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PHYSICAL REVIEW C **70**, 031302(R) (2004)

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(Received 12 July 2004; published 21 September 2004)

The β decay of ^{11}Li has been investigated at TRIUMF-ISAC using a high-efficiency array of Compton suppressed HPGe detectors. From a line-shape analysis of the Doppler-broadened peaks observed in the ^{10}Be γ spectrum, both the half-lives of states in ^{10}Be and the energies of the β-delayed neutrons feeding those states were obtained. Furthermore, it was possible to determine the excitation energies of the parent states in ^{11}Be with uncertainties comparable to those obtained from neutron spectroscopy experiments. These data suggest that the β decay to the 8.81 MeV state in ^{11}Be occurs in the ^{9}Li core and that one neutron comprising the halo of ^{11}Li survives in a halolike configuration after the β-delayed neutron emission from this level.

DOI: 10.1103/PhysRevC.70.031302 PACS number(s): 23.20.−g, 23.40.−s, 27.20.+n

The concept of loosely bound quantum particles having large spatial extent, beyond classical limits, is key to understanding a variety of physical systems [1]. The neutron halo of ^{11}Li has been the subject of intense studies since it was first proposed [2] to explain the abnormally large ratio of the matter-to-charge radius of ^{11}Li [3]. In particular, the study of the β decay of ^{11}Li is expected to shed light on how the weak interaction affects the two neutrons composing the halo. Presently [4], it is believed that the two valence neutrons are effectively decoupled from the core nucleus (^{9}Li). As a result, if the β decay occurs in the core, the neutrons of the halo could in principle remain unaffected, but would then "react" to the fact that the core has changed [5]. In this paper, we discuss the striking possibility that one neutron of the ^{11}Li halo could survive in a halo configuration through the full β-delayed one-neutron emission process.

While the large ^{11}Li-^{11}Be mass difference ($Q_\beta = 20.61$ MeV) and the low neutron separation energy in ^{11}Be ($S_n = 0.503$ MeV) open a large number of decay channels in the β decay of ^{11}Li (see [6] and references therein), most of the β-decay strength leads to classical channels, namely by β emission to the only bound excited state in ^{11}Be at 320 keV (6.3%) and, by β-delayed one-neutron emission (βn) (87.6%), to bound excited states in ^{10}Be [7]. The latter decay path has been investigated recently by different experiments using β-γ and β-n-γ coincidences [6–9]. Discrepancies exist among these experiments. The γ-ray intensities of the transitions in ^{10}Be are found to be significantly different, while some ambiguities arise from the interpretation of the neutron spectra [6].

To study the β-delayed neutron emission of neutron-rich nuclei, it is often necessary to detect both the neutron(s) and γ rays emitted in order to determine the excitation energies of the levels populated in progeny nuclei. However, in the present case, the level structure of ^{10}Be is well known up to the one-neutron separation energy at 6.812 MeV [10,11], and the γ peaks resulting from the decay of the ^{10}Be excited states have characteristic Doppler-broadened line shapes due to the ^{10}Be recoil induced by the β-delayed neutron emission. It is therefore possible, in principle, to make a complete analysis of all the ^{11}Li βn branches that feed the excited states of ^{10}Be through an analysis of the γ-ray energy spectra. In this way, the neutron energy spectrum may be determined, complementing and adding to the information obtained by direct neutron observation. An attempt to analyze these line shapes was made by Fynbo *et al.* [12] using the γ spectrum obtained by Borge *et al.* [7] and again, more recently, with a set of data obtained at ISOLDE [9].

