TRIUMF — RESEARCH PROPOSAL	Experiment no.	Sheet 1 of 22

Title of proposed experiment:

Charged-particle channels in the β-decay of ^{11}Li

Name of group: DELIS (DEuterons in LI decay: Search)

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Members of the group (name, institution, status, per cent of time devoted to experiment)

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Start of preparations:	January 2005
Date ready:	March 2005
Completion date:	December 2005

Beam time requested:

12-hr shifts	Beam line/channel	Polarized primary beam?
14	ISAC/TUDA	No

We aim at studying the charged-particle[1] channels of the β-decay of the halo nucleus ^{11}Li. We are especially interested in the channels fed by the decay through a state at $E^* \sim 18.1$ MeV in ^{11}Be. One particular channel, $^{11}\mathrm{Li} \xrightarrow{\beta} {}^{9}\mathrm{Li} + \mathrm{d}$, can also occur by direct decay into the ^{9}Li + d continuum and provides information about the spatial wave-function of the (halo-) ground state of ^{11}Li.

The total branching ratio to those channels is less than 1%. In order to compare with theoretical models, both the value of each branching ratio and the shape of the charged-particle spectra are of importance.

We plan to use a novel technique by implanting the post-accelerated ^{11}Li nuclei directly into a finely segmented silicon detector and observe the decay events. The high segmentation allows β particles to escape limiting the importance of their background. Further advantages with respect to previous techniques are the very large efficiency, a very reliable normalization for the measured branching ratios, and access to the history of each decay and . Identification of the different modes will be possible via the observation of characteristic daughter decays (energy and half-life).

For this purpose a ^{11}Li beam at 15 MeV should be developed. Also, beams of ^{8}Li at 12 MeV and ^{9}Li at 13.5 MeV should be used to perform two short calibration runs.

[1] Through the proposal we use "charged particles" in the sense of ions emitted in particular decay channels, in contrast to β particles emitted in all channels.

Experimental area

ISAC

Primary beam and target (energy, energy spread, intensity, pulse characteristics, emittance)

p (500 MeV, 40 μA) on Ta

Secondary channel TUDA

Secondary beam (particle type, momentum range, momentum bite, solid angle, spot size, emmittance, intensity, beam purity, target, special characteristics)

^{11}Li (unstable, 8.6 ms) 15 MeV

^{9}Li (unstable, 178 ms) 13.5 MeV

^{8}Li (unstable, 838 ms) 12 MeV

TRIUMF SUPPORT:

Development of a pure post-accelerated 15 MeV ^{11}Li beam (the experiment is feasible with a minimum of 100 particles per second; intensities up to 10^4 particle per second can be used).

Development of post-accelerated ^{8}Li and ^{9}Li beams (maximum usable intensity $\sim 10^4$ particles per second).

NON-TRIUMF SUPPORT

No unusual safety hazards are associated with this experiment. Standard precautions will be taken with the detector high voltages and the vacuum system.

1 Scientific Justification

Halo nuclei were first discovered in a series of experiments in the mid eighties [1,2], and they immediately became an important subject of research in nuclear physics. Their remarkable properties are connected to an extended matter distribution and weak binding energy. Experimental and theoretical efforts try to reproduce such properties by establishing the form of the wave function.

The nucleus ^{11}Li is the most extended such system known so far. It has been investigated in a variety of ways, mainly through nuclear reactions at high and intermediate energies. In order to extract valuable information from such measurements, assumptions need be made on the reaction mechanisms, which are in turn often poorly known.

The β-decay process has the advantage of being well understood. The overlap between mother and daughter states determines the decay probabilities. From these and the Q-value, direct information can be extracted for the mother state if the structure of the daughter states is known.

The scheme of the β-decay of ^{11}Li is presented in Figure 1. The only bound state fed in the decay is the $E^* = 320$ keV state in ^{11}Be: this mode has been accurately studied in various experiments [4–8] and theoretical works [9]. Due to the large Q-value (about 20.6 MeV) many other particle-emission channels are open and have been observed through the years: β2n [10], β3n [11], β^6He [12], βt [13] and βd [14].

