EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Proposal to the ISOLDE and Neutron Time-of-Flight Committee

Assessing the parity inversion in $N = 7$ isotones via ^{9}Li$(d,p)^{10}$Li

September 25, 2023

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Abstract: An unambiguous determination of whether the shell inversion persists in $N = 7$ isotone ^{10}Li still eludes us, despite numerous experimental attempts to resolve this situation. We propose a measurement of the ^{9}Li$(d,p)^{10}$Li reaction with ISS at 9.5

MeV/u, with optimized excitation energy and angular coverage, as well as an ideal Q-value resolution. To acheive this, we request 16 shifts of ^{9}Li beam time at 9.5 MeV/u with an intensity of 2×10^5 pps.

1 Introduction

In weakly bound or unbound nuclear systems, the interplay between localized shell-model states and the continuum dramatically changes the structure of nuclei. This effect is rooted in the behavior of the low-lying $1s_{1/2}$, $0p_{1/2}$ and $0d_{5/2}$ single-particle states in light nuclei, where the $1s_{1/2}$ single-particle binding energy decreases less rapidly than states with higher angular momenta. One of the most recognizable examples is the ground state (g.s.) of the one-neutron halo nucleus ^{11}Be. The ^{11}Be g.s. ($1/2^+$) is strongly influenced by the continuum, causing the g.s. inversion with respect to the $1/2^-$ state, resulting in the breakdown of the $N = 8$ magic number and the formation of neutron halo. Early on, Talmi and Unna commented on the neutron $1s_{1/2}$ orbital, lying well above the $0p_{1/2}$ orbital energy in ^{13}C, but descending to form the ground state in ^{11}Be for the $N = 7$ isotones [1]. However, for the $N = 7$ unbound isotone ^{10}Li, it still remains an open question whether the shell inversion persists.

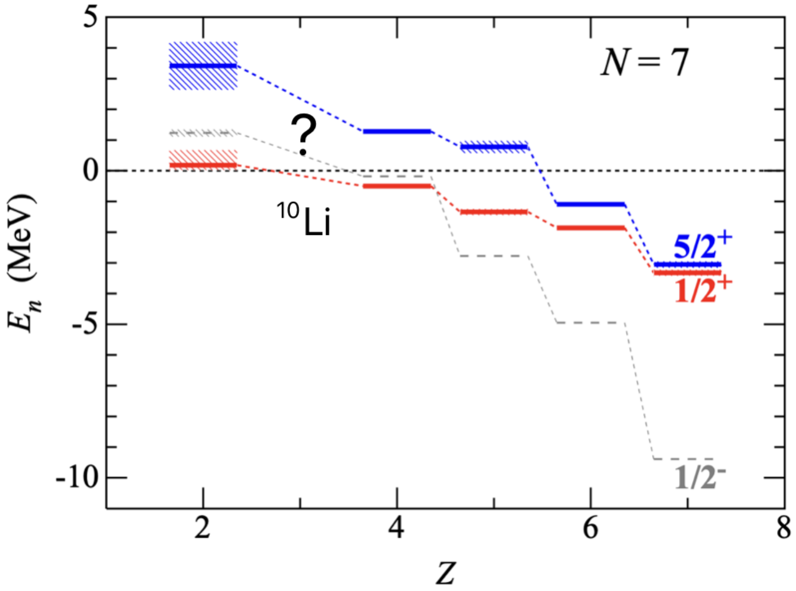

Figure 1: The experimental data available on the neutron binding energies, relative to the neutron threshold, of the $0p_{1/2}$, $1s_{1/2}$, and $0d_{5/2}$ states in the $N = 7$ nuclei. Adopted from Ref. [2]

The unbound ^{10}Li nucleus carries information about the two-neutron halo formation in Borromean nucleus ^{11}Li and on the reaction mechanisms [3]. However, despite the considerable theoretical and experimental effort undertaken over the last four decades, there exists a plethora of fundamental open questions regarding the nature of this extreme nuclear system. According to the evolution of the $N = 7$ isotone chain shown in Fig. 1, an s-wave intruder ground state was favorably expected for ^{10}Li, consistent with the breakdown of $N = 8$ magic number near this region [4] It would support a ground state where a $1s_{1/2}$ neutron would couple to a $0p_{3/2}$ proton to form a 1^- or 2^- state, instead of a pure p-wave coupling. However, a solid experimental consensus among several experiments has not been found yet.

