EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Reaction studies with neutron-rich light nuclei at the upgraded SEC Device

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Abstract: Transfer experiments with radioactive beams in inverse kinematics provide powerful probes of nuclear structure. We propose to continue transfer reaction studies of light nuclei close to the dripline. In particular, we propose to explore the rather poorly known excited structure of the halo nucleus ^{11}Li and the resonant states of ^{13}Be to better understand the ^{14}Be halo formation from the ^{12}Be deformed core. In both cases, we plan to populate their excited states via (t,p) reactions from the relatively intense ^{9}Li and ^{11}Be beams produced at ISOLDE and accelerated at HIE-ISOLDE at energies of 7 MeV/u and using the upgraded setup at SEC. The proposed energy is optimal to ^{11}Be(t,p) and avoid the opening of extra background channels in the ^{9}Li(t,p) case. The detection of protons at backward angles will provide information of the low energy resonances while the forward angles will give information of the higher excited states. Proton-gamma coincidences are compulsory for the ^{11}Be(t,p)^{13}Be case.

Requested shifts: [47] shifts, (split into [2] runs over [2] years)

1 Introduction

This proposal is based on our two previous ones (IS561 and IS606) concerning the use of beams of ^{9}Li and ^{11}Be impinging on a tritium target. The main aim is to investigate excited resonance states in the Borromean two-neutron halo nucleus ^{11}Li and in the unbound nucleus ^{13}Be using two-neutron transfer reactions in a tritium target. We propose an upgraded experimental setup, which together with the higher energy range of the accelerated beams from HIE-ISOLDE will allow to take major steps towards a more detailed understanding of the resonance structures of these two cases.

The Scattering Experiment Chamber (SEC) at HIE-ISOLDE beamline XT03 was designed for general reaction studies with radioactive beams. We have exploited it in several experiments with beams of ^{7}Be, ^{8}B, ^{9}Li and ^{15}C, and intend to pursue this line of research further. Of the two previously mentioned proposals, only IS561 was allocated beamtime before LS2 and valuable experience was gained on running at HIE-ISOLDE. However, due to the low intensity of the ^{9}Li beam (4-40$\times 10^{3}$)/s) and the ageing and glue on the tritium target the main physics outcome [1] was obtained from deuteron targets and is currently being written up for publication.

2 The Physics Cases

Light nuclei at the neutron dripline show exotic properties such as halo and clustering. The archetype of Borromean nuclei ^{11}Li and ^{14}Be provide a good ground to study di-neutron correlations key for their stabilization. The structure of these light neutron-rich nuclei has presented many challenges during the last decades and different methods have been used to study their structure, such as Coulomb dissociation, di-neutron decay or quasifree scattering reactions. The physics interest has expanded to their subsystems, constituted of one neutron and the remaining fragment. The latter (^{10}Li and ^{13}Be) are unbound and their continuum exhibits a resonant structure. Being the level structure of ^{10}Li reasonably well understood [2], we believe the study of (t,p) reactions populating ^{11}Li and ^{13}Be resonances will provide very relevant experimental information.

Study of the ^{11}Li resonant states

The low-lying continuum spectrum of ^{11}Li is dominated by broad structures of dipole type observed in several experiments whereas narrower peaks have been proposed up to 6.2 MeV excitation energy, see Fig. 1 for the position and width of excited resonances in ^{11}Li. Essentially, the knowledge is limited to the existence of states at 1.2 MeV and 2.4 MeV confirmed by several experiments [3]. However, the identification of the 1.2 MeV resonance as a state has been questioned, a three-body model seems to explain this structure as a dipole excitation into the continuum [4].

Recent results on the low-lying continuum structure in ^{11}Li has appeared from inelastic p and d scattering at TRIUMF [5, 6]. Both measurements gave consistent elastic cross sections. However, the inelastic scattering results indicated a resonant state at 0.80(4) MeV, $\Gamma = 1.15(6)$ MeV for the proton inelastic scattering [5], and at 1.03(4) MeV, $\Gamma = 0.51(11)$ MeV for the deuteron case [6]. Although the values are not far apart neither the energy nor the width coincide. It has been argued [8] that the difference could be due to low statistic in the (d,d') case, or problems with the angular determination that is particularly difficult in a cryogenic target. However, there is a more relevant question concerning the physics process involved: excitation to a resonance or excitation directly to the continuum.