The β decay of ^{11}Li was investigated at TRIUMF-ISAC [13] with the 8π spectrometer, an array of 20 Compton-suppressed high-purity germanium (HPGe) detectors [14]. ^{11}Li was produced by bombarding a 22 g/cm^2 Ta target with a 500 MeV proton beam. A pure 30.4 keV ^{11}Li beam of

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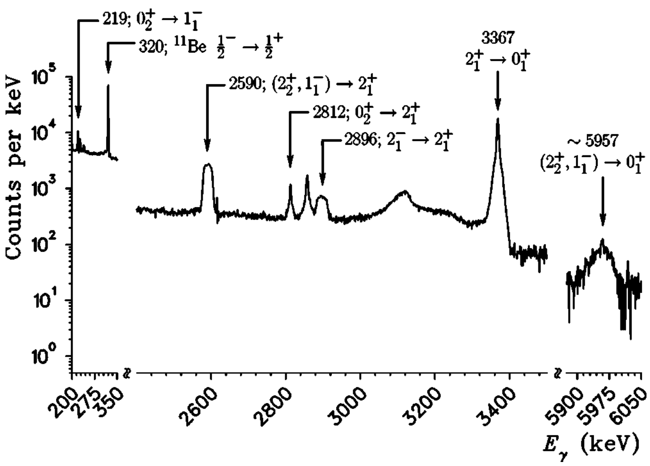

FIG. 1. Compton-suppressed γ spectrum following the β decay of ^{11}Li. Only the relevant parts that contain the γ transitions observed in ^{10}Be and in ^{11}Be are shown (room background subtracted).

about a thousand ions per second was extracted by surface ionization from the target and implanted into a 0.2-mm-thick Al foil at the centre of the γ detector array. A total of 8.1M γ singles were collected over a 2.5 day period.

The γ peaks corresponding to the β and βn decay of ^{11}Li are shown in Fig. 1. Besides the known 320 keV transition to the ground state of ^{11}Be, the other γ rays labeled on the figure are identified as known transitions in ^{10}Be.

The relative efficiency of the array up to 3.4 MeV was measured to an uncertainty of ±2% with calibrated sources of ^{152}Eu and ^{56}Co fit using the RadWare package [15]. The relative efficiency at high energies (up to about 8 MeV) was obtained from known transitions in the β decay of ^{11}Be [16]. A GEANT [17] simulation was also developed to predict the relative efficiency of the array at high energies. This simulation agreed with experiment to about 10% at 6 MeV. The γ-ray energies and relative intensities observed in the present experiment are summarized in Table I.

A new γ ray was observed at 2896.0(5) keV corresponding to the decay of the 6264 keV, 2^- level in ^{10}Be to the 2_1^+ level at 3368 keV. In addition, an unresolved doublet was seen at ~5957 keV corresponding to the ground-state decay of the known $(2_2^+, 1^-)$ doublet in ^{10}Be. Both of these transitions were also reported recently by Fynbo *et al.* [9]. The relative intensities observed in the present experiment are a factor 2–5 times more precise than all previous data [6–9], sufficient to resolve previous discrepancies. In general, the results are in agreement with those obtained by Borge *et al.* [7] and Aoi *et al.* [8]. However, large discrepancies (about a factor of 2) remain for the 2590 and 2812 keV transitions reported by Morrissey *et al.* [6] and the 219 and 5957 keV γ-ray peaks seen by Fynbo *et al.* [9].

The excitation energies of the 1^-, 0_2^+, and 2^- states in ^{10}Be were determined by fitting the Doppler broadened line shapes and correcting for the recoil effect. The energies of both the 1^- and 0_2^+ states were found to be about 1 keV above the previous values [10,11], whereas the precision of the energy of the 2^- state was improved by a factor of 10 (see Table I).

TABLE I. Excited states in ^{10}Be and in ^{11}Be. Energy (E_γ), intensity, and branching ratio (BR) of the γ transitions in ^{10}Be observed after the β-delayed neutron emission of ^{11}Li. The intensities are normalized to the 3367 keV transition.

