Beta-delayed deuteron emission from $^{11}$Li: decay of the halo

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The deuteron-emission channel in the $\beta$-decay of the halo-nucleus $^{11}$Li was measured at the ISAC facility at TRIUMF by implanting post-accelerated $^{11}$Li ions into a segmented silicon detector. The events of interest were identified by correlating the decays of $^{11}$Li with those of the daughter nucleus. This method allowed the energy spectrum of the emitted deuterons to be extracted, free from contributions from other channels, and a precise value for the branching ratio $B_d = 1.30(13) \times 10^{-4}$ to be deduced for $E_{cm} > 200$ keV. The results provide the first unambiguous experimental evidence that the decay takes place essentially in the halo of $^{11}$Li, and that it proceeds mainly to the $^9$Li + $d$ continuum, opening up a new means to study of the halo wave function of $^{11}$Li.

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The nuclear halo [1] is among the most peculiar features discovered in unstable nuclei. The $^{11}$Li nucleus is the showcase of a two-neutron halo system, with its very extended matter distribution related to the small energy necessary to remove the neutrons, $S_{2n} = 378(5)$ keV [2]. Considerable effort has been expended to determine the characteristics of this unstable, short-lived nucleus ($T_{1/2} = 8.5(2)$ ms [3]). Among the available probes, the $\beta$-decay has the advantage of being described by a well-established theory, and thus provides a valuable tool for the investigation of the properties of the ground state of the parent nucleus.

In the case of $^{11}$Li, one decay channel is of special interest: the $\beta$-delayed deuteron emission $^{11}$Li $\rightarrow^d$ $^9$Li + $d$. This mode is related to the possibility that in halo nuclei the core and the halo particles could decay, more or less independently, into different channels [4]. Evidence of the $\beta$-decay of the $^9$Li core in $^{11}$Li with survival of the two-neutron halo was reported in Ref. [5]. On the other hand, according to calculations [6, 7, 8] the deuteron-emission channel should be dominated by the decay of a neutron in the halo: a “halo decay”. This may be measured via the $^{11}$Li $\rightarrow^d$ $^9$Li + $d$ decay probability, or the branching ratio $B_d$. In addition, the $\beta$-delayed deuteron decay of $^{11}$Li could proceed directly to the continuum, without forming an intermediate state (resonance) in the daughter nucleus $^{11}$Be. The information on the initial $^{11}$Li wave function would then be more easily accessible. Both $B_d$ and the energy distribution of the emitted deuterons are related to this.

We report here the first measurement of the relevant quantities, $B_d$ and the energy of the emitted $^9$Li and $d$ ions, without contributions from other channels, by studying the decay correlations of a post-accelerated $^{11}$Li beam implanted in a segmented silicon detector [9, 10].

The $\beta$-decay of $^{11}$Li is complex. The large mass difference between $^{11}$Li and its daughter $^{11}$Be ($Q = 20.6$ MeV) implies that many decay channels to bound and unbound states in $^{11}$Be are open. In the latter cases, the daughter breaks into fragments, and emission of one [11], two [12], and three neutrons [13], $\alpha$ particles and $^3$He [14], tritons [15] and deuterons [16] has been observed. A summary is given in Table I. The $\beta$-delayed emission of deuterons has also been observed in the decay of the two-neutron halo nucleus $^8$He [10, 20, 21, 22]. However, the $^3$He $\rightarrow^d$ $\alpha + d$ channel has contributions from both the halo and core parts of the $^3$He ground-state wave function [23, 24, 25].

| Decay channel | Daughter half life and decay |
|---------------|-------------------------------|
| (a) 6.3% [17] | $^{11}$Be + $\gamma$, $^{93}(1)\%^a$ |
| (b) 87.6% [17] | $^{11}$Be + $n$, $^{10}$y |
| (c) 4.2% [17] | $^9$Be + $2n$, stable |
| (d) 1.0% [18] | $^6$He + $\alpha + n$, $807$ ms, $^6$Li g.s., $\approx$100% |
| (e) 1.9% [17] | $2\alpha + 3n$, stable |
| (f) 0.01% [16] | $^8$Li + $t$, $838$ ms, $2\alpha$, 100% |
| (g) 0.01% [16] | $^9$Li + $d$, $178$ ms, $^8$Be g.s., $49.2(9)\%^b$ |

$^a$From this work, assuming 6.3(6)% [17] as branching ratio for (a).