Table 1: Present existing data for ^{10}Li g.s. inferred from one neutron transfer reactions. Extracted from Ref. [5] and updated with more recent experiments

Reaction	E$_r$ or a$_s$ (MeV or fm)	Γ (MeV)	l	Ref
^{11}Li(p,d)^{10}Li	E$_r$ =0.62(4)	0.33(7)	1	[6]
^{9}Li(d,p)^{10}Li	-0.35±0.1	<0.32	-	[7]
^{9}Li(d,p)^{10}Li	a$_s$=-[13-24] fm		0	[8]
^{9}Li(d,p)^{10}Li	E$_r$ =0.45(3)		1	[9]

The observation of the s-wave is a complicated and challenging task. In order to clarify and disentangle this situation, many experiments have been performed aiming to provide an accurate spectroscopic description of ^{10}Li. The present situation regarding the structure of ^{10}Li studied from transfer reactions shows that there is no firm consensus for the virtual states, as shown in Table. 1. For one-neutron transfer reactions, one $^{11}\text{Li}(p,d)$ and three $^{9}\text{Li}(d,p)$ experiments have been performed previously to investigate the low-lying resonances in ^{10}Li, but the conclusions are not consistent. A strong p-wave resonance peak with energy $E_r = 0.62(4)$ MeV and a total width $\Gamma = 0.33(7)$ MeV was populated by the $^{11}\text{Li}(p,d)$ reaction [6]. The first $^{9}\text{Li}(d,p)$ experiment at an incident energy of 20 MeV/nucleon was performed at NSCL in 2003 [7]. It concluded that the one neutron separation energy of $S_n = -0.35$ MeV appears to be consistent with a p-wave state [10]. Later, another $^{9}\text{Li}(d,p)$ reaction carried at 2.36 MeV/nucleon with the REX-ISOLDE facility supported the existence of a low-lying s-wave virtual state, with a scattering length of 13-24 fm and a $p_{1/2}$ resonance of $E_r = 0.38$ MeV and a width of $\Gamma = 0.2$ MeV [8]. It is worth noting that their angular coverage was just at very large angles in the center of mass (c.m.) frame, 98-134°. However, the energies of these two measurements were not optimized for the (d,p) reaction nor with the best angular coverage, so the data cannot be easily interpreted in terms of well-tested reaction mechanisms. Recently, a new $^{9}\text{Li}(d,p)$ reaction carried out at 11.1 MeV/u at TRIUMF suggested the existence of a $p_{1/2}$ resonance at $E_x = 0.45(3)$ MeV, while no evidence for a significant s-wave contribution close to the threshold [9]. It also showed a significant contribution of s- and d-wave for the 1.5 and 2.9 MeV excitation energy, respectively. The angular coverage of this measurement was at very forward c.m. angles ($6° < \theta_{cm} < 15°$), but spanned a very small angular range.

A solution for the discrepancy between the most recent (d,p) measurements was proposed from a theoretical standpoint (see Fig 2). Two different theoretical models accounting for reaction and structure, transfer to continuum [11] and renormalized nuclear field theory [12], suggest that the absence of a s-wave virtual state in Ref. [9] is a consequence of the angular coverage of the experiment. Both theoretical frameworks support the $N = 7$ parity inversion and, the existence of split p-wave resonance that dominates at forward angles and a s-wave virtual state that is inferred from the data of Ref. [8] at very backward angles. In addition, these calculations point out to an unobserved $d_{5/2}$-wave resonance at around 4 MeV supported by the rather featureless spectrum shown in the lower left panel of Fig. 2.