The decay to excited states in ^{11}Be* up to $E^* \sim 10$ MeV has been studied by the detection of delayed-neutron emission in coincidence with γ-rays [7,8,15], and recently with a novel technique [16] based on the Doppler broadening of γ-lines [17,18].

In this proposal, we are interested in the decay channels proceeding through higher excited states in ^{11}Be, where the B_{GT} is large, as systematically found for light neutron-rich nuclei [19]. Such a phenomenon can have several explanations [19–21]; the large B_{GT} value is in any case an indication of a large overlap between the mother and daughter states. In ^{11}Be such a resonance has been identified at $E^* \sim 18.1$ MeV [22]. Various decay channels are open (see Figure 1): by measuring the branching ratios, partial reduced widths can be obtained and thus information on the structure of this state and the ^{11}Li ground-state. The best measurements performed so far [14,22] succeeded in giving an estimate of the branching ratios, although in some cases only limits were determined. We now aim at improving the uncertainties, together with the ones on the parameters of the 18.1 MeV state in ^{11}Be.

Among the charged-particle channels, ^{9}Li + d can also be reached through a direct transition into the continuum. This type of decay yields even more information about the mother state, since the spatial overlap matrix element is essentially an integral transform of the original spatial wave function. Such a process has been observed for ^{6}He [23–25]. For ^{11}Li different calculations have been performed [26,27]. They predict a branching ratio of order 10^{-4} and a deuteron spectrum that typically peaks at a few hundred keV; they also show that both the total branching ratio and the deuteron spectral shape are sensitive to the structure of ^{11}Li and to the ^{9}Li + d final state interaction. Experimentally this channel was indeed observed [14] with a $\sim 10^{-4}$ branching. This value, of the same order of the ^{8}Li + t channel [13,14], cannot be explained by a decay through the $E^* \sim 18.1$ MeV state in ^{11}Be [22] and was thus interpreted as an indication for the direct-decay mode; however the uncertainties, in particular the problem of separating the ^{9}Li + d and ^{8}Li + t channels, prevented from deriving firm conclusions. With the method proposed here we can separate the two channels and aim at obtaining a spectrum of the $^{11}\text{Li} \xrightarrow{\beta} {}^{9}\text{Li} + \text{d}$ decay with substantially better statistics, which will provide an accurate value of the branching ratio. Another advantage is the possibility of measuring the spectrum down to low energy, possibly determining the position of the maximum of the transition probability. These quantities, together, can put strong limits on the choice of the ^{9}Li + d optical potential and the ^{11}Li wave function [27].

2 Description of the Experiment

A schematic view of the setup is shown in Figure 2.

We will implant the ^{11}Li ions directly in a thin, highly-segmented silicon detector. All charged particles emitted in the decay of ^{11}Li and its daughters will produce a signal, for which the energy information and a time stamp will be recorded. The segmentation in the detector will allow to observe the history of each decay event and reduce the β-background (see further). At the same time, the total number of implanted ions will provide a very accurate normalization. The technique has been already employed for the observation of the charge-particle channel of the ^{6}He β-decay, and it is described in [28] (manuscript attached to this proposal).

2.1 The implantation detector

The double-sided silicon detector is 78 μm thick and 16×16 mm^2 in size. Each side is divided in 48 strips, 300 μm wide, oriented on perpendicular directions on the two faces. Coincident signals from the two sides identify thus one of 2304 “pixels” of less than 0.1 mm^2. The high segmentation provides two main advantages:

- *the background from β-particles emitted in the decays is strongly reduced.* The situation is pictured in Figure 3 (left). Due to their small energy loss, β-particles either escape from the strip where they are emitted, depositing only a limited amount of energy, or travel along one strip on one side and different strips on the other. In either case the energy deposited in one pixel (obtained by selecting events with only one signal on both sides) is small, regardless of the initial energy. This was studied with simulations and then independently measured through the β-decay of ^{6}He and ^{18}Ne [28]. The signal generated by β-particles is mostly lower than the electronic threshold. The ratio between detected β's and total number of emitted β's (suppression factor) depends on the value of the thresholds; with the hardware and settings used in previous measurements, even keeping the electronic threshold as low as possible, a suppression factor of 10^{-3} was observed. Statistically, β particles may also deposit a large energy in one pixel, but such an event is rare. The maximum deposited energy which appears in a spectrum of decay events depends on the total number of actual decays. Figure 3 (right) shows how in the case of implantation of

