EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

A new approach to beta-delayed multi-neutron emission

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Abstract: The beta-delayed 2n and 3n decays of ^{11}Li will be measured at IDS via coincidences between neutrons and heavy charged particles. This will allow neutron energy spectra for the two branches to be extracted separately for the first time. Most of the decay scheme, in particular the multi-particle break-up channels, will be reconstructed up to 18 MeV excitation energy in ^{11}Be and the deduced beta strength compared to theory.

Requested shifts: 17 shifts, (split into 1 run over 1 year)

1 Motivation

We have today, 40 years after the discovery of β2n and β3n decays [1, 2] in ^{11}Li, very little information on these decay modes except for their observation in several (light) near-dripline nuclei. Branching ratios are known, but energy distributions and decay mechanisms are experimentally poorly constrained mainly due to neutron detection difficulties. The lightest and best studied delayed multi-neutron emitter is ^{11}Li with [3] $P_{1n} = 86.3(9)\%$, $P_{2n} = 4.1(4)\%$, $P_{3n} = 1.9(2)\%$ and $P_n = \sum_i iP_i = 100.3(1.4)\%$. This implies that 14% of all neutrons are from multi-n decays, but none of the current suggested decay schemes have this under control (see [4, 5] and references therein). Furthermore, more than half of n-n coincidences will be from β3n processes, a fact that contributes to the difficulties of interpreting the recently published spectrum [6] from IS525. This spectrum gives the first indication on the energy distributions of multi-neutron decays, but is not sufficient to settle the decay mechanism nor the decay scheme. The experimental difficulties in getting so far attest to the need to find alternative ways to proceed.

We propose to obtain detailed information on the β2n and β3n decays of ^{11}Li from coincidence measurements between neutrons and the recoiling heavy charged particles. A first attempt was made in our earlier experiment IS417 employing the TONNERRE array, but technical difficulties during the run meant that all results obtained came from charged particle detectors [7]. The experience gained over the last years with VANDLE and INDIe will allow to do this challenging measurement now at IDS. We note that the neutron background in the ISOLDE hall is considerably lower at the IDS position than at LA1, where the IS417 set-up was placed.

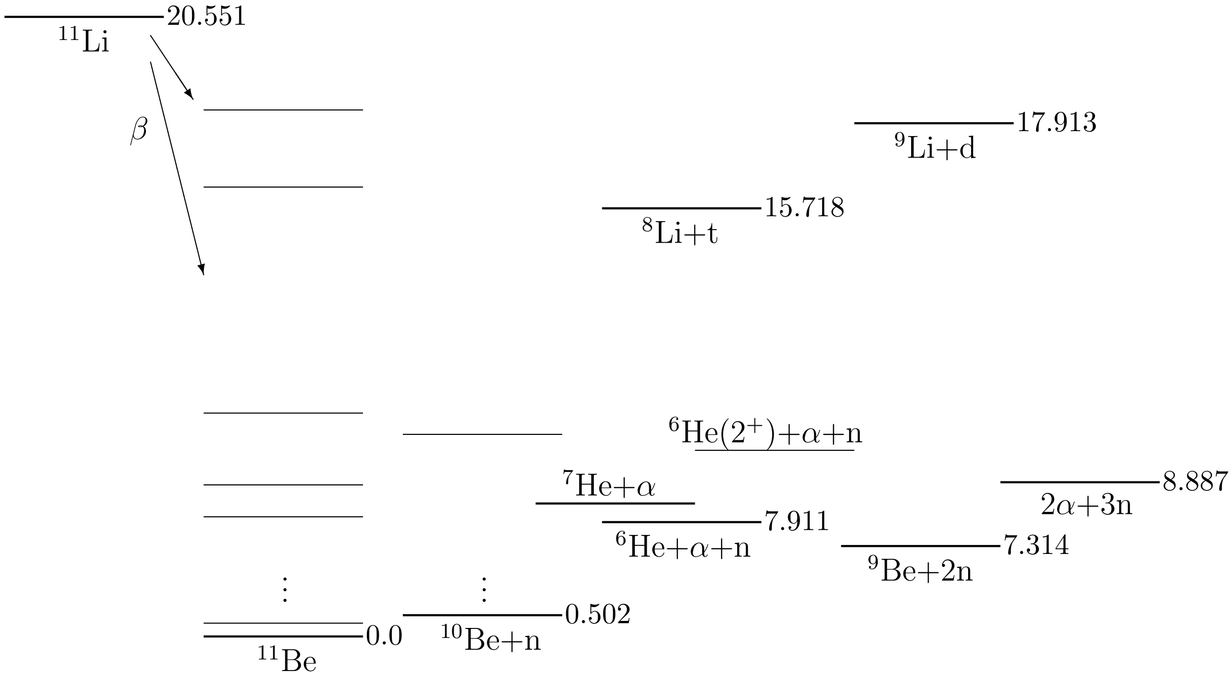

Figure 1: The ^{11}Li decay scheme above the two-neutron threshold. All energies in MeV.

