Elucidating halo structure by β decay: $\beta\gamma$ from the ^{11}Li decay

M. J. G. Borge,[1] H. Fynbo,[2] D. Guillemaud-Mueller,[3] P. Hornshøj,[2] F. Humbert,[4] B. Jonson,[5] T. E. Leth,[2]
G. Martínez-Pinedo,[6] T. Nilsson,[5] G. Nyman,[5] A. Poves,[6] I. Ramos-Lerate,[1] K. Riisager,[2] G. Schrieder,[4] M. Smedberg,[5]
O. Tengblad,[7] and the ISOLDE Collaboration
[1]*Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain*
[2]*Institut for Fysik og Astronomi, Aarhus Universitet, DK-8000 Aarhus C, Denmark*
[3]*Institut de Physique Nucléaire, IN2P3-CNRS, F-91406 Orsay Cedex, France*
[4]*Institut für Kernphysik, Technische Hochschule, D-64289 Darmstadt, Germany*
[5]*Fysiska Institutionen, Chalmers Tekniska Högskola, S-41296 Göteborg, Sweden*
[6]*Departamento de Física Teórica, Universidad Autónoma de Madrid, E-28049 Madrid, Spain*
[7]*PPE Division, CERN, CH-1211 Genève 23, Switzerland*

(Received 15 July 1996)

New values for the γ ray intensities following the β decay of ^{11}Li are presented. Special emphasis is put on the determination of the Gamow-Teller transition $^{11}\mathrm{Li} \rightarrow {}^{11}\mathrm{Be}$ ($1/2^-$, 320 keV) to the only bound excited state in ^{11}Be. We show that a shell-model calculation can simultaneously reproduce the half-life of ^{11}Li and the newly measured branching ratio to the $1/2^-$ state provided the ^{11}Li ground state wave function contains about 50% of s-wave neutron components. [S0556-2813(97)50301-3]

PACS number(s): 23.40.Hc, 21.10.Pc, 21.60.Cs, 23.20.Lv

This paper presents new data on γ rays following the β decay of ^{11}Li. Contrary to predictions [1], this nucleus was identified in 1966 [2] to be bound. The first spectroscopic information was obtained nine years later [3] at PS (CERN) where the mass excess, two-neutron separation, and half-life were determined. In the following nine years the β decay studies of ^{11}Li have uncovered many different decay modes: β2n [4], β3n [5], β^6He [6], and βt [7]. All were first observed in the decay of ^{11}Li.

In 1985, Tanihata *et al.* [8] observed that the ratio of the matter-to-charge radius of ^{11}Li is abnormally large. The modeling of this nucleus as a core of ^{9}Li surrounded by two distant neutrons [9] opened a new field of research: halo nuclei. This subject has become a very attractive topic in nuclear physics in the last decade (see the recent reviews in the field [10] and references therein). The halo structure, which is investigated through nuclear reaction studies, still present challenges: a good understanding of the two neutron halo wave function has not yet been achieved.

Because the weak interaction is well understood, we have decided to investigate the role played by the halo in the β decay and vice versa. We try to obtain information about the wave function of the last two neutrons from the observed β feeding to the different states in ^{11}Be. Various estimates [11–15] indicate the presence of a substantial amount of $1s_{1/2}$ components in the halo of ^{11}Li. These components play a crucial role in the β decay of ^{11}Li and may determine the branching ratio to the unique bound excited state in ^{11}Be. Since the two previously published measurements of this branching ratio gave very different values, 5.2(14)% [16] and 9.2(7)% [17], and since this transition is sensitive to the structure of the ^{11}Li ground state, we have decided to remeasure the γ spectrum following the decay of ^{11}Li.

