EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Probing the ^{11}Li low-lying dipole strength via ^{9}Li(t,p) with the ISS

October 3, 2020

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CERN-INTC-2020-067 / INTC-P-582
05/10/2020

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1 Introduction

In exotic, light nuclei lying along the neutron dripline, $N = 6$ becomes a magic number as a result of the phenomenon of parity inversion. Consequently, ^{9}Li$_6$ is a single closed shell system. While ^{10}Li, just one extra neutron is not bound, the nucleus ^{11}Li is, if ever so weakly bound ($S_n \approx 380$ keV). A fact whose origin points to pairing correlations of the two neutrons outside the closed shell.

The differential cross section for Coulomb breakup for ^{11}Li exhibits a pronounced peak at very low relative energy of the two neutrons, $E_{rel} \approx 0.35$ MeV –corresponding to an excitation energy $E_x \approx 0.75$ MeV– with a large cross section of almost 0.3 b/MeV [1, 2]. A low-lying $E1$ resonance in ^{11}Li was also observed in the inelastic processes –(p, p') and (d, d')– with centroid $E_x \lesssim 1$ MeV, width $\Gamma \approx 0.5$ MeV and carrying $\approx 8\%$ of the Thomas-Reiche-Kuhn (TRK) dipole energy weighted sum rule [3, 4, 5], which confirms the resonant character of the $E1$ transition strength observed in Coulomb excitation.

There is evidence which testifies to the fact that this $E1$ resonance $|1^-(^{11}\mathrm{Li})\rangle$[*], acting as intermediate boson –together with the low-lying quadrupole mode of the core ^{11}Li, central in dressing the $s_{1/2}$ and $p_{1/2}$ single-particle states leading to parity inversion– provides an important part of the binding energy of the two halo neutrons. Within this scenario, and to a good approximation, the wave-function of the ground state of ^{11}Li is [6, 7, 8]:

$$\begin{aligned}|gs(^{11}Li)\rangle &= 0.55|p^2_{1/2}\rangle + 0.45|s^2_{1/2}\rangle + 0.7|(s_{1/2}, p_{1/2})_{1^-} \otimes 1^-; 0^+\rangle \\ &+0.1|(s_{1/2}, d_{5/2})_{2^+} \otimes 2^+; 0\rangle, \end{aligned} \tag{1}$$

explicitly showing the importance of the $E1$ phonon[†].

While much have been learned concerning the low-lying $E1$-resonance of ^{11}Li through Coulomb-excitation and inelastic scattering experiments, key questions regarding its microscopic structure remain open. Among them one can mention:

- Viewed it as a two-quasiparticle state, which is the relative role played by particle-hole (ph), particle-particle (pp) and hole-hole (hh) components?
- To which extent can this dipole mode be viewed as a vibration of the halo neutrons against the nucleons of the core moving in phase and, within this context, how important is the contribution of the associated ground state correlations to the neutron (halo) skin of ^{11}Li?
- How important the role of vorticity is in the velocity field of this $E1$ mode?

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[*] In what follows it is assumed that the odd $p_{3/2}$ proton acts as a spectator. For this reason and for the sake of simplicity, it is omitted when writing the different states.

[†] The soundness of this description has been confirmed by the ^{1}H(^{11}Li,^{9}Li)^{3}H reaction [8], the 1^- component of Eq. (1) being essential to account, through normalization, for the absolute differential cross section of the ground state and the 2^+ one for the direct population of the first excited state of ^{9}Li, $|^{9}\mathrm{Li}(1/2^-; 2.69\mathrm{MeV})\rangle$.

These questions can, to a large extent, be answered by probing the soft $E1$-mode through the reaction $^{9}\mathrm{Li}(t,p)^{11}\mathrm{Li}(1^-)$, and compare the measured differential cross-sections with state of the art calculations [9, 10]. This is in keeping with the fact that ground state correlations of mainly (pp)-type contribute constructively coherent to the absolute two-neutron transfer cross section, the opposite being true in the case of mainly (ph)-modes. As expected, ground state correlations of (pp)-, (hh)- and (ph)- modes behave in an opposite fashion regarding their contribution to the absolute inelastic differential cross sections. Within this context, enhancements close to an order of magnitude are expected using correlated wavefunctions to describe the states associated with the soft dipole mode of ^{11}Li [11, 10] with respect to a single-particle $s_{1/2}p_{1/2}(1^-)$ state. Further insight into these questions can be obtained by assessing the eventual role that two step inelastic processes, namely $^{9}\mathrm{Li}(t,p)^{11}\mathrm{Li}(\mathrm{gs})(p,p')^{11}\mathrm{Li}(1^-)$ may play in the population of the dipole mode.