E_{Level} (keV)	E_γ (keV)	Assignment	Intensity	BR (%)
320.04(1)	320.0(5)	$^{11}\mathrm{Be}: \frac{1}{2}^- \rightarrow \frac{1}{2}^+$	23.3(12)	
3368.03(3)	3367.1(5)	$2_1^+ \rightarrow 0_1^+$	100(2)	
5958.39(5)	2590.3(5)	$2_2^+ \rightarrow 2_1^+$	26.5(6)^a	90(3)^a
	5956.5(10)	$2_2^+ \rightarrow 0_1^+$	2.9(9)^a	10(3)^a
5961.1(5)^b	2592.7(5)^c	$1^- \rightarrow 2_1^+$	0.7(3)^a	35(15)^a
	5959.2(10)^c	$1^- \rightarrow 0_1^+$	1.3(3)^a	65(15)^a
6180.3(5)^b	219.2(5)	$0_2^+ \rightarrow 1_1^-$	2.04(11)	39(2)
	2811.8(5)	$0_2^+ \rightarrow 2_1^+$	3.13(10)	61(2)
6264.5(5)^b	2896.0(5)	$2^- \rightarrow 2_1^+$	6.21(16)	100

[a] Intensities/branching ratios determined from fitting doublets (see text).
[b] Level energies determined in this experiment (see text).
[c] Energies determined from fitting doublets (see text).

A Monte Carlo simulation has been developed to analyze the complex shape of the γ lines observed in this experiment. The line shape of a given γ peak mainly depends on the energies and relative intensities of all the neutron branches feeding, directly or indirectly, the state from which the γ transition arises, and on the lifetimes of the excited state populated in ^{10}Be. The line shape of the peaks can also be affected by the angular correlation between the recoil (neutron) and the γ ray [12]. Using the energy loss data computed in the latest version of SRIM [18], the implantation profile of ^{11}Li atoms in the Al foil was generated and the β-delayed one-neutron emission simulated. The recoil was assumed to be emitted isotropically in the laboratory frame. The treatment of the recoil escaping the foil, before it stops, in the backward angles is included in the simulation, as it affects the line shape of the peaks. However, in all cases, the recoil travels only a few micrometers before the γ rays are emitted and therefore the efficiency of the HPGe detector array is not affected. The intrinsic response of the HPGe detectors was approximated with a Gaussian shape, with an energy-dependent width σ. No significant asymmetry was found in the data when comparing the γ spectra of the individual HPGe detectors. The spectra from all 20 detectors were summed and the analysis was performed on the resulting spectrum. To compare the data with the Monte Carlo simulation, the Compton background underneath the peaks was subtracted with the appropriate error propagation. The neutron feeding intensities deduced from the line-shape analysis, together with the γ-ray intensities, are shown in Fig. 2.

No angular correlation between the recoil and the γ ray is expected in the line shapes of the 2812 and 2896 keV transitions corresponding to the decay of the 6180 keV, 0_2^+ and 6264 keV, 2^- states, respectively, to the 3368 keV, 2_1^+ level. This arises from the fact that the 2^- state is believed to be fed mainly by the emission of an $\ell = 0$ neutron from a $(3/2, 5/2)^-$ state in ^{11}Be (discussed later in the paper),

