a structure is not possible for  $^{10}\text{Li}$  and the configuration of the  $^{10}\text{Li}$  ground state is expected to be a  $^9\text{Li}$  core + one neutron in the  $1p_{1/2}$ .





**Figure 1.** Relative energy of the  $1d_{5/2}$  (green),  $2s_{1/2}$  (blue) and  $1p_{1/2}$  (red) shells for the  $N = 7$  isotones in the region of  $^{10}\text{Li}$ .

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 [3,4]. 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 [5]. Examples of such phenomena have been recently found in light neutron rich nuclei such as the Li isotopes.

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

Recently  $^{10}\text{Li}$  has been the subject of different theoretical and challenging experimental studies [6-8], including two attempts to explore the resonant energy spectrum by the  $d(^9\text{Li},p)^{10}\text{Li}$  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. [6], the energy spectrum of  $^{10}\text{Li}$  was measured up to about 1 MeV excitation energy in an angular range between  $100^\circ$  and  $140^\circ$  in the centre of mass. Due to the low beam intensity of about  $5 \times 10^4$  pps, a relatively thick target of deuterated polyethylene CD<sub>2</sub> ( $660 \mu\text{g}/\text{cm}^2$  thick) was used in order to maximize the yield, which slightly exceeded 100 events in total. The recoiling protons were detected by large area telescopes of position sensitive silicon detectors located between  $18^\circ$  and  $80^\circ$  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  $^{10}\text{Li}$  around the neutron emission threshold.

In the NSCL-MSU experiment [7], 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 ( $\sim 7 \times 10^3$  pps) and the emittance considerably worse. The CD<sub>2</sub> target was about  $2 \text{ mg}/\text{cm}^2$  thick. The recoiling protons were measured at backward angles by a series of large area silicon detectors in

coincidence with the  ${}^9\text{Li}$  detected by the S800 spectrometer at forward angles. The obtained energy resolution was about 700 keV and the reconstructed  ${}^{10}\text{Li}$  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 was added to our understanding of  ${}^{10}\text{Li}$  states.

In a recent theoretical study of the  ${}^{10}\text{Li}$  low energy resonances [4], 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 was shown that, despite the complications due to the resonant structure of the final states, the cross sections can be accurately described within the DWBA.

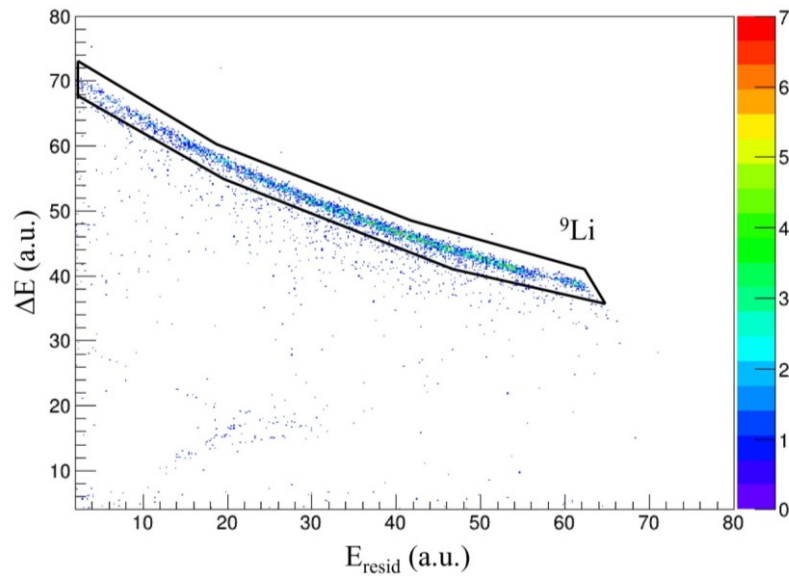
Nevertheless, due to the limitations of the existing data, many of the details predicted by the theory were not tested. For example only a measurement of the angular distribution at forward angles in the centre of mass would disentangle contributions from  $s$ ,  $p$  and  $d$  orbitals in different portions of the energy spectrum. Also the behaviour 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  ${}^{10}\text{Li}$  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  ${}^{10}\text{Li}$  spectrum are still very uncertain, especially from an experimental point of view. As a consequence the description of the  ${}^{11}\text{Li}$  halo nucleus is quite deficient, since the binding energy strongly depends on the same  $n$  -  ${}^9\text{Li}$  interaction responsible for the  ${}^{10}\text{Li}$  structure.

### 3. The experiment

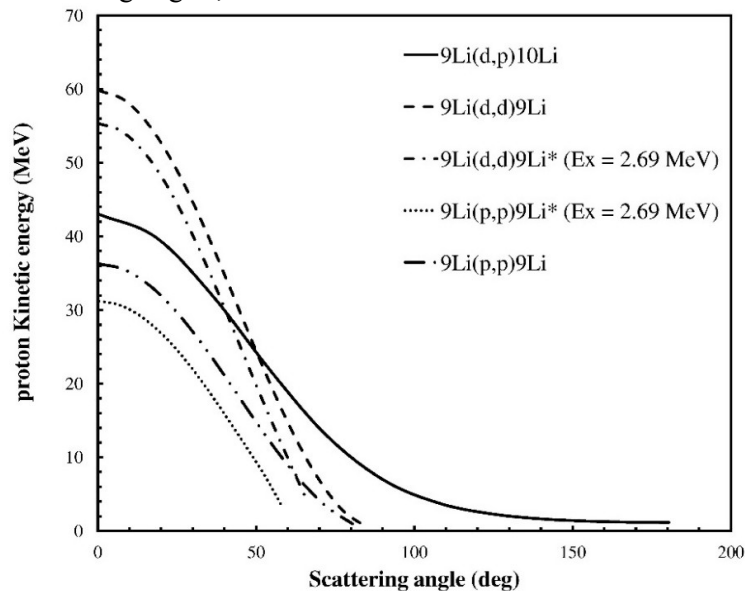
We studied the  $d({}^9\text{Li},p){}^{10}\text{Li}$  reaction at 11 AMeV incident energy at the TRIUMF laboratory. At this energy the recoiling protons can be detected at backward laboratory angles, thus allowing the exploration of the crucial region at forward angles in the centre of mass.