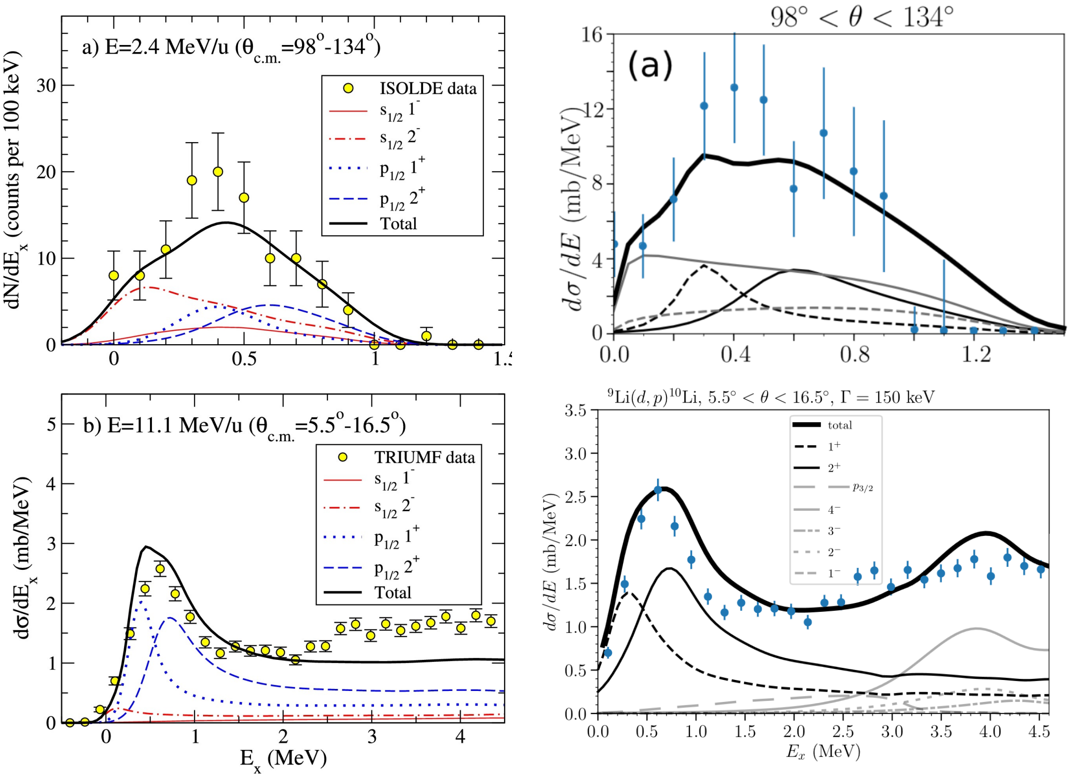

Figure 2: Lower and upper left panels: Ref. [11]. Lower and upper right panels: Ref. [12].

Based on these results, a clear signature of the population of the ^{10}Li virtual ground state via the ^{9}Li(d,p) reaction has not been claimed yet as there exist several experimental inconsistencies within the available data. The ISOLDE spectrum features pronounced fluctuations as a consequence of the rather low statistics. In addition, because of the low bombarding energy, the range of excitation energy is limited to 1 MeV. The angular distribution was determined in a very narrow domain and shows some important deviations from the calculations, as seen in Ref. [12]. Based on these results, there are many open questions to address in an improved ^{9}Li(d,p) experiment:

- Extract ^{10}Li spectroscopic information in a broad angular and excitation energy domain in one unique experiment.
- Unambiguously determine the existence of parity inversion in ^{10}Li via the ^{9}Li(d,p) reaction and the mass of the ground state with good precision.

- Resolve the $p_{1/2}$ 1^+ and 2^+ doublet and their relative intensity.
- Determine the existence and strength of the $d_{5/2}$-wave resonance of importance for the ^{11}Li structure.

