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Proposal to the ISOLDE and neutron Time-of-Flight Experiment Committee

# Delayed particle study of neutron rich lithium isotopes

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## Abstract

We propose to make a systematic complete coincidence study of beta-delayed particles from the decay of neutron rich lithium isotopes. The lithium isotopes with A=9,10,11 have proven to contain a vast information on nuclear structure and especially on the formation of halo nuclei.
A mapping of the beta-strength at high energies in the daughter nucleus will make possible a detailed test of our understanding of their structure. An essential step is the comparison of beta-strength patterns in $^{11}$Li and the core nucleus $^{9}$Li, another is the full characterization of the break-up processes following the beta decay. To enable such a measurement of the full decay process we will use a highly segmented detection system where energy and emission angles of both charged and neutral particles are detected in coincidence and with high efficiency and accuracy.
We ask for a total of 30 shifts (21 shifts for $^{11}$Li, 9 shifts $^{9}$Li adding 5 shifts for setting up with stable beam) using a Ta-foil target with surface ioniser. We will make use of the ISOLDE DAQ system.

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## 1 Motivation

Halos have caught the interest of nuclear physicists during the last decade. States with a seemingly simple few-body structure situated close to a threshold can develop an unusually large spatial extension. The detailed study of this phenomenon has already given many results as reflected in the recent review papers [1, 2, 3, 4], but questions remain, in particular concerning two-neutron halo systems like $^{11}$Li.

A halo-structure in a state could affect the beta-decay in the following different ways [5] [6]. Firstly, the spatial extension of the halo state might reduce the spatial overlap with daughter states. This might be seen either in specific well-understood transitions or as a general reduction of beta-strength. Secondly, the halo particle(s) might beta-decay more or less independently from the core. This might give rise to specific patterns in the decay, or, if the halo is quite extended, could lead to decays going directly to continuum states. Beta-decay can furthermore be helpful in establishing details of the structure of the halo state via the patterns observed in the decay. For this, one of course must understand the structure of the daughter states. In short this could be summarised by the following formula. Denoting the beta-decay operator $\mathcal{O}_\beta$ and assuming that the halo state can be factorized into a core and a halo part one then formally gets:

$$\mathcal{O}_\beta|\text{halo state}\rangle = \mathcal{O}_\beta\left(|\text{core}\rangle|\text{halo}\rangle\right) = \left(\mathcal{O}_\beta|\text{core}\rangle\right)|\text{halo}\rangle + |\text{core}\rangle\left(\mathcal{O}_\beta|\text{halo}\rangle\right) \qquad (1)$$

Both terms on the right hand side are needed in order to have the correct isospin in the final state.

### 1.1 $^{11}$Li

The study of the very complex $\beta$-decays of $^{9,11}$Li presents an experimental challenge that has not yet been fully met. Early experiments showed that many $\beta$-delayed particle emission branches are present and that the decay pattern is rather complex; furthermore most decays involve emission of neutrons and even a significant part of the particle emission probability (6%) leads to the emission of two or three neutrons that are hard to detect. The fact that $^{11}$Li is the most prominent two-neutron halo nucleus prompted for several $\beta$-decay experiments a decade ago. These experiments have enlarged our knowledge in many aspects of the decay, including new information on $\beta$-delayed gammas [7, 8, 9], deuterons [10] and feeding to a high-lying state at about 18 MeV excitation energy in $^{11}$Be [11]. The complexity and present knowledge of the decay scheme of $^{11}$Li is shown in Fig. 1.

However, there is today still no full understanding of the feeding of states above 8–10 MeV excitation energy in $^{11}$Be where most of the $\beta$-strength resides. Further there is a very limited understanding of decay channels involving more than one emitted particle (there is essentially only one published coincidence measurement [12]) as well as of the highly interesting $\beta$-delayed deuteron branch. this branch might provide rather direct information on the halo composition in $^{11}$Li [13, 14], in particular when one includes information on the d+$^{9}$Li interaction at low energy that now is becoming available through experiments recently performed at REX-ISOLDE (IS367).