$\sim 10^8$ ^{6}He and ^{18}Ne ions, such maximum energy is about 600 keV [28]. In the case of ^{11}Li the number of implanted ions will be smaller.

Ions emitted in the charged-particle decay channels, on the other hand, are almost always completely stopped within the same pixel[2] and are detected with efficiency close to 100% above the electronic noise threshold. Above 600 keV, the spectrum of events with one strip firing on each side is a almost pure charged-particle spectrum;

- *the history of each implanted ^{11}Li nucleus can be followed.* By controlling the rate of the implanted ^{11}Li nuclei, it is possible to observe the decay events in each pixel where an implantation was detected. Some decay channels of ^{11}Li lead to unstable daughters, which in turn decay with different half-lives, emitting, in some cases, charged particles. Using the recorded information on the energy emitted and lifetime, the channels can be identified.

2.2 Implantation: the ^{11}Li beam

In order to spread the implantation on the whole detector, the incoming beam should be de-focused. This can be achieved using the magnets on the beam line (see Figure 2) and constantly controlled on line by observing the profile on the detector itself.

The ^{11}Li ions should be implanted on the middle plane of the detector to optimize the detection geometry of subsequent decay events. Calculations made with SRIM [30] indicate that the beam energy should be $E_{\text{impl}} = 15$ MeV; the resulting width of the depth distribution of the ^{11}Li ions is only a few micrometers. The same calculations performed for the ^{6}He case proved sufficiently accurate [28].

Identification of decay channels is based on the spatial correlation of subsequent events (implantation, decay, possible daughter-decay). In some cases, it is necessary to allow sufficient time to observe such events in each pixel where an implantation occurred. In particular the identification of daughter-decay channels with half-lives of the order of 1 s requires keeping the beam intensity within 200-300 particles per second (pps). For other channels, larger beam intensity can be used; to preserve the detector, however, the implanted dose should not exceed 10^4 pps.

2.3 Identification of the decay channels

The relevant characteristics of the decay channels of ^{11}Li and its daughters are shown in Figure 4 and summarized in Table 1. We are especially interested in the emission following the ^{11}Li decay through the $E^* \sim 18.1$ MeV state in ^{11}Be and the direct decay into ^{9}Li + d (see Figure 1). We discuss here briefly the procedures to identify the various channels and evaluate the branching ratios.

[2] The worst case is that of deuterons, which have a range of about 33 μm for an energy of 2 MeV. But given a uniform distribution in the three-dimensional volume of the pixel, the number of deuterons actually escaping detection remains small.

Table 1 Channel of the β-decay of ^{11}Li and its unstable daughters. Particle spectra are evaluated based on previous results [14,22,29].

^{11}Li channel ($T_{1/2} = 8.2$ ms)			Spectrum	Daughter channel			Spectrum
1a.	$\sim 7\%$	^{11}Be (320 keV)	pure β	13.81 s	96.9%	^{11}B	pure β
1b.				13.81 s	3.1%	^{7}Li+α	see Fig. 5d
2.	$\sim$75%	^{10}Be+n	β; ions (Fig. 5a)[3]	10^6 y	–	–	–
3.	$\sim$15%	^{9}Be+2n	β; ions (Fig. 5a)[4]	stable	–	–	–
4.	$\sim$1%	^{6}He+α+n	β; ions (Fig. 5b)	806.7 ms	100%	^{6}Li	pure β
5.	$\sim$2%	2α+3n	β; ions (Fig. 5b)	stable	–	–	–
6.	$\sim 10^{-4}$	^{8}Li+t	ions (Fig. 5c)	838 ms	100%	2α	see Fig. 5d
7a.	$\sim 10^{-4}$	^{9}Li+d	ions (Fig. 5c)	178.3 ms	50%	^{9}Be	pure β
7b.				178.3 ms	50%	2α+n	see Fig. 5d