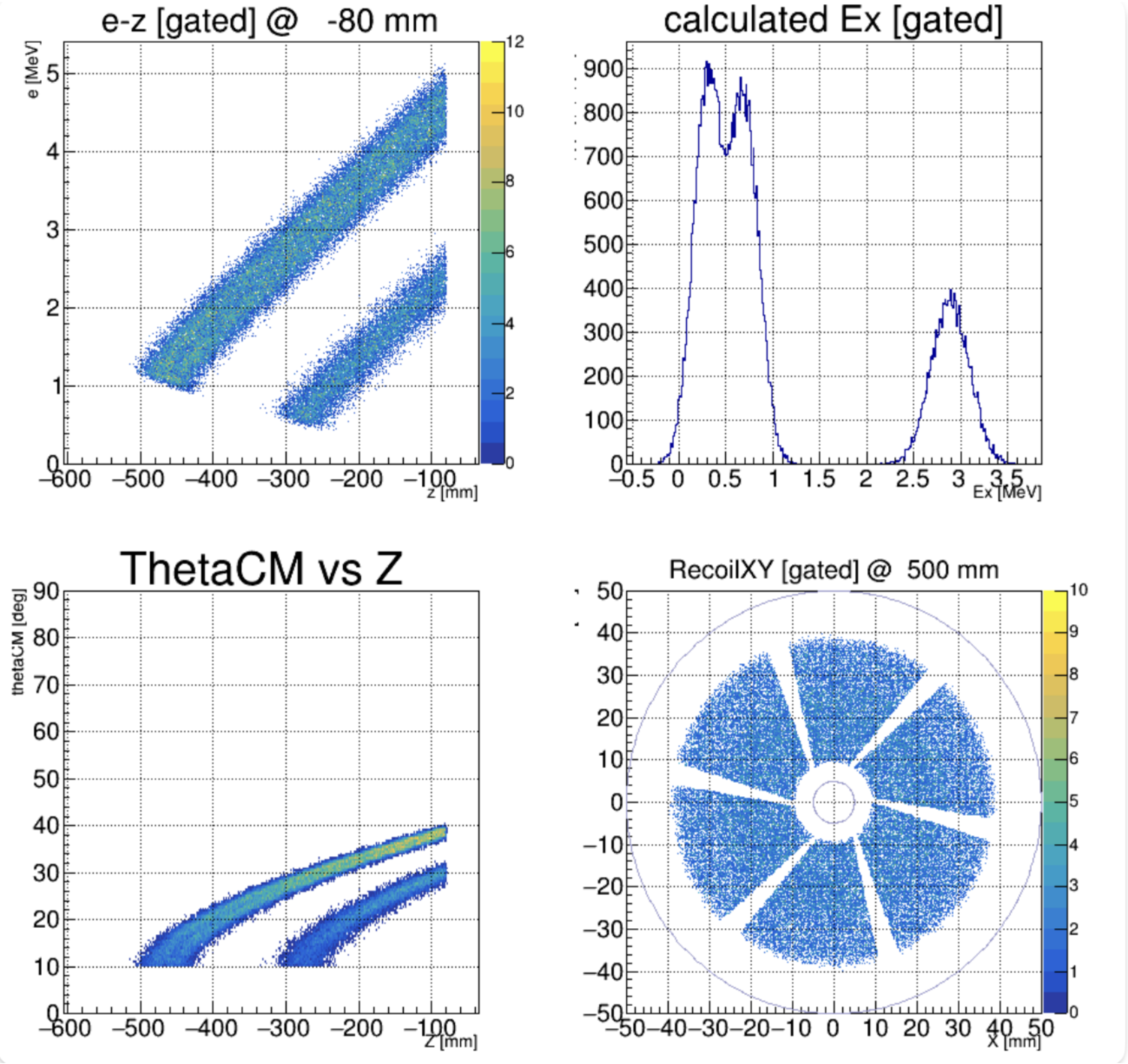

Figure 3: Kinematics simulation for protons at 1.5 T for the ^{9}Li$(d,p)^{10}$Li reaction at 9.5 MeV/u, assuming resonances at and 0.3, 0.7 and 2.8 MeV, with widths of 0.35 MeV. (b) The excitation energy spectrum constructed from the simulated data. (d) The hit pattern on the recoil detectors.