### 1.2 $^{9}$Li

The nucleus $^{9}$Li lies at the neutron dripline and is the core of the halo nucleus $^{11}$Li. Its decay has been studied carefully at ISOLDE and analysed within the R-matrix theory [15]. It includes a transition with a $B_{GT}$ of 5–6 at an excitation energy of 11.8

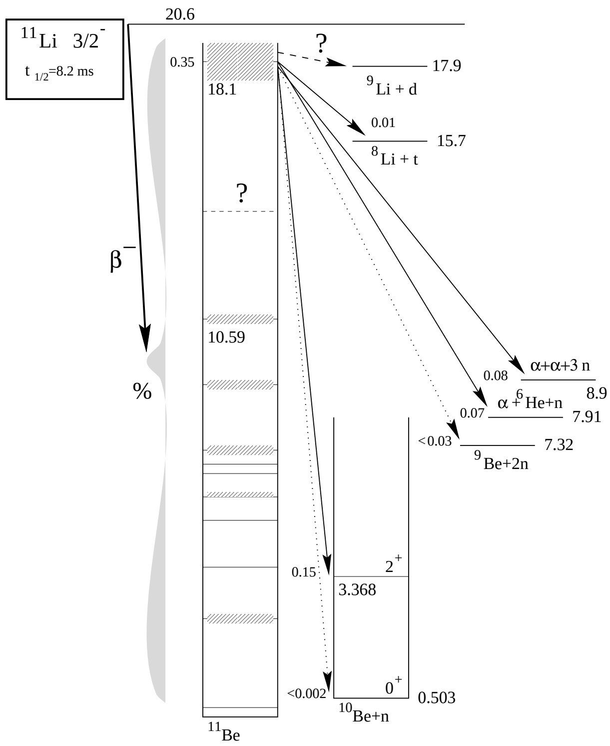


Figure 1: Schematic diagram of the $\beta$-delayed particle emission from $^{11}$Li. At the right threshold values in MeV relative to $^{11}$Be are shown. At the left, observed branching ratios given in %.

MeV. As for $^{8}$He, an alternative analysis involving three-body decays of the states fed in the beta-decay has been attempted. It is striking that the four well-studied nuclei at the neutron drip-line, $^{6,8}$He and $^{9,11}$Li, all have transitions, with rather large $B_{GT}$-value feeding to states a few MeV below the initial state [16]. Several explanations have been offered for this phenomenon. It might be related to the existence of halos in this region; more specifically the "2n $\rightarrow$ d" transition that occurs in the $^{6}$He decay could be involved also in the other cases. Support for this interpretation has been given in shell-model calculations [17] on the (probably unbound) doubly magic nucleus $^{28}$O where transitions showing this feature have been identified. Finally, it has been argued that the Gamow-Teller Giant Resonance (where most of the $B_{GT}$ strength is situated) comes down in energy for these light very neutron-rich nuclei [18]. The different explanations may not necessarily exclude each other.

### 1.3 Method

We propose to take advantage of the developments of detector technologies that have taken place during the last decade — in particular what concerns the multi-particle detection capabilities — and remeasure the $\beta$-decays of $^{9,11}$Li with particular attention to the decay branches going to the highest excitation energies.

Segmented, large solid-angle charged-particle and neutron detectors today allow for a much more complete characterization of the decay. We propose to increase the power of the set-up further by combining two such detector systems, namely the DSSSD detector array recently employed in several experiments at ISOLDE [19, 20] and the TONNERRE neutron detector array [21]. On top of this the target developments during the last decade have led to new target designs that enhance the yield of the short-lived $^{11}$Li [22].