- ^{8}Li + t and ^{9}Li + d

  Some of the channels are characterized by *two* subsequent decays, and can be identified by requiring that the two consecutive signals observed in a pixel fulfill the corresponding conditions for the energy signals (Figure 5 shows schematically the shape of the energy spectra of the ions emitted in the different channels). Taking into account the strong suppression (a factor 10^{-3}) of pure β-decay channels, the ^{8}Li + t and ^{9}Li + d channels (no. 6 and 7b in Table 1) are the dominant ones in this selection. They can be further separated based on the energy of the second event. For this purpose, the exact knowledge of the spectra of the ^{9}Li and ^{8}Li in our detector is very important: we plan to measure them directly implanting directly ^{8}Li and ^{9}Li ions in two short runs. This will also provide the efficiency for the detection of ^{9}Li decay events, which partly lie under the detection threshold.

  The main background would be due to spurious identification of random events from other channels (in particular the decay of the long-living ^{11}Be nucleus, channels 1a and 1b in Table 1). For the case of ^{8}Li + t the selection in energy on the daughter decay will completely suppress such background; for the case of ^{9}Li + d, the short lifetime of ^{9}Li (compared to that of other daughter channels) can be used by choosing an appropriate time window after the ^{11}Li decay.

  The beam intensity need be kept low to observe the daughter decay in the same pixel before another implantation takes place. We have evaluated that, with a beam of about 200 pps, in one day we can obtain more than 1000 events for each of these two channels. The branching ratios and the form of the particle spectra can thus be accurately measured *even below the β "noise" at 600 keV*, since no condition is required on the energy of the first decay event. The background expected in the ^{9}Li + d channel is about 30%; the precise amount is mainly determined by the (well-studied) branching ratio to the ^{11}Be channel and to the ^{6}He + α + n channel, discussed below.

[3] The fraction giving charged-particle signals is $< 1.5\%$ [22].
[4] The branching ratio giving charged-particle signals is $< 1.5\%$ [22].

- ^{6}He + α + n and 2α + 3n

  The energy spectrum of these two channels extends much further than for all others ^{11}Li-decay events. The latter can be selected by requiring a short time interval between an implantation and the subsequent event. The decay to these channels through the $E^{*} \sim 18.1$ MeV in ^{11}Be determines in fact the high-energy part of their spectra. The branching ratios can be therefore extracted with a procedure similar to the one used in [22]. The *total* branching ratios need to include the decay through other excited states in ^{11}Be, which has been measured in triple β + n + ^{4,6}He coincidences [29].

- ^{10}Be + n and ^{9}Be + 2n

  These events represent about 70% of the total number of ^{11}Li decays with energy less than 1.5 MeV, not followed by any daughter decay. The rest is given by the ^{6}He + α + n and 2α + 3n channels discussed above. An accurate branching ratio can be obtained for the sum of all these channels; separate values may have larger uncertainties.

3 Experimental Equipment

The equipment for this experiment is limited to the implantation silicon detector with related electronics (less than 100 channels in total). Coupled to these are low-noise, high-sensitivity preamplifiers available form the Nuclear Spectroscopy group in Leuven.

We plan to use the electronics (amplifiers, ADCS, TDCs) and data acquisition system available at TRIUMF (TUDA), through the collaboration with the local staff participating in this proposal. The beam line usually hosting the TUDA chamber is particularly suited for its low-noise conditions, which would allow measuring particle spectra down to a low energy threshold.

4 Readiness

The detector has been already successfully employed in previous measurements with a post-accelerated ^{6}He beam from the Louvain-la-Neuve accelerator complex, and is available for use. A short preparation would be needed in order to define the mechanical details for the mounting of the detector on the TUDA beam line.