Using ISS to measure the ^{9}Li$(d,p)^{10}$Li reaction will allow us to achieve an outstanding energy resolution of about 130 keV and a large angular coverage where the different l-values are distinguishable. We propose a measurement at 9.5 MeV/u. Our aim is to extract cross sections and relative spectroscopic factors at the $\sim$10% level for these states.

2 Experimental details

We will use a single target-array setting covering a c.m. angle range of at least $10^\circ < \theta_{\text{c.m.}} < 35^\circ$, which is possible with a magnetic field of 1.5 T (see Fig. 3). The silicon array will cover 8 cm$< Z <$58 cm upstream of the target. A simulation of the proton kinematic lines can be seen in Fig. 3. Recoil detection will be achieved by the standard Si E-ΔE technique using annular Si detectors of 80 μm and 500 μm. This thickness is enough to stop all the forward-going Li isotopes from the ^{9}Li(d,p) reaction. It will be placed 70 cm downstream of the target, which will have a full acceptance for the Be isotopes in the c.m. angles of interest. Such a setup is routine using ISS. Here, the resolution is important and we will use a thin deuterated polyethylene (CD$_2$) target of around 100 μg/cm^2. A Q-value resolution of ∼130 keV will be achieved based on the amount of energy loss in the target.

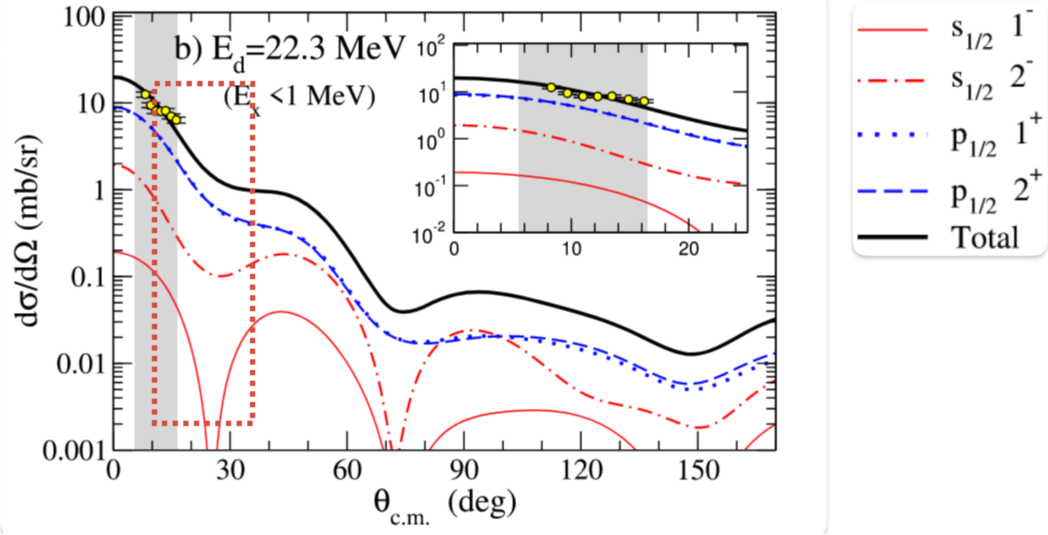

Figure 4: Calculated differential cross sections adapted from Ref. [11]. The data points are from Ref. [9]. The red dashed area shows the coverage of the proposed measurement with the ISS array.

3 Beam time request and estimates

Rate estimates are based on the assumption of an angular coverage of $10^\circ < \theta_{\text{c.m.}} < 35^\circ$ on the Si array. The beam intensity is expected to be $2{\times}10^5$ ions per second. The relatively higher energy (9.5 MeV/u) is necessary to have the appropriate c.m. angular coverage for protons following the population of states in the ∼2-4 MeV excitation-energy range.