$^b$From [19].
the two contributions interfere destructively leading to a very small value of the corresponding branching ratio of about $10^{-6}$. In $^{11}$Li, on the other hand, the long-range behaviour of the wave function, which is more extended than in $^6$He, could favour the unperturbed decay of the halo particles and the suppression of the core contribution, producing a comparatively larger branching ratio of the order of $10^{-4}$ [6, 7, 8].

The experimental detection of the deuterons from the $^{11}$Li $\beta^-$, $^9$Li $+ d$ decay is complicated by their low energy – the $^9$Li $+ d$ threshold in $^{11}$Be is at $E^* = 17.9$ MeV, thus the energy available in this channel is $Q_d = 2.7$ MeV. In addition, deuterons are difficult to separate from the tritons emitted in the $^8$Li $+ t$ channel ($Q_t = 4.9$ MeV). The only previous work reporting their detection is that by Mukha et al. [16]. The authors measured a cumulative spectrum for $Z = 1$ particles from the activity of $^{11}$Li nuclei deposited on a thin foil, and estimated a branching ratio $B \gtrsim 10^{-4}$. Evidence of the actual presence of deuterons was provided by the correlated detection of a few decay events of the associated nucleus $^9$Li.

In the present work we used a different experimental technique and directly implanted the $^{11}$Li nuclei in a thin, highly segmented silicon detector. The decay channels were identified through the time and position correlation between the implanted nuclei and subsequent parent and daughter decays.

The $^{11}$Li nuclei were produced by bombarding a thick Ta target with the 500 MeV, 35 $\mu$A proton beam from the TRIUMF Cyclotron. After extraction and selection by a magnetic analyzer, the $^{11}$Li nuclei were post-accelerated to an energy of 1.5 MeV/nucleon in the ISAC-I accelerator [26]. The $^{11}$Li implantation into the detector was continuous; to preserve the correlation between an implantation event and the subsequent decays, we used only a fraction of the available intensity (about 200 particles per second of the total few thousands). This also helped reduce the dead time of the acquisition system. The beam was de-focused to spread the implantations on the whole detector surface. About $85 \times 10^6$ $^{11}$Li ions were implanted in 130 hours of beam time.

The double-sided silicon strip detector was 78 $\mu$m thick, with an active area of $16 \times 16$ mm$^2$. The 48 strips on each side (300 $\mu$m wide, with those on the back face perpendicular to those on the front) defined a total of 2304 pixels. The efficiency for the detection of low-energy events, measured using pulsed signals of calibrated amplitude, was about 75% at 200 keV, rising to 100% at 300 keV. For all events in each pixel, the recorded information included the deposited energy and a timestamp. The main characteristics of the method have been described in Ref. [10]. A precise normalization is ensured by the direct correlation between implanted ions and detected decays. By selecting single-pixel events (only one signal in each set of strips), $\beta$ particles are strongly suppressed since their specific energy deposition is low – less than 1% of all $\beta$'s are detected above the threshold, and less than one in $10^6$ deposit more than 600 keV [10]. Conversely, the energy deposited by ions in virtually all $^9$Li $+ d$ decay events is completely collected in a single pixel. The range of 1 MeV deuterons in silicon is 12.2 $\mu$m and the interstrip distance was 35 $\mu$m. The implantation depth of the $^{11}$Li was 43(2) $\mu$m according to SRIM [27] calculations; this results in 99.9% of the $^9$Li $+ d$ events being contained in the implantation pixel [10].

Fig. 1 shows the events immediately following a $^{11}$Li implantation in the same pixel. The time behavior has a short component with a half life $T_{1/2} = 8.7(1)$ ms as expected for $^{11}$Li decays. The energy spectrum of events within the first 40 ms – $(E_1, t_1)$ events – contains less than 0.1% background from uncorrelated activity. The features of this $^{11}$Li $\beta$-decay spectrum will be discussed in a separate publication.

$(E_2, t_2)$ events were defined as the first decay events following the $^{11}$Li decays $(E_1, t_1)$ in the same pixel, before a subsequent implantation took place. Such daughter-decay events were used to identify the decay channels of interest (Fig. 2). Referring to Table I, and taking into account that pure $\beta$-emission (or $\beta$-$\gamma$) decays are strongly suppressed in our setup, we expect contributions mainly from the daughters in channels $(f)$ and $(g)$. The considerably shorter half-life of the $^8$Li daughters compared to the average time between two implantations in the same pixel (about 8.5 s) shows that these daughter decays are truly correlated with the previous $^{11}$Li decay. Daughter decays from channel $(a)$ also appear, but they are uncorrelated because their $^{11}$Li mother decay branch is mostly not detected (pure $\beta$-$\gamma$), and due to the long half life of $^{11}$Be. Finally, the spectrum of $(E_2, t_2)$ contains uncorrelated decays of $^{11}$Li, due to undetected implantations taking place between the decays at $t_1$ and $t_2$. The undetected implantations (mainly caused by the dead time of the acquisition system) are only a few percent of the
total; still, because of the small branching ratios of the other channels, at low energy the uncorrelated $^{11}\text{Li}$ decays dominate the spectrum of $(E_2, t_2)$ events.