The experiment was performed at the PSB-ISOLDE (CERN) facility. The ^{11}Li beam was produced by bombarding a 80 g/cm^2 Ta target with a 2.4 μs proton beam pulse of 1 GeV energy. It was then ionized on a W surface and accelerated to 60 keV for transport and mass separation. Two different experiments were performed in order to study the $\beta\gamma$ branches of the ^{11}Li decay. In one experiment the ^{11}Li beam was stopped in an aluminum foil. A plastic scintillator to detect β particles and a HPGe detector for γ's were situated close to the collection point, but outside the vacuum chamber. The Ge detector was background shielded by a 2–3 mm thick lead sheet. An 8 mm thick Al absorber was placed in front of the Ge detector, since backscattering of β's in the detector gave a considerable distortion of the γ lines. Spectra of β-gated γ's, γ singles, and time-gated (first 100 ms after the proton pulse) β's and γ's were recorded. An off-line analysis showed that the β efficiency was energy dependent. We repeated this part of the experiment to more reliably extract the branching ratio to the 320 keV level. The information from both experiments was used to determine the

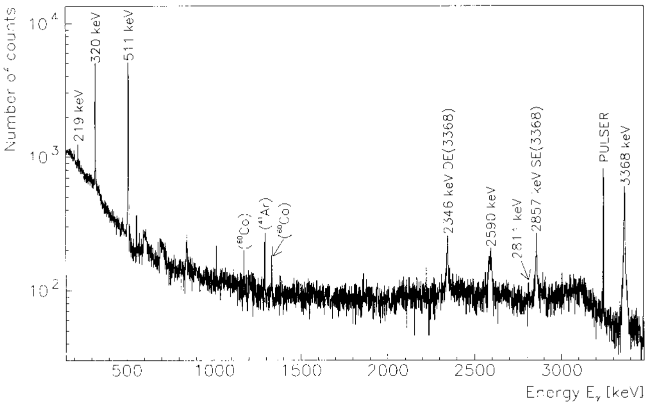

FIG. 1. Time-gated (gate=100 ms/proton pulse) ^{11}Li γ spectrum. The time-gate enhance the contamination lines produced by Ge(n,n') reactions as seen in the energy range from 550 to 1100 keV.

TABLE I. γ intensities from the β decay of ^{11}Li.

E_γ	Energy Levels (keV)		I_γ %	
(keV)	$E_i \rightarrow E_f$ (Ref. [29])	This work	Ref. [16]	Ref. [17]
219	6179.3→5959.9 in ^{10}Be	0.55 (10)	0.95 (35)	-
320	320.0→ 0.0 in ^{11}Be	6.3 (6)	5.2 (14)	9.2 (7)
2590	5958.3→3368.0 in ^{10}Be	8.0 (12)	3.5 (10)	-
2811	6179.3→3368.0 in ^{10}Be	0.8 (2)	1.6 (7)	-
3368	3368.0→ 0.0 in ^{10}Be	29 (3)	21 (6)	35 (3)

relative intensities of the γ emissions following the decay.

In the second experiment the ^{11}Li beam traversed a 1000 μm thick 300 mm^2 annular Si detector and was then stopped in a 2 mm Al plate. An HPGe was placed outside the chamber behind a 10.6 mm thick Al flange. β particles, γ rays, and corresponding time information were recorded in coincidences as well as in singles.

In both experiments a commercially available calibrated mixed source was used for efficiency determination. A ^{56}Co source was used to obtain a more precise determination of the efficiency at high energies. A ^{106}Ru source was used to calibrate the β-γ coincidence efficiency. Calibration spectra recorded in ‘‘self-gate’’ mode yielded the efficiency of the coincidence setup at different energies. Furthermore, the ratio $N_{\beta\gamma}/N_\gamma = 0.14(1)$ from different γ transitions following the ^{11}Li decay is in good agreement with the calculated geometrical solid angle of 15% for the surface barrier β detector. This demonstrates that the intrinsic efficiency of the β detector was approximately constant at 100% over the full-energy range of interest.

The intensity ratio between the 320 keV γ line and the 2125 keV γ line (following the ^{11}Be β decay) showed that ^{11}Be was directly produced and ionized. This amounted to 7.3(18)% of the $A=11$ beam. Up to 10% contamination of the alkali-earth elements is not unusual when this type of target-ion source unit is used. The branching ratio for the feeding from the ^{11}Li$(3/2^-)$ ground state to the 320 keV excited level $(1/2^-)$ in ^{11}Be is found by normalizing with the known total ^{11}Be 2125 γ-ray intensity ratio of 0.355(18) [18]. Our result, $b(320)$ = 6.3(6)%,[1] together with a Q_β value of 20.62(3) MeV [19] and a $T_{1/2}$ of 8.35(14) ms (weighted averaged of the values given in Ref. [21] and Ref. [20]) gives a $\log ft$ equal to 5.73.