In summary, the two correlated halo neutrons in the ground state of ^{11}Li can be viewed as a nuclear realization of a Cooper pair. This nucleus has proved to be a unique system to discover unexpected features and correlations of both structure and reaction aspects of pairing correlations. Here, taking advantage of the unique capabilties of HIE-ISOLDE and the ISOLDE Solenoidal Spectrometer (ISS), we propose to study the $^{9}\mathrm{Li}(t,p)^{11}\mathrm{Li}$ reaction, with particular interest in the population of the $|1^-(^{11}\mathrm{Li})\rangle$ state. The experiment will, in an important way, shed light on the basic features characterizing the low-energy dipole response of the system, which appears to be a critical ingredient to bind ^{11}Li, as clearly seen in Eq. 1.

2 Experimental details

We will use the ISS to analyze protons from the (t,p) reaction on ^{9}Li at 10 MeV/u. The specific details for the proposed measurement are discussed in the following sections.

Beam energy—A beam energy of 10 MeV/u has been chosen as a compromise between cross section and kinematics. The $^{9}\mathrm{Li}(t,p)^{11}\mathrm{Li}$ reaction has, somewhat counter intuitively, a large negative Q value of -8.1 MeV. This has the effect of lowering the energy of the outgoing protons compared to less negative Q values. At 10 MeV/u, protons populating states/resonances up to approximately 5 MeV in excitation energy will be detected by the Si array. The energies of the outgoing protons will greater than 500 keV for $10^\circ \lesssim \theta_{\mathrm{c.m.}} \lesssim 40^\circ$. At this incident beam energy, the angular distributions for $L = 0$ and 1 transfer are distinctive.

ISOLDE Solenoidal Spectrometer status—The ISS was developed by a UK-European collaboration. Two experiments were completed at the end of 2018, just prior to the LS2. These experiments, a study of the $^{28}\mathrm{Mg}(d,p)^{29}\mathrm{Mg}$ reaction at 9.4 MeV/u [12] and of the $^{206}\mathrm{Hg}(d,p)^{207}\mathrm{Hg}$ reaction at 7.4 MeV/u [13], emphatically demonstrated the capabilities of the ISS for the measurement of transfer reactions in inverse kinematics with outstanding resolution. Prior to the next campaign of measurements, a new Si array will installed, providing ideal solid angle coverage.

Reaction kinematics and experimental setup—The Si array, which surrounds the beam axis, is upstream of the target inside the solenoid. Simulations, shown in Fig. 1, suggest that an optimal set up will use a field of 1.6 T, with the Si array covering a distance of approximately $-600 < \Delta z < -100$ mm from the target. The characteristic kinematic lines are shown in Fig. 1 in terms of proton energy versus Δz, the distance between the target and the point at which the emitted proton intercepts the array. These simulations assume a FWHM Q-value resolution of 150 keV for the ground state and $\sim$500 keV for the $L = 1$ excitation. Recoil detection will be achieved by means of annular silicon detectors in a telescope arrangement to determine energy loss and residual energy. These detectors impose an cut of $\theta_{\mathrm{c.m.}} > 10^\circ$, due to the inner diameter of the annular detectors. We note that the reactions to unbound states will be clearly separated in the recoil detector, appearing as ^{9}Li as opposed to ^{11}Li. At these energies the (t,d) reaction is not clearly observed, with deuterons from just a small portion of the forward center-of-mass angles likely to hit the Si array. With recoil detection, the outgoing spectrum will be essentially background free and unambiguous.

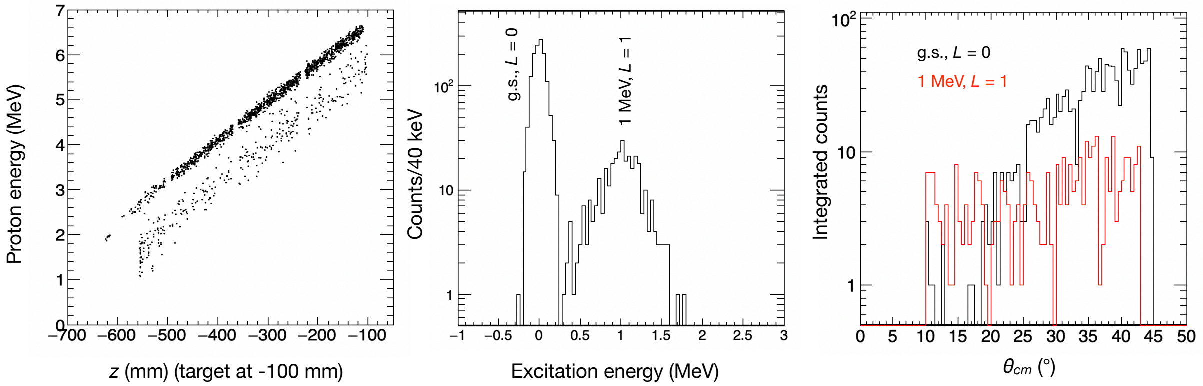

Figure 1: Simulations of the outgoing proton energy as a function of position along the beam axis (left) and the resulting excitation energy spectrum (middle). The integrated counts across the Si array for each state are shown in right-hand panel. All spectra are constrained by the condition of $\theta_{\mathrm{c.m.}} > 10^\circ$, imposed by the inner diameter of the recoil detector. The $L = 1$ excitation is simulated to have a FWHM of $\sim$500 keV. A solenoidal field of 1.6 T was assumed, and a beam energy of 10 MeV/u.