The decay scheme of $^{11}$Li is the most challenging among the very neutron-rich nuclei known today, but we should point out that a similar complexity can be expected to be quite common wherever we reach close to the dripline in heavier isotopic chains, since a similarly large number of decay channels will be present there. The techniques we propose to develop here for $^{11}$Li should therefore find general use in the future when increased yields of the heavier dripline nuclei become available at ISOLDE and in a more distant future at EURISOL or RIA. (The detailed spectral properties of course differs somewhat since we expect the level densities in the involved nuclei to be higher for heavier systems, whereas the mean level width decreases. However, this does not affect the need for multi-particle detection capabilities in line with the ones we are to employ here.)

## 2 Physics questions

The $\beta$-transitions from $^{11}$Li that directly involve the halo neutrons are most likely to be concentrated at the highest excitation energies that can be reached experimentally [6]. However, it is not known whether these transitions will take place through excited states in $^{11}$Be, as would be the case for a normal $\beta$-decay, or occur directly to continuum states, as appears to be the case for the $\beta$-delayed deuteron branch. In the first case the resonances fed in $^{11}$Be would be able to decay by emission of several particles but the decay mechanism in this step is also unknown at present. Our experience from the studies of $^{9}$C, $^{12}$B and $^{12}$N [20, 23] is that coincident detection of all emitted particles makes it possible to answer such questions in an unambiguous way. It is hard to detect both energy and direction for a neutron with high efficiency, so we cannot aim for a complete kinematics set-up. Still, by employing momentum conservation one can in principle extract all needed information even when one particle is missing. This requires an experimentally well verified understanding of the detectors performance. The perfect test case is $^{9}$Li, where half of the decays give two $\alpha$-particles and a neutron. By comparing double (only $\alpha$'s) and triple (also neutrons) coincident events for $^{9}$Li we can test the set-up to the required accuracy. We refer to $^{9}$C [20] for a detailed example of how the decay mechanism will be settled experimentally.

As an example of the importance of the decay mechanism we can take the level at about 18 MeV excitation energy in $^{11}$Be. In the previous analysis [11] this level is clearly seen to be present in several singles spectra, but at that time one had to assume that the $\alpha$-spectrum from the level followed 3- and 5-body phase space (with some correction for Coulomb repulsion). Most known cases of such breakup proceed via resonances in subsystems, hence this assumption might not be correct in which case the conclusions drawn on the feeding to lower-lying states easily could change. A realistic treatment of the decay channels is needed in order to obtain the complete feeding pattern. Since several of the states involved are rather broad the way to enlarged the information is to do multi-particle coincidences rather than to increase the statistical accuracy of the singles spectra.

It is worth noting that we will obtain information on the spectroscopic properties of both bound and continuum states in this region, not only at mass 11 but also at lower masses (by looking at later stages in the sequential decay channels). This is a distinguishing feature for nuclei close to the driplines compared to $\beta$-decay studies closer to the line of $\beta$-stability and adds to the value of the experiment. As a concrete example we should mention the excited states just below the one-neutron threshold in $^{10}$Be. The $1^-$ and $2^-$ states seem to have a large component with an s-wave neutron around a $^{9}$Be core and could well be halo states. Their structure is therefore interesting in itself, but harder to access since they are excited states. One needs information from as many probes as possible and very valuable data already exists from a single neutron removal reaction on $^{11}$Be [24]). The $\beta$-decay is interesting since it populates these states from resonances in $^{11}$Be that have an appreciable overlap with the halo nucleus $^{11}$Li. With the decay scheme settled one will be able to extract more quantitative information that should strengthen our understanding of this interesting region.

The present knowledge of the $^{9}$Li decay [15] is based on a singles experiment with no possibility to resolve the transitions to the two states at 11.28 MeV and 11.8 MeV. We have made tests with a more complete setup and found that this is rather easy with a setup of the kind proposed here [25] and described in the following section. The relative feedings to these two states as well as the $B_{GT}$ value would be an important outcome of this part of our experiment. This would provide a precise value of the large asymmetry of $\frac{(ft)^+}{(ft)^-}$ -1 = 3.7(1.2) observed [20] for the mirror transitions in $^{9}$Li and $^{9}$C

We finally note that the improvements in detector technology now allow us to improve considerably on the first experiment where the $\beta$d branch was detected [10]. It was shown there that the $\beta$d and $\beta$t branches can be distinguished in a clean way by tagging deuteron and triton events recorded in a gas telescope (where d and t cannot be separated) with $\alpha$-particles recorded from the subsequent decay of $^{9,8}$Li. We propose to perform a detailed measurement of the deuteron spectrum making use of this decay tagging. As mentioned above the deuteron spectrum should provide the most direct information on the halo structure one can obtain from beta-decay.