To correctly evaluate each contribution, the decays of the daughter channels of interest were separately studied in dedicated measurements with our setup. Beams of $^{9}\text{Li}$ and $^{8}\text{Li}$ ions were produced at ISAC and implanted in the segmented detector at depths (close to the detector middle plane) to ensure that the ions emitted in the decay would not escape. Beams modulations of 0.5 s “beam on” - 0.5 s “beam off” and 2.5 s on - 2.5 s off were used for $^{9}\text{Li}$ and $^{8}\text{Li}$ respectively. For the decay of $^{11}\text{Be}$ we used again a $^{11}\text{Li}$ beam, with a modulation 20 s on - 20 s off: a short time after stopping the beam, only the long-living $^{11}\text{Be}$ activity remained. The shapes of the collected spectra differed from the ones from literature, reflecting the fact that the sum energy of all ions emitted in each decay was measured in our setup. These measurements also allowed the efficiency for the detection of each decay in our setup to be determined. In particular, the efficiency for the decay of $^{8}\text{Li}$ was $100(1)\%$ (equal to the branching ratio reported in Table I) because of the high energy of the emitted $\alpha$-particles; for $^{9}\text{Li}$, it was only $36(1)\%$, resulting from the convolution of the spectrum of the low-energy $\alpha$ particles from the decay with our detection efficiency at energies below 300 keV.

We adopted two procedures to extract the branching ratio and the energy spectrum of the $^{11}\text{Li} \rightarrow^{\beta} _{\alpha} ^{9}\text{Li} + d$ channel. The first consisted of counting the $^{9}\text{Li}$ decays among the $(E_2, t_2)$ events. For this purpose, we fitted the $(E_2, t_2)$ spectrum with the measured spectra of the daughter decays in the channels $(a)$, $(f)$ and $(g)$ (the one of interest), and the spectrum of $^{11}\text{Li}$ decays (from the undetected implantations). The fit was repeated for different time windows $\Delta t$ (with $t_2 - t_1 < \Delta t$) and various energies $E_1$ of the first decay; an example is shown in Fig. 2. The asymptotic value of the number of $^{9}\text{Li}$ decays for $\Delta t \to +\infty$ (about 3200 for the whole energy range in $E_1$), corrected for the detection efficiency, yields the number of deuteron-emission events. An additional small correction was applied to account for the possibility that a subsequent implantation event took place in the same pixel before the $^{9}\text{Li}$ decay. By repeating the procedure for different energy intervals in $E_1$, a differential branching ratio was obtained or, in other words, the decay probability $dW/dE$ as function of the total $^{9}\text{Li}-d$ energy $E_{c.m.}$. The result is shown in Fig. 3 (filled circles); the uncertainties (statistical only are plotted) propagate from the errors in the fit of the $(E_2, t_2)$ spectra.

The second approach consisted of directly selecting deuteron-emission events among the $(E_1, t_1)$ ones by applying conditions on the subsequent $(E_2, t_2)$ events in order to maximize the number of $^{9}\text{Li}$ decays. This was achieved by requiring $t_2 - t_1 < 200$ ms and $E_2$ between 0.55 MeV and 0.8 MeV (see also Fig. 2). The amount of “background” present in the selection was determined from the fit of the $(E_2, t_2)$ spectrum; after subtraction, about 700 $^{9}\text{Li} + d$ events remained in the $(E_1, t_1)$ spectrum. The normalization took into account the detection efficiency for the $^{9}\text{Li}$ decay events, plus the factors introduced by the narrow selection of the $(E_2, t_2)$ events. The resulting spectrum is shown in Fig. 3 (hollow squares); because of the smaller statistics, the uncertainties are larger than for the first method.

The two methods produced consistent results within the statistical uncertainties. An additional 8% systematic error is present in both cases, related to the overall normalization. For the total branching ratio of the deuteron-emission channel, the first method (with the better statistics) yields $B_d = 1.30(13) \times 10^{-4}$ for a $^{9}\text{Li}-d$ total energy $E_{c.m.} > 200$ keV. The value obtained with the second method is $B_d = 1.08(23) \times 10^{-4}$.