E^* (MeV)	I^π	$T_{1/2}$ or Γ	Decay
g.s.	$3/2^-$	$T_{1/2}$=8.75(14) ms	β^-
1.22(4)	?	Γ =0.53(15) MeV	n
2.42(5)	?	Γ =1.26(30) MeV	n
3.70(13)	?	Γ <200 keV	n
4.86(6)	?	Γ <100 keV	n
6.23(6)	?	Γ <100 keV	n

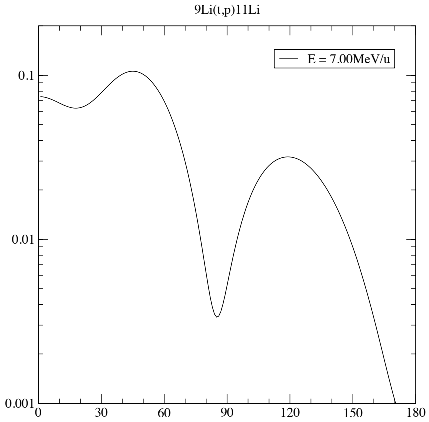


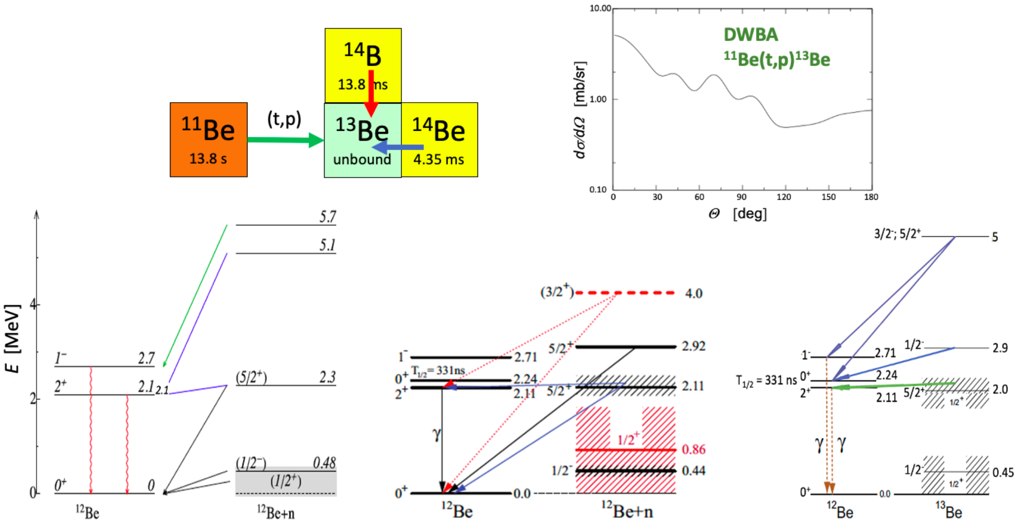
Figure 1: The table shows the energy levels of ^{11}Li as compiled in Ref. [3] up to year 2012. On the right the angular distribution (X-axis) of the differential cross section in mb/sr (Y-axis) for the ^{9}Li(t,p) reaction to the ^{11}Li ground state(gs) is calculated using DWBA with potential based in [7].

The influence of the reaction mechanism is not resolved, so an independent population of the resonances from a different starting point is essential. The only experiment so far that may have observed the 1.2 MeV structure without starting from ^{11}Li gs is the ^{14}C(π^-,p+d) reaction [9], however the resolution did not allow for a detailed characterization. The two-neutron transfer to ^{9}Li is therefore a logical way of probing the continuum structure of ^{11}Li. We note that a recent calculation in a three-body model that reproduces most ^{11}Li properties predict [11] three close-lying resonance states around 800 keV excitation energy, all with L=1.