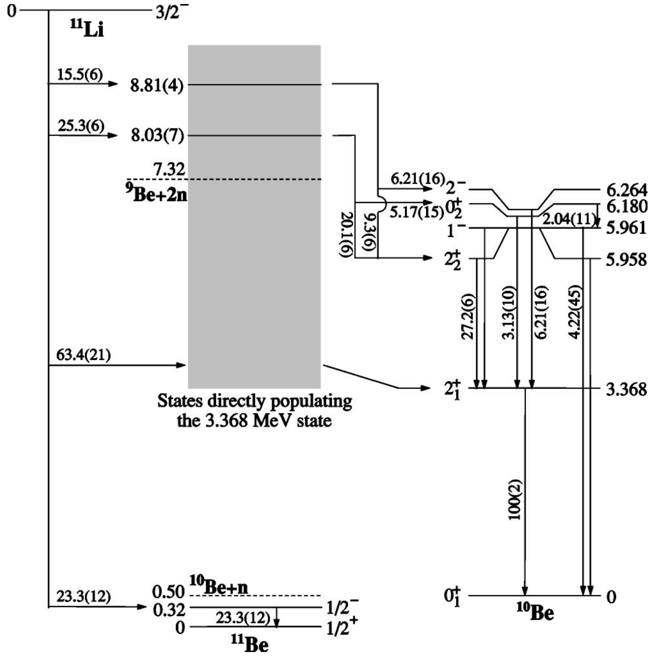

FIG. 2. Decay scheme of ^{11}Li deduced from this work. The energies of the first two excited states in ^{10}Be were taken from [11]. All transitions are labeled with γ-ray intensities, normalized to the 3367 keV transition (100). The intensity breakdown of the decay of the $(1^-,2_2^+)$ doublet can be found in Table I.

whereas the γ-ray emission from the 0_2^+ state is naturally isotropic. The remaining free parameters are the energy E_γ of the transition, the half-life $T_{1/2}$ of its state of origin, and the energy of the neutron that gives rise to the observed Doppler broadening (or the excitation energy E_X of the parent state in ^{11}Be).

The line shapes of both peaks were produced in the Monte Carlo simulation as a function of E_γ, $T_{1/2}$, and E_X, and compared to the data using a χ^2 minimization method. The procedure was iterated until the minimum was found for the best triplet (E_γ, E_X, $T_{1/2}$) that fits the data; acceptable fits (reduced $\chi^2/\nu\sim 1$) were obtained for both transitions. For the 6180 keV, 0_2^+ state, the half-life was found to be $T_{1/2}=870\pm 70(\text{stat})\pm 160(\text{syst})$ fs, consistent with the previous published value of 800^{+300}_{-200} fs [10,11], for a neutron originating from an 8.03(7) MeV state in ^{11}Be. Similarly, for the 6264 keV, 2^- state, the half-life was found to be $T_{1/2}=85\pm 6(\text{stat})\pm 10(\text{syst})$ fs for a neutron originating from an 8.81(4)MeV state in ^{11}Be. The systematic error on the half-lives was estimated by considering a ±10% deviation from the SRIM tabulated energy loss of ^{10}Be in aluminum. The best fits for the 2812 and 2896 keV transitions are shown in Fig. 3. No need was found to add any other neutron branch to fit the experimental line shape of either transition. This analysis unambiguously confirms the existence of the 8.03 MeV state suggested by Aoi [8] (but not confirmed by Morrissey [6]). Furthermore, the uncertainties in the excitation energies of the parent states in ^{11}Be obtained in this experiment are, remarkably, comparable to those obtained from neutron spectroscopy experiments.

The analysis of the transitions originating from the $(1^-,2_2^+)$ doublet of states is more complex, because it involves the indirect feeding of the 1^- state from the 0_2^+ state as well as the direct feeding of one or both states of the doublet. We note that the branching ratios from the 2_2^+ and 1^- states to the 2_1^+ state were previously found to be $>90\%$ and $17^{+6}_{-10}\%$ respectively [10,11]. The relative intensities of the 2590 and 5957 keV transitions observed in the present experiment (see Fig. 2) strongly suggest that most, if not all, of the direct feeding proceeds through the 2_2^+ member of the doublet. We