A  ${}^9\text{Li}$  beam, produced by the ISAC-II facility with an average current of  $10^6$  pps, impinged on a CD2 target,  $126 \mu\text{g}/\text{cm}^2$  thick, evaporated at the INFN-LNS laboratory (Catania). The target thickness was chosen to improve the energy resolution maintaining an acceptable count rate. The recoiling protons were detected at backward angles  $127^\circ < \theta_{LEDA} < 152^\circ$  by the LEDA array of silicon strip detectors [12], thus allowing the study of the  ${}^{10}\text{Li}$  emitted at forward angles. Protons were detected in coincidence with the  ${}^9\text{Li}$  fragments produced from the break-up of the corresponding  ${}^{10}\text{Li}$ .  ${}^9\text{Li}$  fragments were detected and identified by a  $\Delta E$ -E telescope of annular Double Sided Silicon Detectors located downstream the target. Fig. 2 shows an example of  $\Delta E$ -E identification plot where the  ${}^9\text{Li}$  locus is well identified and contoured by a solid line.



**Figure 2.** Energy loss ( $\Delta E$ ) measured by the first stage of the S2 telescope of annular silicon detectors as a function of the residual energy ( $E_{\text{resid}}$ ). The graphical contour indicates the  ${}^9\text{Li}$  events.

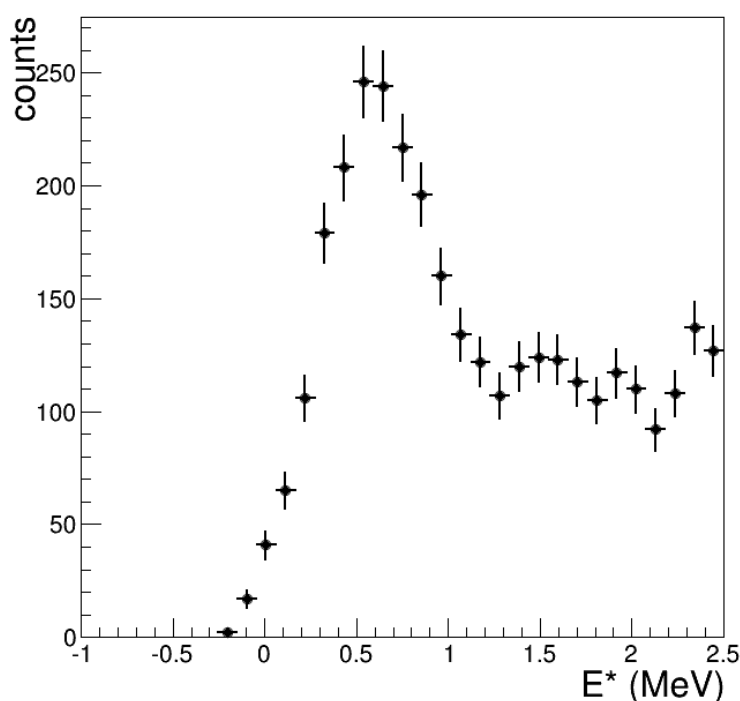
An additional benefit of placing the proton detectors at backward scattering angles is that no background is expected from other reaction channels. In Fig. 3 the calculated kinematics of the outgoing deuteron from for the  ${}^9\text{Li} + d$  elastic and inelastic scattering are shown. Since there may be also a small proton contamination in the  $\text{CD}_2$  target, the  ${}^9\text{Li} + \text{proton}$  scattering reactions are also shown in Fig. 3. In all these cases, the kinematics of the reaction does not allow to produce a light nucleus at backward scattering angles, where the LEDA detector was located.



**Figure 3.** Energy of the emitted protons as a function of the scattering angle in the laboratory frame for the  ${}^9\text{Li}(d,p){}^{10}\text{Li}$  in inverse kinematic at 100 MeV (solid curve), in comparison with the kinematics of the lighter recoiling nuclei from competing reaction channels. The angular range covered by the LEDA detectors is  $127^\circ < \theta_{\text{LEDA}} < 152^\circ$ .

The  $^{10}\text{Li}$  excitation energy was reconstructed with significant statistics allowing to explore its level structure. Fig. 4 shows the excitation energy spectrum obtained up to 2.5 MeV in the angular region  $8.3^\circ < \theta_{CM} < 16.2^\circ$ . The centroid ( $E_0 = 0.6$  MeV) and full width at half maximum ( $\Gamma = 0.6$  MeV) of the unbound ground state were deduced and also the presence of a structure at higher excitation energy at around 1.5 MeV is visible. The sharp fall down of the tail of the first peak toward zero excitation energy shows that there is no evidence in the present data of the existence of a  $s_{1/2}$  low lying virtual state as supposed by [6].

The highly segmented detection system 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  $^{10}\text{Li}$  unbound ground state.



**Figure 4.**  $^{10}\text{Li}$  reconstructed excitation energy from the  $d(^9\text{Li},p)^{10}\text{Li}$  reaction at 11 AMeV.

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