We propose here to populate the excited structure of ^{11}Li by (t,p) reactions. The 2n-transfer reaction is expected to proceed via a one- or a two-step process. In the dominant one step process the two neutrons will be transferred together, in L=0 to the surface of ^{11}Li gs [10], which cross section is displayed in Fig. 1. The DWBA calculations for L=1 gives three nearby excitations with differential cross section peaking for inverse kinematics at backward angles and with a cross section that is similar to one to the ^{11}Li gs. For higher excited states the information will come from the telescopes at former angles. We note further that the (t,p) reaction to the ^{11}Li, would complement the ^{11}Li(p,t)^{9}Li experiment carried out at TRIUMF [12], both reactions being sensitive to the halo composition in ^{11}Li. The sequential two neutron process with lower cross section benefits from the knowledge of the intermediate ^{10}Li resonances [2]. The Q-value of the reaction is Q = -8112.5 (6) keV, with threshold at 32.4 MeV. We propose to run at 7 MeV/u as we noticed in our previous experiment done with ^{9}Li(d,p) at 8 MeV/u [1] that the background channel increased largely, anyhow the identification of proton versus α particles is essential. The energy of the ^{11}Li resonances will be determined from the energy and momentum distribution of the protons, using the information of forward and backward angles and coincidences with γ-rays if the count rate permits. Finally, we would like to stress that our set-up allows for the study of other interesting reaction channels. This includes the elastic scattering channel that will be essential to fix the optical potentials in the theoretical models.

Study of the ^{13}Be resonances

The unbound nucleus ^{13}Be has an important role in the understanding of the structure of the



A. Corsi *et al.*, 2019 G. Ribeiro *et al.*, 2018 Yu. Aksyutina *et al.*, 2013

Figure 2: The different resonances of ^{13}Be deduced by neutron removal from ^{14}Be at RIKEN [15] and GSI [13] or proton removal from ^{14}B at GSI [14] experiments are shown. The expected differential cross section for ^{11}Be(t,p) reaction to the resonant state $1/2^{+}$ in ^{13}Be calculated is shown using DWBA using potentials taken from [7].

two-neutron halo nucleus ^{14}Be, which has a deformed core. The ^{13}Be resonances has been studied by missing mass and invariant mass techniques using charge exchange, fragmentation, proton removal from ^{14}B ($I=2^{-}$) and neutron removal from ^{14}Be ($I=0^{+}$), see the latest works at GSI [13, 14] and RIKEN [15] and references therein. The missing mass experiments, that yields the absolute energy above the neutron threshold, found resonances between 1.2 and 10 MeV depending on the experiment while the invariant mass analysis, that requires knowledge of the excitation energy of the daughter nucleus, indicated a broad resonance at 0.5 MeV above the neutron threshold and another broad resonance at 2 MeV. Fig. 2 shows the proposed excited resonances in ^{13}Be obtained from recent proton removal [14] and neutron removal [13, 15] reaction studies. All agree in the position of the $1/2-$ resonance while the position and width of the $1/2+$ and $5/2+$ resonances differ greatly. Part of the diversity in the position and spin assignment of the proposed resonances can be due to the fitting procedure used in the analysis. However, the main reason is the complexity of the ^{13}Be spectrum due to the admixtures of single-particle structures with core-excited components. In the latest work [15] from RIKEN data, the spectroscopy of ^{13}Be via invariant mass was determined using a realistic 3-body model of ^{14}Be that incorporate ^{12}Be (2^{+}) excitations and a sound reaction framework. By comparison between the model and the ^{13}Be relative energy spectrum they [15] pinned down the dominant $l = 1$ contribution to the low resonant peak in agreement with [14] and opposite to [13].

Our proposed experiment will provide a complementary way to study these low-energy levels in ^{13}Be, including their decay to ^{12}Be, and explore the higher energy resonances. In particular, we would like to characterize the broad $1/2^{+}$ resonance in ^{13}Be highly favoured in the (t,p) process. This experiment will probe ^{13}Be from the low-mass side rather than the high mass, which will enable us to probe other single-particle structures in ^{13}Be. The suggestion of a $1/2^{+}$ ground state and a $1/2^{-}$ slightly above, see Fig. 2, is strikingly similar to the situation in ^{11}Be.