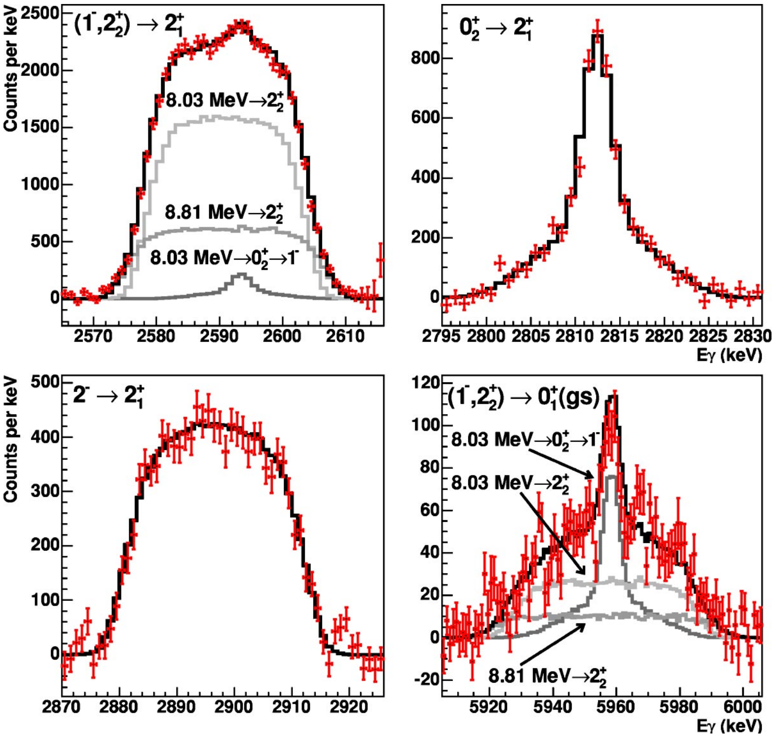

FIG. 3. (Color online) Comparison between the experimental data and the best-fit obtained by the Monte Carlo simulation (black line). For the transitions involving the $(1^-,2_2^+)$ doublet, the three contributions discussed in the text are also shown.

did not find any compelling evidence that the 1^- state is directly populated. For example, adding a direct feeding component to the 1^- state provokes a shift in the center of gravity of the simulated 2590 keV transition line shape, resulting in a larger χ^2. The analysis is, however, limited by the relatively poor quality of the 5957 keV transition line shape, which would be the most sensitive to a 1^- direct branch. We disagree with the analysis of [9], which assumes that a direct feeding of the 1^- state is responsible for the broad component of the 5957 keV transition. In our case, this broad component is attributed to the direct feeding of the 2_2^+ state. In principle, the half-life of the 1^- state could be deduced from the analysis of the sharp component of the 5957 keV transition. However, this line shape is dominated by the effect of the half-life of the 0_2^+ state. We can only presume that the half-life of the 1^- state is smaller than a few hundred femtoseconds.

The parity change necessary to connect the states in ^{11}Be, fed by the β decay of ^{11}Li, to the 2_2^+ state in ^{10}Be implies the emission of an odd-ℓ neutron, most likely $\ell=1$. It is therefore necessary to consider angular correlation effects. Careful analysis of these effects shows a strong correlation of the half-life with the A_2 parameter, as defined in [19], but no significant correlation with the other free parameters of the simulation: E_γ, E_X and, in this case, the branching ratios. Therefore, the simulations were first performed assuming no angular correlation ($A_2=0$). It was found that the neutron branch from the 8.03 MeV state suggested by [8] cannot account for all the Doppler broadening of the 2590 keV peak, resulting in a poor $\chi^2/\nu\sim 8$. The situation is greatly improved ($\chi^2/\nu\sim 1$) by adding a neutron branch from the 8.81 MeV state with an appropriate intensity. The excitation energy of the 1^- state was deduced from the centroid of the indirect contribution of the 0_2^+ state to the 2590 keV line shape. The best fit is obtained with a half-life of $T_{1/2}=60.0\pm 1.6(\text{stat})\pm 6.0(\text{syst})$ fs for the 5958 keV, 2_2^+ state. The line shape of the 5957 keV peak was fit using this half-life and neutron branching ratios determined for the $2_2^+\rightarrow 2_1^+$ transition together with the intensities of the $2_2^+\rightarrow 0_1^+$ and $1^-\rightarrow 0_1^+$ transitions as free parameters. The best overall fit was obtained for intensities corresponding to branching ratios of $10\pm 3\%$ and $65\pm 15\%$, respectively in agreement with previously measured values $<10\%$ and $83_{-6}^{+10}\%$ [10,11]. The best fits (with $A_2=0$) for both transitions and the individual contributions of the three separate components to the line shapes, are shown in Fig. 3. At this point, we note that the 8.03 MeV state in ^{11}Be is likely a $3/2^-$ state as it feeds both the 0_2^+ and the 2_2^+ states, which could be reached by an $\ell=1$ neutron. A $1/2^-$ or $5/2^-$ assignment is unlikely since it would require an $\ell=3$ neutron to reach one of the two states.