Several shell-model calculations of the beta strength distribution have been carried out, but none that at the same time predict the break-up patterns of the populated unbound

^{11}Be states. We therefore turn to the simple model from Ref. [8] that may explain several features of the break-up. The decay of the halo nucleus ^{11}Li is here described as the decay of the core, ^{9}Li, with the halo neutrons as spectators or as decay of the halo with ^{9}Li as a spectator. The latter component would mainly appear at the highest excitation energies and the model obviously fails below the ^{9}Be+2n threshold at 7.3 MeV, so the interesting excitation energy region is the one between about 7 and 18 MeV, see figure 1. The ^{9}Li beta decay proceeds half of the time to unbound levels in ^{9}Be that break up either via ^{4}He+^{5}He or n+^{8}Be to a final $\alpha\alpha$n configuration. The IS417 finding [7] — that much of the ^{11}Li decays to the 10–18 MeV region can be described via ^{4}He+^{7}He or ^{6}He(2^+)+^{5}He intermediate states — could be a reflection of the ^{4}He+^{5}He branch from ^{9}Li with the two spectator neutrons added to one or the other partner. Coincidences between neutrons and charged particles are needed to confirm this, as well as to search for parallels to the n+^{8}Be branches.

We note that the IS417 results account for much of the β3n decays, whereas there is no solid data (only suggestions) on where the β2n branch fits into the decay scheme. New coincidence data will help in settling this point.

The key objective of this proposal is to measure coincidences between neutrons and heavy charged particles in order to find the 2n and 3n emission paths, thereby probing the beta strength above the two-neutron threshold. (We showed for ^{31}Ar [9] that the β2p and β3p branches carried a sizable strength and expect this to be even more pronounced for a neutron rich nucleus.) Gamma rays will also be recorded, partly for normalisation purposes, partly to cross-check the lower part of the decay scheme where the two most recent experiments [4, 5] differ in quite a few places.

2 The proposed experiment

As shown convincingly in Ref. [6] cross-talk will be a major issue in extracting true two-neutron coincidences out of double hits in a neutron array. We therefore focus on identifying the decay channel through the information obtained from the Si-detectors. A challenge is that He, Li and Be nuclei at low energy are difficult to separate in detector telescopes, see e.g. the inset in figure 4 in [10]. We shall proceed as follows.

The β1n branch has mainly a two-body final state with the neutron and ^{10}Be going in opposite directions with energies inversely proportional to the mass. This gives a clean signal, as demonstrated with the weak t-^{8}Li branch [11]. The strong neutron lines may be used to check for effects from neutron scattering etc; if resolution is a problem gamma coincidences [4] may be useful. The efficiency for detecting the two charged particles in the n-α-^{6}He branch will be high and if one neutron is detected in coincidence, momentum conservation will allow to separate this from 3n$\alpha\alpha$ events.

Non-collinear neutron-recoil events could be due to nα^{6}He, 2n^{9}Be or 3n$\alpha\alpha$ processes. The high efficiency for detecting two charged-particle coincidences should allow to separate also the β2n branch.

The most difficult events to place in a decay scheme will be neutrons where the recoil nucleus energy is below the detection threshold. The lowest ^{11}Be level to emit neutrons to the ^{10}Be ground state is at 2.654 MeV so all neutrons to the ^{10}Be ground state can be identified. Neutron emission to excited levels in ^{10}Be (below the ^{9}Be+n threshold) can also be identified via gamma coincidences [4]. The challenging events therefore have three-body or five-body final states, here excited ^{11}Be levels above 11 MeV are likely to give detectable recoils (the energy limit may be slightly higher for decays through the ^{8}Be ground state). The ability to distinguish the 2n and 3n branches, in contrast to what is possible with multiplicity-two neutron detection [6], allow for the determination of the break-up mechanism for excitation energies beyond 11 MeV, in particular for the region above 15 MeV where shell-model calculations place the majority of the beta strength [12, 13, 14].

Having determined, for the first time, the neutron energy spectra separately for the β2n and β3n branches makes it possible to subtract them from the single-neutron spectrum and thereby extract a reliable β1n spectrum. This removes a systematic uncertainty from the currently suggested decay schemes at excitation energies up to 10 MeV.