In the dominant (t,p) process the two neutrons will be transferred together, from the $1/2^{+}$ of ^{11}Be leading to the population of $I^{\pi} = 1/2^{+}$ (L=0), $I^{\pi} = 1/2^{-}$ (L=1), and $I^{\pi} = 5/2^{+}$ (L=2),

resonances in ^{13}Be. The two-step processes can occur either by a sequential transfer of the two neutrons, or by the excitation to the $1/2^-$ state in ^{11}Be nucleus and then the 2n-transfer. To distinguish all possible processes it is essential that the setup includes detection of γ-rays, as seen from our ^{11}Be(d,p) experiment [16].
Similarly to the previous case, we will be able at the same time to study other reaction channels, such as the elastic scattering, the ^{11}Be(t,α)^{10}Li (Q = -350.6 keV) channel or ^{11}Be(t,d)^{12}Be (Q = -3088 keV). The bound states in ^{12}Be are well understood, however, the lowest-lying resonance known in ^{12}Be assigned an excitation energy of $\approx$4.4 MeV, has observed in proton removal from ^{13}B without γ-rays information, so the assigned energy, spin and parity are uncertain [17]. Our aim is to provide additional experimental information to this discussion by measuring this state and by determining the branching ratio of the decay.
We plan to determine the resonance energies using the energy and momentum of the proton in coincidences with γ-rays, a method independent on the decay of ^{13}Be. The Q-value of the reaction is Q = -5821.1 keV with threshold at 27 MeV, hence we will be able to populate all the known states with a beam energy of 7 MeV/u.

3 Experimental set-up

Our upgraded detection set-up at SEC (Scattering Experimental Chamber) will consist of three detector structures, the particle detector, the SAND detector for neutron detection and eight GAGG scintillators for gamma detection. The particle detection will provide information on the excitation energy with an estimated resolution of 200 keV due to the thickness of the target used. This estimation is based on previous experiments at REX-ISOLDE. The SAND and gamma detectors are used to measure the decay products of the resonance decays, e.g. emitted neutrons and sub-sequent gamma decays from the daughter nuclei or the state in which the (t,p) reaction takes place.
The setup is currently undergoing a significant upgrade, see Fig. 3. It will incorporate new detectors and electronics in order to improve the detection efficiency and data rate capacity.
The charged particle setup is consisting of 5 DSSD+PAD telescopes in a pentagon configuration just downstream the reaction target covering from 35° to 80° degrees with high pixelation and an angular resolution of 3 degrees both in θ and ϕ. Downstream and upstream the pentagon is closed by CD type S3 DSSD detectors having segmentation of 2 x 768 pixels, with angular coverage of 8° to 27° and 122° to 157° degrees, respectively and an angular resolution from 1°-3° degrees. The charged particle set-up gives a total angular coverage from 8° to 157° degrees, with total solid angle coverage of 50% of 4π. The forward CD is crucial to detect particles from the highest-lying resonances as well as for detecting fragments in coincidence with light particles. The CD at backward angle is very important for the study of the low energy resonances.
Scintillators are being installed inside the chamber to add gamma-detection capability. Eight GAGG scintillators of 15x15x30 mm^3 will be placed facing the target with a solid angle coverage of 16%, and having a 50% internal efficiency for 2 MeV γ-rays. The scintillator light will be detected by SiPM readout directly to MDPP16 digitizer.
To avoid noise from ground loops we change to more compact electronics where time multiplexing, analogue to digital conversion, is performed locally on SEC, and the triggered data transmission is done via optical link (10m) to the central data collector module. The new DAQ system is also fully adapted to the read out electronics of the SAND neutron-detector that can be incorporated in the future as already available at ISOLDE. We determine the resonance energies in ^{11}Li and ^{13}Be using the energy and momentum of the proton, with the possibility of the γ-ray coincidence study.

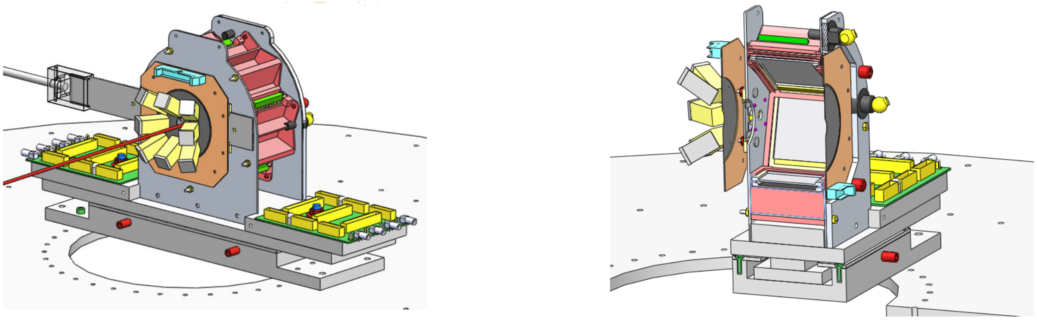


Figure 3: The detection setup inside the SEC chamber with the actuator for the target holder on the left hand side. The charged particle detection and identification covered total solid angle coverage of 50% of 4π. Gamma detection is done by an array of 8 GAGG scintillators. On the right hand side, a vertical cut of the setup is shown.