The effect of the n-γ angular correlation was studied using the half-life and A_2 value as the only free parameters. The range of A_2 values corresponding to a mixed E_2/M_1 transition ($-0.68<A_2<0.68$) was obtained from [19]. Assuming the worst case scenario that both neutron decay branches have angular correlations with the same sign of A_2, the minimum $\chi^2/\nu=0.9$ is obtained for $A_2=0\pm 0.07$ corresponding to a half-life of 60 ± 10 fs (stat+syst). We note that although this range of A_2 values is consistent with that of a pure $E2$ transition, this possibility can be ruled out because of the corresponding large $B(E2;\, 2_2^+\rightarrow 2_1^+)$ of about 57 Weisskopf units (W.u.).

The remainder of this paper focuses on the interpretation of the information obtained for the 2^- and 2_2^+ states in ^{10}Be and discusses the nature of the 8.81 MeV state in ^{11}Be. The likely molecularlike structures of the four excited states in ^{10}Be ($2_2^+, 1^-, 0_2^+, 2^-$) lying just below the ^{9}Be$+n$ and ^{6}He$+\alpha$ thresholds have recently been investigated in various theoretical studies [20–23]. The dominant structure of the two states ($2_2^+, 2^-$) fed by the neutron decay from the 8.81 MeV state in ^{11}Be is found to be $^9\text{Be}\otimes 1s_{1/2}$ for the 2^- state and $^9\text{Be}\otimes 0p_{1/2}$ for the 2_2^+ state, i.e., a valence neutron, in a relative s or p wave, loosely bound to a ^{9}Be core, possibly in a halolike spatial distribution [21]. Recent work on the one-neutron knockout reaction (^{11}Be, ^{10}Be) has suggested that the 2^- state is populated when a $p_{3/2}$ neutron is removed from the ^{10}Be core, leaving the $1s_{1/2}$ valence (halo) neutron intact [24], suggesting that this state in ^{10}Be might be an excited state halo as proposed by [25]. Indeed, it shows remarkable similarity to the ground state of ^{11}Be with a single valence neutron in a $1s_{1/2}$ state bound by about 0.5 MeV to a ^{9}Be (^{10}Be) core. Can we understand the structure of the 2_2^+ and 2^- states in ^{10}Be in light of our β-decay study of ^{11}Li?