5 Beam Time required

We performed various calculations for the efficiency of our method for the identification of the decay channels, using the simple shape for the energy spectra shown in Figure 5 and varying the beam intensity. A non-uniform distribution of the beam was taken into account. While the actual experimental conditions may change the details, a beam intensity of 200 pps seems optimum for the identification of the ^{8}Li + t and ^{9}Li + d channels. This would allow collecting about 1000 events in 24 hours for each of these channels, and a higher statistics for the others.

We refer to the most difficult case, the ^{9}Li + d channel. Taking into account background, within 12 hours the branching ratio can be determined with a precision of 10%. But a higher statistics is necessary to attain a good precision on the determination of the shape of the spectrum: about 2500 (background-free) events in the 0-2 MeV are necessary. Thus this measurement can be performed with 8 12-hours shifts of ^{11}Li beam on target. Note that, if a higher precision on other channels is desired, short runs with a higher beam intensity can provide the necessary statistics when no correlation with a daughter decay is required.

One shift is then devoted to the complementary measurements with ^{8}Li and ^{9}Li beams.

A certain amount of time should be foreseen for the development of the Li radioactive beams, which need be post-accelerated (for the first time in TRIUMF). This time is difficult to estimate, and we suggest that, were this proposal accepted, 4 shifts should be devoted to a production to be performed in advance, before the actual experiment. This will determine also the time needed for beam tuning during the experiment; for the time being, we estimate the latter in 1 shift.

The total beamtime requested is therefore **10 12-hour shifts** for the experiment plus **4 12-hour shifts** for a production test for the Li radioactive beams.

6 Data Analysis

The data analysis will be performed at the K.U.Leuven by R.R. and J.Po.; no other facilities are required at TRIUMF.

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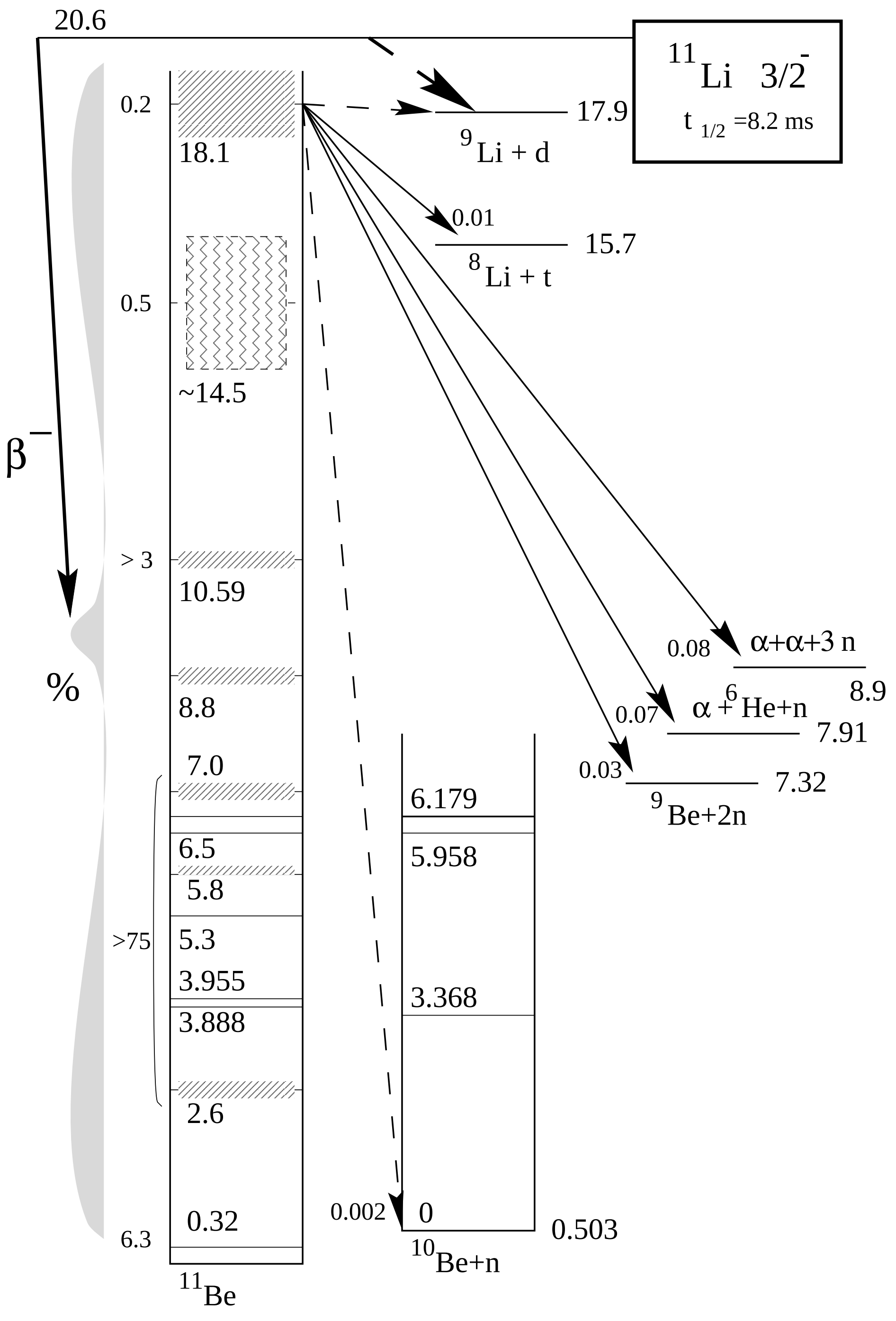