The estimation of the unbound state cross sections is adapted from Ref.[11] (see Fig. 4), which was calculated at a similar beam energy. In order to distinguish between the $\ell = 0$ and 1 angular distributions or determine their ratios, the uncertainty around $\theta_{cm} =$

$15^\circ - 35^\circ$ needs to be small (see Fig. 4), which sets the lower limit to calculate the beam time. The measured proton angular distributions will be binned into 6 data points, with an average solid angle of $d\Omega = 0.22$ Sr for each point. By using the formula Yield $=$ $beam \times N_{target} \times (d\sigma/d\Omega) \times d\Omega$, we estimate that with 15 shifts of measurement, we should achieve around 50 counts per angular bin, which is good enough to get $< 15\%$ statistical uncertainty to distinguish between $\ell = 0$ and $\ell = 1$. A total of 15 shifts of beam time is therefore requested. As such, we estimate approximately 320 and 2400 counts for the $\ell = 0$ and 1 resonances, respectively. Another shift is required to optimise the tune into the ISS and the experimental setup of beam time. **16 shifts** are required in total.

4 Summary

In spite of efforts in recent years, there still remain many open questions regarding the structure of ^{10}Li low-lying states, which is essential for understanding the structure of two-neutron halo nucleus ^{11}Li. One of the most important questions is whether the shell inversion persists in ^{10}Li. Therefore, we propose a measurement of ^{9}Li(d,p) reaction at ISOLDE with ISS to resolve the long-standing questions in the low-lying structure of ^{10}Li and to determine the ground state parity. We request 16 shifts of beam time to measure the ^{9}Li(d,p) reaction at 9.5 MeV/u. The ^{9}Li beam will be produced at an intensity of 10^5 pps and the outgoing protons will be measured with ISS to acheive a resolution of 130 keV, an excitation energy range of 0-4 MeV, and an angular coverage of $10^\circ < \theta_{cm} < 35^\circ$. This will allow for unambiguous determination of the parity order in ^{10}Li.

Appendix 1

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *The ISOLDE Solenoidal Spectrometer*

Part of the	Availability	Design and manufacturing
ISOLDE Solenoidal Spectrometer	☒ Existing	☒ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed ISS installation.

Additional hazards:

Hazards			
Thermodynamic and fluidic			
Pressure			
Vacuum			
Temperature			
Heat transfer			
Thermal properties of materials			
Cryogenic fluid			
Electrical and electromagnetic			
Electricity			
Static electricity			
Magnetic field	1.5 T		
Batteries			
Capacitors			
Ionizing radiation			
Target material	Deuterated polyethylene (50-400 μg/cm^2)	Tritium tritide (45 μg/cm^2 tritium)	
Beam particle type	^{9}Li	^{9}Li	
Beam intensity	2×10^5	2×10^5	
Beam energy	9.5 MeV/u	9.5 MeV/u	
Cooling liquids			
Gases			
Calibration sources:	☒		
• Open source	☒ (α calibrations source 4236RP)		

• Sealed source			
• Isotope	^{148}Gd, ^{239}Pu, ^{241}Am, ^{244}Cm		
• Activity	1 kBq, 1 kBq, 1 kBq, 1 kBq = 4 kBq		
Use of activated material:			
• Description			
• Dose rate on contact and in 10 cm distance			
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic			
Harmful			
CMR (carcinogens, mutagens and substances toxic to reproduction)			
Corrosive			
Irritant			
Flammable			
Oxidizing			
Explosiveness			
Asphyxiant			
Dangerous for the environment			
Mechanical			
Physical impact or mechanical energy (moving parts)			
Mechanical properties (Sharp, rough, slippery)			
Vibration			
Vehicles and Means of Transport			
Noise			
Frequency			

Intensity			
Physical			
Confined spaces			
High workplaces			
Access to high workplaces			
Obstructions in passageways			
Manual handling			
Poor ergonomics			

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): N/A

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