## 3 The set-up

The known open channels in the $^{11}$Li decay are n-$^{10}$Be, 2n-$^{9}$Be, 3n-2$\alpha$, n-$^{6}$He-$\alpha$, t-$^{8}$Li and d-$^{9}$Li. Hence the ideal setup should be able to measure in $4\pi$, the charged particles with particle identification (PID) as well as the neutrons and all in coincidence. The setup envisaged for the present experiment is based on a compact cubic geometry for the particle detectors (shown in Figure 2) covering almost $4\pi$, together with a scintillator array for neutron Time of Flight detection (covering $\sim$ 25% of $4\pi$), see figure 3.

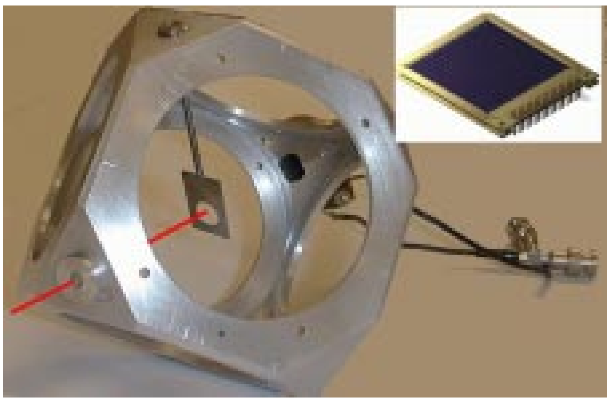

Figure 2: The collection spot is in the center of a cubic construction with 10cm sides where each face is covered by a DSSSD telescope (inset).

The extracted beam of $^{9,11}$Li ions from ISOLDE is implanted into a thin carbon foil at the centre of the cubic support structure (10x10x10 cm$^3$) containing charged particle detectors on each side. The cube is surrounded by $\beta$-detectors for the n-ToF signal. At

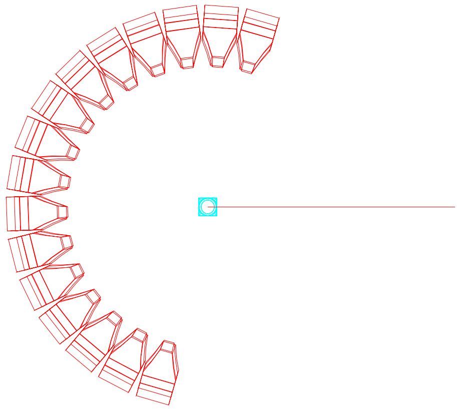

Figure 3: The figure show (to scale) the particle detector support with the TONNERRE neutron Time of Flight Array (1.2 m radius).

1.2m distance from the collection point outside the vacuum chamber a neutron detector array is placed.

The charged particle detectors to be used are of a new kind of double sided Si strip detectors (DSSSD) developed by us [26] in collaboration with MICRON Semiconductor Ltd [27]. The new design with a very thin deadlayer (100 nm) allows for charged particles to be detected down to ≃100 keV energy with high granularity. These detectors were recently commissioned and used with great success in the IS404 experiment at ISOLDE where $3\alpha$ final states from $^{12}$C were detected. With a Si thickness of only 60 $\mu$m the beta-response in these detectors is negligible. The collaboration has also through the IS361 ($^{9}$C decay) and IS339 ($^{31}$Ar decay) experiments reached considerable experience in characterizing multi-particle final states using highly segmented detectors. Behind each DSSSD detector is placed a thick 1000 - 1500 $\mu$m Si PAD detector for full energy determination and $\beta$-detection.