Figure 1 shows the γ spectrum and Table I lists the energies and intensities of the main γ rays following the ^{11}Li decay. The intensities presented in this table are weighted averages of the values obtained with the two described setups. The assignment of the 2590 keV γ transition followed Ref. [20]. The results of Détraz *et al.* [16] are in reasonable agreement with our present values, except for the 2590 keV γ line. This is a very broad peak as seen in Fig. 1 and it has a very different shape than the 3368 keV γ line. The shape of these γ lines is determined by the Doppler broadening produced by the recoiling of the excited ^{10}Be nuclei populated in βn emission. From the shape of the peak of these γ lines, we can deduce the recoil energy of the excited ^{10}Be nuclei and consequently the levels in ^{11}Be from which the neutron was emitted. This method constitutes an interesting tool in the study of βn emission and the GT strength of the ^{11}Li β decay (Ref. [21,22]).

The new value for the branching ratio to the 320 keV state in ^{11}Be modifies the P_{in} values for $i=1,2,3$. The ratios $P_{2n}/P_{1n}=0.048(5)$ and $P_{3n}/P_{1n}=0.022(2)$ are taken from Ref. [5,17], respectively. If we neglect the contribution of the decay to the ground state of ^{11}Be as well as that of the βt [7] and βd [21] branches (in the order of 10^{-4}), we find

$$1-b(320)=P_{1n}+P_{2n}+P_{3n}, \tag{1}$$

which gives the following new values for the different P_{in} branches:

$$P_{1n}=87.6(8)\%,$$

$$P_{2n}=4.2(4)\%,$$

$$P_{3n}=1.9(2)\%.$$

From the experimental half-life, $T_{1/2}=8.35(14)$ ms, and branching ratio, $\mathrm{BR}(1/2^-)=6.3(6)\%$, we can extract the ‘‘experimental’’ value of the reduced Gamow-Teller transition probability to the 320 keV level in ^{11}Be from,

$$B(\mathrm{GT})=\frac{6146(6)(\mathrm{Ref.}[23])}{ft}, \tag{2}$$

and

$$B(\mathrm{GT})=\left(\frac{g_A}{g_V}\right)^2\langle\boldsymbol{\sigma\tau}\rangle^2, \quad \langle\boldsymbol{\sigma\tau}\rangle=\frac{\langle f||\sum_k \boldsymbol{\sigma}^k \boldsymbol{t}_\pm^k||i\rangle}{\sqrt{2J_i+1}}, \tag{3}$$

giving $B(\mathrm{GT})=0.011$.

A shell-model calculation assuming a core of ^{4}He and valence particles in the p shell with the interaction of Ref. [24] gives the following predictions: $B(\mathrm{GT})=0.216$ and $T_{1/2}=1.45$ ms (using the bare GT operator) or, $B(\mathrm{GT})=0.149$ and $T_{1/2}=2.10$ ms (using the quenching factor 0.83 as in Ref. [25]).

In order to explain these very large discrepancies, we shall proceed in a way similar to that of Suzuki and Otsuka in Ref. [14], trying to understand not only the $B(\mathrm{GT})$ value, as they did, but also the half-life. Indeed, we shall use the new experimental value of the branching ratio.

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[1] We cannot explain the discrepancy with the value of Ref. [17] since too few experimental details were given there.

TABLE II. The half-life of ^{11}Li and the B(GT) value to the 320 keV level of ^{11}Be for different percentages of closed p shell.