Fig. 1 ^{11}Li decay scheme, taken from [3]. The branching ratios are given in %.

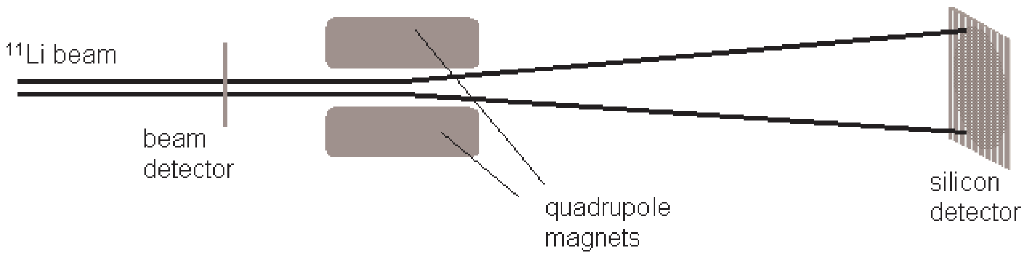
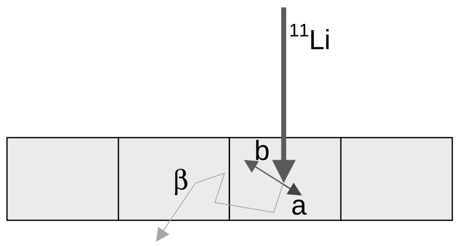


Fig. 2 Schematic view of the experimental setup (not to scale).



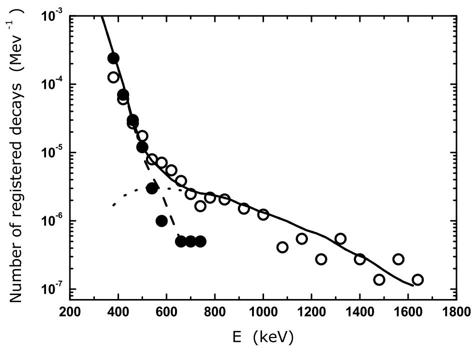


Fig. 3 (Left) β-particles emitted in a decay have a long range and, statistically, deposit only a limited amount of energy in a single pixel (defined by selecting events with only one signal on both detector sides). Heavy ions (a and b in the figure), on the other hand, have a short range and deposit their whole energy in the same pixel. (Right) The energy deposited by β particles is a statistical quantity, therefore its maximum depends on the number of actual decays. The figure shows the spectra measured for ^{6}He($\circ$) and ^{18}Ne($\bullet$) decays after more than 10^8 implantations [28]. The ^{6}He decay has a small branch (10^{-6}) into α + d, while the spectrum of ^{18}Ne is of pure β particles. The curves are the results of simulations.