It has been suggested [5] that if the β decay of a halo nucleus takes place within its core then it is possible for the halo wave function to retain its features after the β decay, even though the core may now have a rather different structure. The excitation energy of such a daughter state should then be roughly equal to the difference in Q values of the decaying halo nucleus and its core. The 8.81 MeV state in ^{11}Be is a strong candidate for just such a state and would thus have a large overlap with a ^{9}Be$+n+n$ configuration. Support for this is provided from studies of the β-delayed two-neutron decay of ^{11}Li, which is suggested to originate in part from this state [26,27]. In addition, this state is strongly populated in $2n$-transfer reactions (see [28] and references therein). It is, however, clearly in contradiction to the interpretation [20,28] that this state is part of a rotational band with a spin of $9/2^-$. The ^{9}Be core cannot be in its ground state, because this state lies 1.49 MeV above the ^{9}Be$+2n$ threshold. The 8.81 MeV state can however be built around a ^{9}Be excited state plus two neutrons coupled to spin 0, namely the $5/2^-$ state located 2.429 MeV above the ground state of ^{9}Be. The Q_β of $^{11}\text{Li}-^{11}\text{Be}$ (8.81 MeV) and $^9\text{Li}-^9\text{Be}$ ($5/2^-$) are only 635 keV apart. A $5/2^-$ spin assignment for the 8.81 MeV state would explain why we do not observe any decay of the 8.81 MeV state in ^{11}Be to the 1^- state in ^{10}Be, which is believed to have a similar structure to the 2^- state [21]. Instead, we observe its decay via single-neutron emission to just two bound excited states in ^{10}Be: the 2_2^+ and the 2^- states with ^{9}Be$+n$ separation energies of 854 and 548 keV, respectively. In each case, we suggest it is one of the original ^{11}Li halo neutrons (55(10)% $(0p_{1/2})^2$, 45(10)% $(1s_{1/2})^2$ [29]) that is emitted from the 8.81 MeV state in ^{11}Be, with the surviving valence neutron remaining in its $0p_{1/2}$ or $1s_{1/2}$ state and contributing to the structure of the 2_2^+ or 2^- states in ^{10}Be, respectively. Indeed, shell model calculations by Brown [30] show that the 2_2^+ and 2^- states have a strong

$5/2^-$ core component coupled with a $p_{1/2}$ and $s_{1/2}$ neutron, respectively. Note that we here neglect a possible (small) $(d_{5/2})^2$ component in the ^{11}Li wave function, which could also populate the 2^- state via $\ell=2$ neutron emission.

The possible halolike structure of the 2^- state in ^{10}Be deserves special mention here as it is the best candidate to date of an excited neutron halo state. Our half-life measurement of $T_{1/2}=85\pm12$ fs corresponds to an experimental $B(E1;2^-\rightarrow2_1^+)=7.7\times10^{-4}$ W.u. This value disagrees with the (preliminary) theoretical estimate of 0.02 W.u. obtained within a microscopic four cluster $(\alpha+\alpha+n+n)$ model using the resonating group method [31]. However, such a discrepancy is not surprising given the weakness of this transition. The theoretical value depends very sensitively on details of the wave functions of the two states involved; further theoretical work is in progress.

In summary, we have investigated the β decay of ^{11}Li through the study of the Doppler-broadened transitions in ^{10}Be observed in the β-delayed one-neutron emission of ^{11}Li. From the line-shape analysis of these transitions, we determined both the energies of the states in ^{11}Be feeding the excited states in ^{10}Be and also the half-life of some of these ^{10}Be excited states. We also find that the β decay of ^{11}Li to the 8.81 MeV state in ^{11}Be is likely to occur in the ^{9}Li core, leaving the two original halo neutrons of ^{11}Li unperturbed. The 8.81 MeV state is interpreted as a ^{9}Be $(5/2^-)$ core plus the two surviving halo neutrons coupled to spin 0. The one-neutron emission paths from the 8.81 MeV state in ^{11}Be are consistent with the emission of one of the two halo neutrons and provide a supporting evidence that the 2_2^+ and 2^- states in ^{10}Be have a halolike character, as predicted by various theoretical models.

This work was partially supported by the Natural Sciences and Engineering Research Council of Canada and the U.S. Department of Energy through Grant/Contract Nos. DE-FG03-93ER40789 (Colorado School of Mines), DE-FG02-96ER40958 (Georgia Tech) and W-7405-ENG-48 (University of California, Lawrence Livermore National Laboratory). We would like to thank the staff of the ISAC facility for their work in delivering the high-quality ^{11}Li beam. TRIUMF receives federal funding via a contribution agreement through the National Research Council of Canada.

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