![Figure 2](image_url)  
**FIG. 2:** (Color online) Example of a fit of $(E_2, t_2)$ events, with contributions from daughter decays in channels $(a)$, $(f)$ and $(g)$, and uncorrelated $^{11}\text{Li}$ decays. This spectrum was obtained for $t_2 - t_1 < 200$ ms and for $E_1$ between 0.5 MeV and 2.0 MeV. The insert shows the number of $^{9}\text{Li}$ decay events in the $(E_2, t_2)$ spectra for $t_2 - t_1 < \Delta t$ as function of $\Delta t$. The fitted time behaviour is in agreement with the expected $^{9}\text{Li}$ half life, $T_{1/2} = 178.3(4)$ ms [19].

![Figure 3](image_url)  
**FIG. 3:** (Color online) Transition probability for the $^{11}\text{Li} \rightarrow^{\beta} _{\alpha} ^{9}\text{Li} + d$ decay channel. The procedures to obtain the experimental data are explained in the text. The curves are predictions from Refs. [7] ($V_C$) and [8] ($V_a, V_b$).
$B_d$ is sensitive to two aspects: the decay of the halo part of the $^{11}\text{Li}$ wavefunction, and the decay directly to the continuum rather than to a resonance in the daughter nucleus $^{11}\text{Be}$. Concerning the first aspect, we have already pointed out how contributions from the core, in the case of $^6\text{He}$, interfere destructively with those from the halo, reducing the branching ratio to about $10^{-6}$. As for the second aspect, in the calculations published so far [6, 7, 8], it has been shown that a maximum value of $B_d \approx 10^{-4}$ could only be reduced (by as much as two orders of magnitude) if a resonance existed below the $^9\text{Li} + d$ threshold in $^{11}\text{Be}$. We conclude that the value which we measured confirms that the deuteron-emission decay takes place essentially in the halo of $^{11}\text{Li}$, without significant interference of contributions from the decay of the $^9\text{Li}$ core (which was in turn observed in other channels of the $^{11}\text{Li}$ decay [5]).

The question of whether the decay proceeds directly to the continuum or through a resonance is also related to the energy distribution of the emitted ions, Fig. 3. In Refs. [6, 7, 8], different potentials for the $^9\text{Li}-d$ interaction were used to reproduce a resonance around the $^9\text{Li} + d$ threshold in $^{11}\text{Be}$. The curves in Fig. 3 are taken from those studies and are representative of the results. The curves labeled $V_a$ and $V_b$ (from Ref. [8]) correspond to potentials producing a resonance, respectively 0.33 MeV above and 0.18 MeV below the $^9\text{Li} + d$ threshold; the one labeled $V_c$ (from Ref. [7]) corresponds to the Coulomb potential only, without a resonance. The integral value of the transition probability rules out the $V_b$ case. A resonance above the threshold, curve $V_a$, generates a pronounced maximum, shifting the spectrum towards lower energies and reducing it at energies above the resonance; absorption into other decay channels [8] may reduce the height of the maximum but would not affect the spectrum above 1 MeV. This, and the fact that our data are better reproduced by the curve $V_c$, indicate that we do not see a resonance in our observation window or just below it. We recall here that a resonance in $^{11}\text{Be}$ has been observed at an excitation energy $E^* \approx 18.1$ MeV by Borge et al. [28], about 200 keV above the $^9\text{Li} + d$ threshold. Their analysis, however, based on a branching ratio $B_d \approx 10^{-4}$, showed that it is unlikely that the deuteron-emission decay takes place through this level. Our results thus support the picture of a decay proceeding mainly to the continuum. This implies that the decay matrix elements represent a Fourier transform of the $^{11}\text{Li}$ ground-state wave function to which our data should then be very sensitive. These aspects should be addressed in future theoretical studies.

In conclusion, we have measured the deuteron-emission channel in the $\beta$-decay of $^{11}\text{Li}$ by implanting a post-accelerated beam of $^{11}\text{Li}$ ions into a highly-segmented silicon detector and identifying the channel of interest by time and position correlation of implantation events and subsequent parent-daughter decays. Precision data were obtained for the branching ratio and the $^9\text{Li}-d$ total energy spectrum down to an energy threshold of 200 keV. The results provide the first clear experimental support for the deuteron-emission decay taking place essentially in the halo of $^{11}\text{Li}$ and indicate that the decay proceeds mainly to the $^9\text{Li} + d$ continuum, opening up the possibility for a detailed study of the halo wave function of $^{11}\text{Li}$ complementary to those based on nuclear reactions.

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