4 Beamtime request

Both ^{9}Li and ^{11}Be ions can be produced from Ta or a UC$_x$ targets. the Be-beam requires laser ionization. The low-energy beams are of high purity.

With a beam energy of 7 MeV/u of ^{9}Li we can populate by (t,p) states in ^{11}Li up to 9 MeV covering all known resonances. We request to run fully ionized ^{9}Li, i.e. A/q = 3, although ^{12}C^{4+} and ^{18}O^{6+} may appear as contaminants we did not see any significant contribution of these contaminants previously [1]. The energy chosen for the experiment is high enough to populate the states of interest and sufficiently clean to disentangle the different channels. To reduce losses we request a synchronization of the PSBooster and the REX-TRAP that is currently available with the new control system.

Considering the current ^{9}Li yield for a Ta-target and an efficiency[1] close to 10 % for the breeding process, we expect about 10^{6} ^{9}Li/s on our chamber, assuming a $8{\times}10^{18}$tritium/cm^{2} loaded titanium foil and a cross section of 0.1 mb/sr we expect to get about 55 protons feeding the ^{11}Li ground state and detected at backward angles. A similar number for the feeding to the 1^{-} state. In this way we will determine the differential cross section at backward angles We request **18 shifts** for the main ^{9}Li run and **9 shifts** for the background run with the pure titanium foil.

We assume a production of ^{11}Be on a Ta-target, as quoted in [18], of $8{\times}10^{6}$ ions/μC. We request to use fully ionized ^{11}Be beam with A/q = 11/4 and a beam energy of 7 MeV/u. In this way we will populate by ^{11}Be(t,p) reaction most of the resonances in ^{13}Be. The main contaminant is ^{22}Ne. We required therefore purified ^{20}Ne as buffer gas in the EBIS. The DWBA gives an estimate of cross section of 1 mb/sr corresponding to around 550 protons per shift detected at backward angles from the reaction to the $1/2^{+}$ resonance, see Fig. 2.

We estimate **12 shifts** with tritium-Ti foil, **6 shifts** with Ti-target and **2 shifts** with Neon buffer gas. In total 20 shifts.

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[1] We have been informed that during the commissioning of the new non-adiabatic gun, last autumn, an efficiency for ^{7}Li^{3+} ions for the TRAP+EBIS system of 12 % was achieved with a breeding time to reach ^{7}Li^{3+} of 20ms. Therefore, no major losses in the charge breeding process of the ^{9}Li beam are expected.

References

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: (*name the fixed-ISOLDE installations, as well as flexible elements of the experiment*)

Part of the	Availability	Design and manufacturing
SEC installation at XT03	☒ Existing	☒ To be used without any modification
MAGISOL DSSD setup	☒ 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
GAGG scintillators	☐ Existing	☐ To be used without any modification ☐ To be modified
	☒ New	☐ Standard equipment supplied by a manufacturer ☒ MAGISOL collaboration design and manufacturing

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

Additional hazards:

Hazards	[Part 1 of experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum	10 E-6		
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			

Target material	Ta-Target	Ta-target + Laser	
Beam particle type (e, p, ions, etc)	^{9}Li	^{11}Be	
Beam intensity	2×10^{7} ions/μC	8×10^{6} ions/μC	
Beam energy	7 MeV/u	7 MeV/u	
Secondary Target material	3H	less than 10 GBq	
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☒	ISOLDE 4x alpha source	
• Sealed source	☒ standard gamma sources		
• Isotope	152Eu	60Co	
• Activity	3H	less than 10 GBq	
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chem. agent], [quant.]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chem. agent], [quant.]		
Corrosive	[chem. agent], [quant.]		
Irritant	[chem. agent], [quant.]		
Flammable	[chem. agent], [quant.]		
Oxidizing	[chem. agent], [quant.]		
Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		
Dangerous for the environment	[chem. agent], [quant.]		

Mechanical			
Physical impact or mechanical energy (moving parts)	XT03 fixed wall crane		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): [make a rough estimate of the total power consumption of the additional equipment used in the experiment]: less than 2 kW