Further, one of the faces will be covered by an array of 25 5x5 mm$^2$ integrated detector telescopes with active areas of 3.5x3.5 mm$^2$, where the thickness of the $\Delta E$ stage is 1 $\mu$m and the E stage is 400 $\mu$m. However, even with this very thin $\Delta E$ detector, low-energy particles (E$\alpha$ $\sim$ 600 keV and Ep $\sim$ 200 keV) will not reach the E-detector. Thus the nature of a $\leq$ 200 keV particle cannot be determined. It is possible to circumvent this difficulty by applying a time-of-flight technique using the beta detectors to provide the start signal. Each of the E detectors can also act as beta detectors. In table 1 flight times for different low-energy charged particles are listed for a path length of 5 cm (distance in the cube).

| | ToF @ 150 (keV) | ToF @ 500 (keV) |
|---|---|---|
| | (ns) | (ns) |
| Proton | 9.6 | 5.3 |
| Deuteron | 13.6 | 7.5 |
| Triton | 16.7 | 9.1 |
| Alpha | 19.3 | 10.1 |

Table 1: Flight times for a path length of 5 cm of protons, deuterons, tritons and alpha particles of different kinetic energies.

For the neutrons we take advantage of the unique opportunity offered by the presence this year of the TONNERRE array from LPC-CAEN at ISOLDE. TONNERRE at ISOLDE combines 18 scintillator elements of 160 cm length, 20 cm width and 4 cm thickness with a 120 cm radius curvature, viewed at both ends by photomultiplier tubes. The array has a large acceptance (as installed at ISOLDE up to 25% of $4\pi$), with an energy resolution of ~10% for neutrons up to 5 MeV and a high overall efficiency of 15%. The low energy threshold is at about 300 keV.

For the decay tagging measurement of the d/t branches we plan to implant the $^{11}$Li beam in the front window of a gas-telescope. At backward angles to this implantation point a segmented charged particle setup will be placed to record the $^{9,8}$Li recoils and their subsequent $\alpha$-decays.

We propose to use a Ta-foil target optimized for the production and fast release of $^{11}$Li nuclei.

## 4 Summary and Beam time request

We propose a further investigation of the beta decay of $^{9,11}$Li, to obtain conclusive information of the multi-particle break-up channels. For $^{11}$Li these decay branches are believed to be most sensitive to the structure of the decaying state.

The beam time requirement is estimated in the following. The yield of $^{11}$Li from thin foil Ta-targets quoted in the PSB-yield database is 7000 per $\mu$C, this is a record yield and since the yield of very short lived isotopes fluctuate significantly from run to run we cannot use this in beam time estimates. Instead we use a conservative value of 400 per $\mu$C, which has been measured several times by members of the collaboration. For detecting coincidences between neutrons with TONNERRE and charged particles with the DSSSDs we aim for reaching 100 counts in total for a branching ratio of $10^{-4}$ (the typical for the high energy region near 18 MeV in $^{11}$Be). With the combined efficiency for detecting $\beta$s for ToF (25%), neutrons with TONNERRE (25% solid angle, 15% intrinsic efficiency) and charged particles (25%) we require 14 shifts. For the $^{9}$Li part we require 9 shifts of beamtime with the same setup to have sufficient statistics in the $\alpha\alpha$ channel. For measuring the deuteron and triton (d/t) branches we require 1000 coincidences between d/t in the gas-telescope (10 %) and $^{9,8}$Li recoils in the opposing detectors (50 %). With branching ratios of the order $10^{-4}$ this results in 7 shifts of requested beam time.

We request, from a Ta-foil target with a surface ionizer, a total of 30 shifts of on-line data taking plus additional 5 shifts for stable beam adjustments and calibration measurements.

The experiment will naturally have to be performed at the La1 beamline where the TONNERRE array is situated. We also request the use of the ISOLDE data acquisition system.

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