Interaction	g_A	$1s_{1/2}$ neutron shell occupancy	% of closed p shell	Overlap $\langle 0p^{\pi}_{3/2}\vert 0p^{\nu}_{1/2}\rangle$	B(GT)	$T_{1/2}$ ms
WBT/LKS	1.05	1.21	11	1.00	0.011	8.3
WBT/LKS	1.05	1.06	21	0.84	0.011	8.2
WBT/LKS	1.15	1.15	15	0.84	0.010	7.6
MK	1.15	0.74	20	0.84	0.012	11.7
				EXP	0.011	8.35

We start by assuming that the p-shell description is adequate. Therefore, the neutron halo in ^{11}Li will be produced by the neutron $0p_{1/2}$ orbit and there will be a mismatch with the proton p orbits in ^{11}Be. Hence, the GT transition probability will be reduced. It is extremely difficult to get a reliable estimate of the overlap between these orbits. To generate the radial wave functions, we have used a Woods-Saxon well, with parameters taken from Ref. [26], except for $a = 0.57$ fm. The resulting $0p_{1/2}$ neutron orbit in ^{11}Li has $\langle r^2\rangle^{1/2} = 5.0$ fm while the proton p orbits in ^{11}Be have $\langle r^2\rangle^{1/2} = 2.6$ fm. The overlap between them is 0.84. With these values of the overlaps and the renormalized value $g_A = 0.83 g_A(\text{bare}) = 1.05$ we obtain: $B(\text{GT}) = 0.070$ and $T_{1/2} = 3.4$ ms; still very far from the experimental results. Agreement could only be obtained for unrealistic values of the overlaps (smaller than 0.6).

We are thus led to go beyond a pure p-shell description, i.e., we have to allow for sd components in the description of ^{11}Li and ^{11}Be. We have made unrestricted shell-model calculations in the space spanned by the orbits $0p_{3/2}$, $0p_{1/2}$, $0d_{5/2}$, and $1s_{1/2}$, using an effective interaction that consists of the p-shell part of the WBT interaction [24], and the LKS interaction [27] for the sd shell and the cross shell matrix eleents (WBT/LKS). The resulting ^{11}Li wave function has the following structure in the valence space,

$$\Phi = \alpha[(0p_{3/2})^{\pi},(0p_{3/2})^{4\nu},(0p_{1/2})^{2\nu}] + \beta[(0p_{3/2})^{\pi},(0p_{3/2},0p_{1/2})^{n_1\nu}(1s_{1/2},0d_{5/2})^{n_2\nu}] \quad (4)$$

(ν neutron, π proton, $n_1 + n_2 = 6$).

In order to explore the influence of the sd components in both the half-life of ^{11}Li and the branching ratio to the 320 keV state in ^{11}Be, we have varied the energy gap between the p and the sd shells—and, consequently, the percentage of closed p shell—until the best possible agreement with experiment is achieved. This has been done for different values of the overlap and for different values of g_A. We have also made calculations using the interaction of Millener and Kurath (MK) [28]. This interaction tends to give a lesser occupancy of the $1s_{1/2}$ neutron shell, in favor of the $0d_{5/2}$ neutron shell, but their predictions are still compatible with those of the WBT/LKS interaction. The results are shown in Table II. The percentage of configurations with two neutrons in the $1s_{1/2}$ neutron orbit is around 40% for the different WBT/LKS cases and 30% for MK. It is evident that the β decay data demand a small percentage of closed (neutron) p shell in the ground state of ^{11}Li correlated with a large occupancy of the $1s_{1/2}$ neutron orbit. The occupation numbers of the neutron orbits are on average 3.5, 1.0, 1.0, and 0.5 for the $0p_{3/2}$, $0p_{1/2}$, $1s_{1/2}$, and $0d_{5/2}$, respectively. Therefore, in this picture the halo is dominantly ($\approx 50\%$) s wave. Notice that this qualitative conclusion pertains to any of the entries of Table II. Our results do not contradict those of Ref. [14], but we predict more sd mixing than they do, partly due to the new value of the branching ratio.

In conclusion, we have remeasured the γ activity from the ^{11}Li decay giving special attention to the determination of the GT strength to the 320 keV state in ^{11}Be due to the relevance of this transition in the study of the $2n$ halo wave function of ^{11}Li. Our calculation shows that a substantial s-wave neutron component ($\approx 50\%$) is needed in order to bring theory and experiment into agreement for the half-life and for the branching ratio of the decay of ^{11}Li to the first excited state of ^{11}Be.

Financial support for this study from the Spanish CICyT (Contract AEN94-0833-C02-02) and DGICyT (Contract PB93-263) and Bundesministerium für Forschung und Technologie (contract No. 06DA665I) is gratefully acknowledged.

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