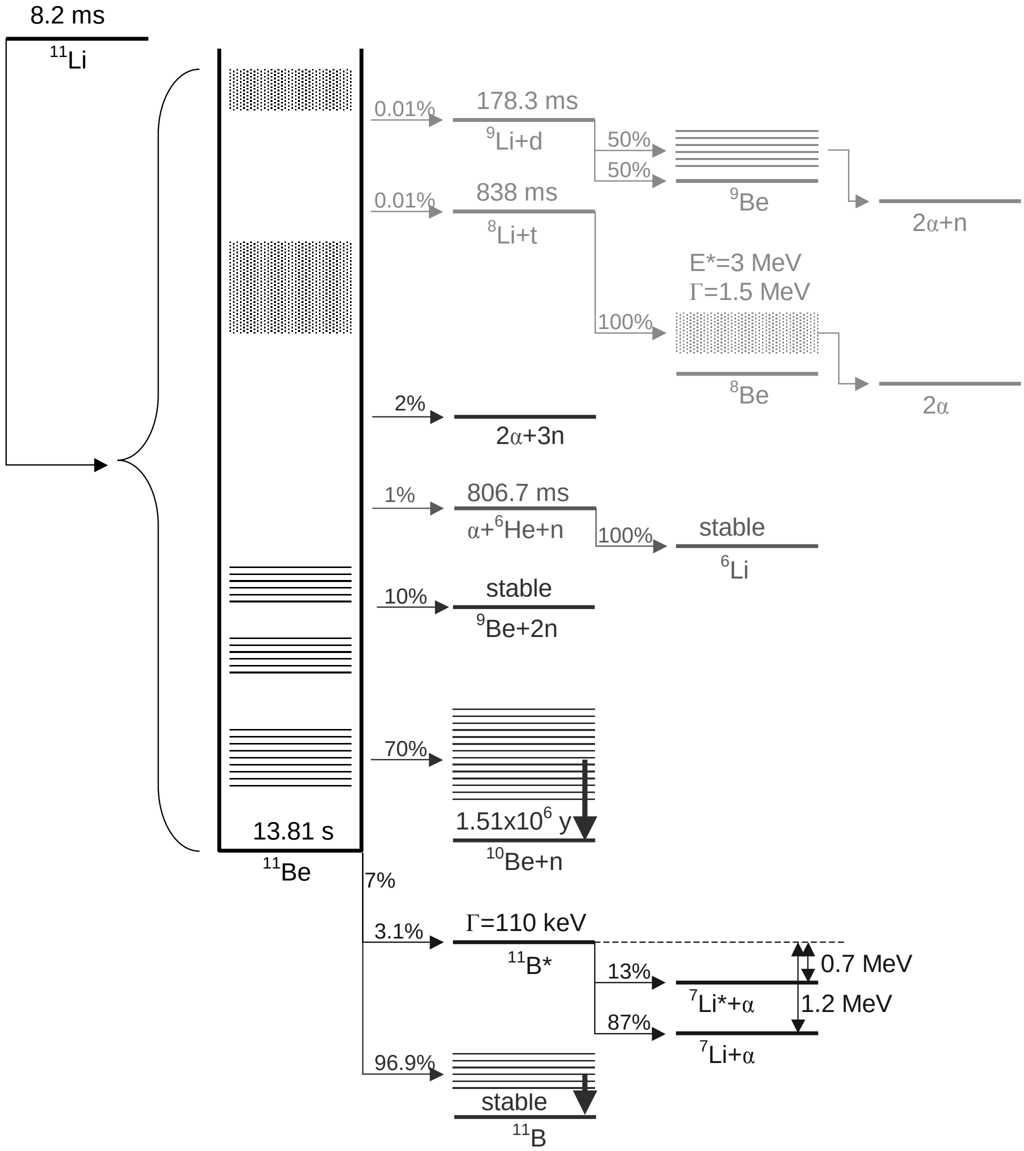


Fig. 4 Parameters of the decay channels of ^{11}Li and its unstable daughters ^{11}Be*, ^{10}Be, ^{6}He, ^{8}Li and ^{9}Li.