The tritium target—We will use a tritium tritide target with an effective thickness of $\sim$45 μg/cm^2 in $\sim$450 μg/cm^2 of titanium. This amounts to about 1 Ci of tritium. This will have similar properties to the target used in the T-REX and Miniball study of ^{30}Mg$(t,p)^{32}$Mg [15] and the previous study of the ^{9}Li$(t,p)^{11}$Li reaction at ISOLDE (IS561) [16]. The same type of target is used routinely in the HELIOS spectrometer, with similar beams (see Fig. 2). The tritium content of the target is monitored throughout the experiment using an annular monitor detector downstream of the target, and upstream of the recoil detector. The elastically scattered tritons are thus monitored continuously. The

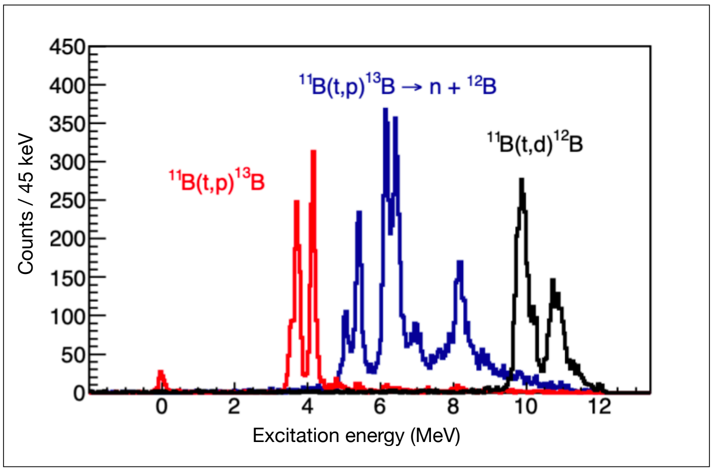

Figure 2: The outgoing proton spectrum following the ^{11}B(t,p)^{13}B and ^{11}B(t,d)^{12}B reactions recorded simultaneously in inverse kinematics at 8.6 MeV/u [14] using the HELIOS solenoidal spectrometer at Argonne National Laboratory. For this experiment, a tritium-implanted titanium target of thickness ~450 μg/cm^2 (~45 μg/cm^2 of tritium) was used —the same thickness as proposed here for the measurement of the (t,p) reaction on the isotone of ^{11}B, ^{9}Li. A Q-value resolution of 150 keV FWHM was achieved.

activity of the target complies with CERN Specification N^0 4229RP20070405-GD-00 [17].

Rate estimates and shifts required—Rate estimates are based on the assumption of an angular coverage of $10^\circ \lesssim \theta_{\text{c.m.}} \lesssim 30^\circ$, with a 70% efficiency in the azimuthal angle and 94% efficiency in the theta angle. The evaluation of the absolute value of the 2n transfer reaction implies the consideration of simultaneous and successive transfer contributions, along with non-orthogonality corrections. The cross section, calculated following Ref. [9], is about 0.1 mb at 10 MeV/u, around a factor of 4 lower than to the ground state. Assuming a beam intensity of ~1 MHz from the ISOLDE yield data base, and 45 μg/cm^2 of ^{3}H, then approximately 300 counts can be accumulated in the $L = 1$ excitation in a 5-day (15-shifts) run. The spectra in Fig. 1, which are normalized to this value, demonstrate that this is sufficient to observe and determine the L value of this excitation.

3 Summary

We request 15 shifts of beam time to study the (t,p) reaction on ^{9}Li at 10 MeV/u in inverse kinematics, with the main goal of populating the low-lying E1-resonance of ^{11}Li. We will use the ISOLDE solenoidal spectrometer to analyze the outgoing protons. In addition, recoil detection will be required to reject protons from reactions on titanium and other reaction channels. The number of shifts requested is based on a beam of 1 MHz of ^{9}Li on target. We will use a titanium tritide target with an effective tritium thickness of ~45 μg/cm^2. It is expected that a Q-value resolution of 150 keV will be achieved, though the states are expected to be broader than this.

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	1.75 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		
Beam intensity	1×10^6		
Beam energy	10 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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