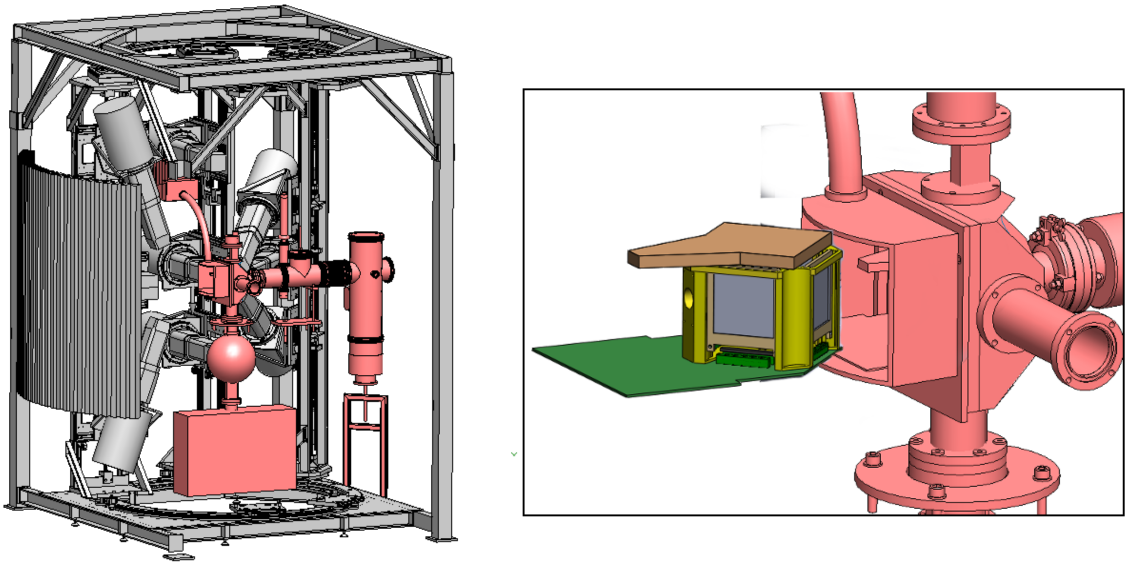

Figure 2: The experimental set-up. A cube of Si-telescopes surround the collection foil, with the beta detector in one side, neutrons are detected in the INDIe array positioned downstream and high-efficiency Ge detectors surround the Si-detectors.

The proposed set-up is shown in figure 2. It includes detection of beta particles, neutrons, heavier charged particles and gamma rays.

We expect the neutron detection efficiency (intrinsic efficiency times total solid angle) to be around 6% for neutrons in the 0.5–2 MeV range with a gradual fall-off to higher energies and extending down to at least 200 keV neutrons. The Si strip detectors have close to 100% intrinsic efficiency and will cover a total solid angle of at least 60% of 4π, the lower threshold for detection of the heavy charged particles is at most 250 keV. The beta particles that start the time-of-flight measurement for the neutrons are measured with a plastic scintillator placed in one of the sides of the Si detector cube (in order to not shadow the heavy particles), it will have a solid angle close to 15% of 4π.

3 Beam time request

The yield of a short-lived isotope as ^{11}Li will naturally fluctuate from target to target, but recent experiments at ISOLDE [6, 14, 15] quote yields of order 1000 ion/s in the experimental set-ups, so we shall use that number for our estimates. This gives 10 beta-neutron events per second, most of these will have a recoil nucleus hitting the Si-detectors opposing the INDIe array. The count rate of coicidences between neutrons and two charged particles will depend on angular correlations and the energy distributions of the particles, but is expected to be in the range of one per 10 seconds to one per minute. We base this estimate on the total branching ratio to final states with ^{4,6}He of 1.7% from [7], where the identified individual branches range from 1.1% to 0.035% in intensity. With 15 shifts of beamtime the weakest branch should give around 500 counts; this gives sufficient intensity to check also for feeding to the 11–15 MeV excitation energy range in ^{11}Be that is predicted theoretically [14] but not observed so far.

We request a Ta foil target similar to the one used in the last ^{11}Li runs.

For calibration and on-line tests of the set-up, 2 shifts with ^{9}Li will be needed. We note that our set-up is sufficiently similar to the one of P549 (aiming to measure the decays of ^{9}Li and ^{8}He) that the calibration run will not be needed if the two experiments are scheduled close together.

Summary of requested shifts: 15 shifts of ^{11}Li and 2 shifts of ^{9}Li from a Ta target.

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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
IDS	☒ Existing	☒ To be used with INDIe for neutron detection and a Si strip detector array

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed IDS 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			
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 [material]			
Beam particle type (e, p, ions, etc)			
Beam intensity			
Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☒	Triple α source	

• Open source	☐		
• Sealed source	☒ [ISO standard]		
• Isotope			
• Activity	^{148}Gd, ^{239}Pu, ^{244}Cm		
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)	[location]		
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): negligible