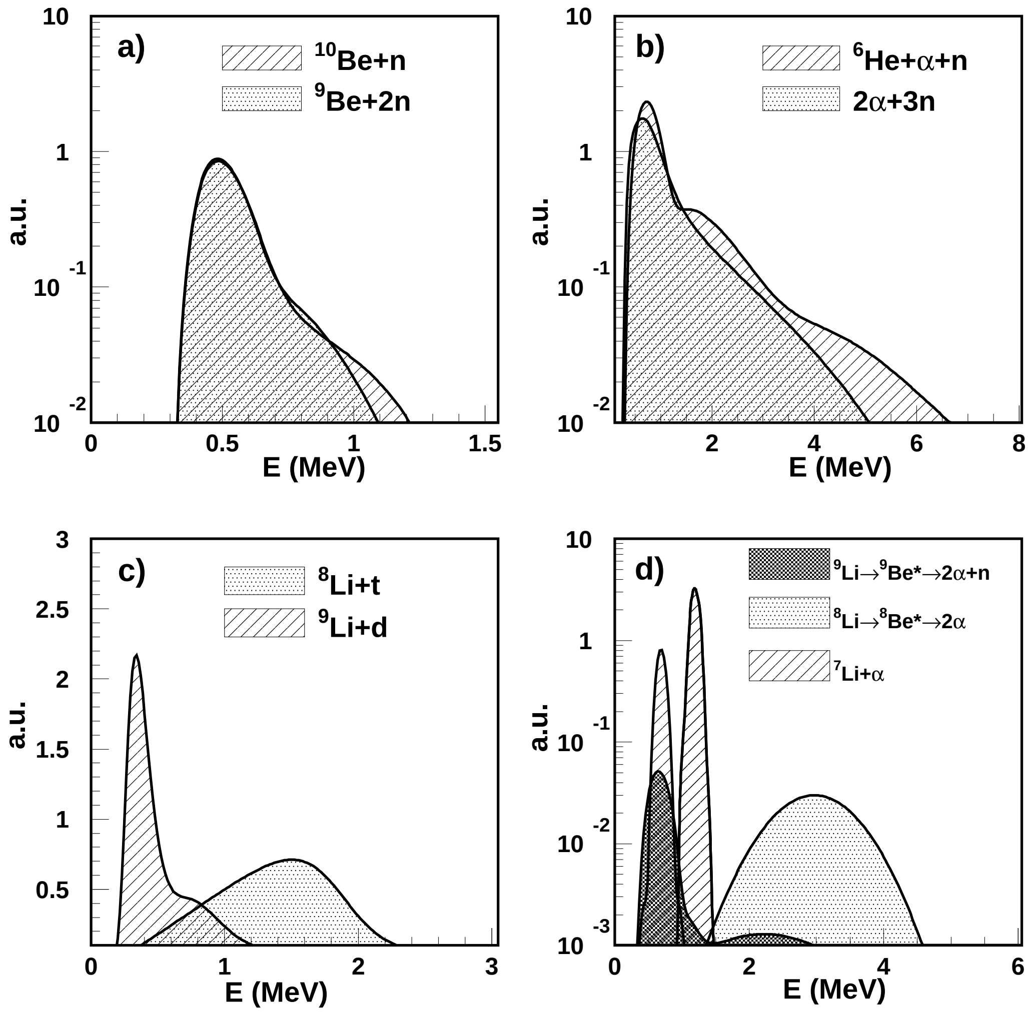


Fig. 5 Simple shapes for the spectra of ions emitted in the β-decay of ^{11}Li (a, b, and c) and its daughters (d) were assumed for the calculations for this measurement. The spectra are based on the measurements in [14,22]. Units are arbitrary, but within each panel the distributions are scaled according to the expected branching ratios.

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