New Binding Energy for the Two-Neutron Halo of ^{11}Li

C. Bachelet,[1] G. Audi,[1] C. Gaulard,[1] C. Guénaut,[1] F. Herfurth,[2] D. Lunney,[1,*] M. de Saint Simon,[1] and C. Thibault[1]

[1]*Centre de Spectrométrie Nucléaire et de Spectrométrie de Masse (CSNSM), IN2P3-CNRS-Université Paris-Sud 11, 91405 Orsay, France*

[2]*GSI, Planckstrasse 1, 64291 Darmstadt, Germany*

(Received 22 January 2008; published 6 May 2008)

The extended radius of a halo nuclide is very sensitive to the minute binding energy of its valence nucleons. The binding energy of ^{11}Li has been measured with high precision by using the radio-frequency spectrometer MISTRAL at CERN's ISOLDE facility. The new two-neutron separation energy of 378 ± 5 keV is 25% higher than the previously accepted value with an uncertainty 5 times smaller.

DOI: 10.1103/PhysRevLett.100.182501 PACS numbers: 21.10.Dr, 21.10.Gv, 27.20.+n, 29.30.Aj

Maverick neutrons, roaming well beyond classical confines dictated by the strong interaction, form so-called nuclear halos. The understanding of such systems continues to defy the considerable scientific efforts focused upon them in the past two decades (described in recent reviews by Jonson [1] and Jensen *et al.* [2]). While the original, and most famous, halo nuclide is ^{11}Li, other halo nuclides are now under scrutiny: ^{6}He, ^{11}Be, ^{14}Be, and ^{19}C. The first production of ^{11}Li was reported by Poskanzer *et al.* in 1966 [3], and its special spatial properties were discovered by Tanihata *et al.* in 1985 [4]. ^{11}Li belongs to a special category of halos called Borromean, a term introduced by M. Zhukov after the heraldic symbol of the Borromeo family showing three rings linked in such a way that breaking one link frees the other two. Such is the case with the bound ^{11}Li system and unbound subsystems: a dineutron and ^{10}Li.

The Borromean nature of the two-neutron halo of ^{11}Li makes the comprehension of its three-body binding mechanism one of the most intriguing problems of nuclear structure. The halo of ^{11}Li hangs in fragile equilibrium since its two-neutron separation energy (S_{2n}) is only a few hundred keV—more than an order of magnitude smaller than stable nuclei and the lowest of all bound nuclear systems. The radial wave function of the two-neutron halo depends critically on its binding energy to the core. As such, the S_{2n} is an input parameter to many nuclear halo models, most often used to adjust the ^{9}Li-n interaction (see, for example, [5–8], to name a few, and also the review by Jensen *et al.* [2]). The halo binding energy also strongly conditions the halo dynamics, particularly its soft electric-dipole excitation (unique to halo nuclides), as recently shown by Nakamura *et al.* [9], and also its breakup, as described by Orr *et al.* [10], and its nuclear charge radius, recently determined with precision laser spectroscopy by Sanchez *et al.* [11].

Borromean nature seems to be governed largely by pairing. Pairing energies are very small compared to the mass—almost on the scale of the neutron-separation energy for ^{11}Li. This alone makes a precision determination difficult since the quantity in question is small. Added to this is the very short half-life of only 8.75 ms as well as the minute production rate. In this Letter, we report on a new, direct measurement of this important quantity and its surprising result.

The measurement was performed by the radio-frequency transmission spectrometer MISTRAL, located at CERN's low-energy rare isotope facility ISOLDE [12]. The MISTRAL spectrometer (illustrated in Fig. 1) was designed specifically for mass measurements of the shortest-lived nuclides (see [13–16] for technical descriptions). Since the beam is not stopped in any way, the only temporal limitation for a measurement is the time of flight through the apparatus (< 100 μs). The mass m is determined by comparing the cyclotron frequency $f = qB/2\pi m$ of an ion (with charge q) injected into the spectrometer's homogenous magnetic field B to the cyclotron frequency f_r of a reference mass m_r. The latter is alternately sent along the same trajectory (shown in the inset in Fig. 1) with a kinetic energy inversely proportional to its mass in order to keep B constant during the measurement. By using a radio-frequency voltage to modulate the kinetic energy of the injected beam, transmission peaks (shown in the inset in Fig. 1) are produced by scanning the frequency over an integer-plus-one-half (high) harmonic of the cyclotron frequency. A resolving power of over 100 000 has been obtained, and measurements have been made with uncertainties down to a few parts in 10^{-7} (see [16–19]).

The ISOLDE facility has a large catalog of targets that create exotic nuclides when bombarded by a pulsed 1.4-GeV proton beam. For this measurement, a 2-micron-thin Ta-foil target was used which favors release of the short-lived, surface-ionized ^{11}Li [20]. The ^{11}Li yield from this target (with proton intensity limited to 2×10^{13}/pulse to prolong the target lifetime) was roughly 2000 ions/pulse at the beginning of the experiment, falling to less than half of this after two days. The mass of ^{11}Li was measured in two experiments. In the first, the beam was delivered from the ISOLDE high-resolution separator, which consists of two magnetic-separation stages. Calibration uncertainties with both magnets in the $A = 7$–11 mass range caused great problems as well as a mass-dependent beam trans-

 © 2008 The American Physical Society

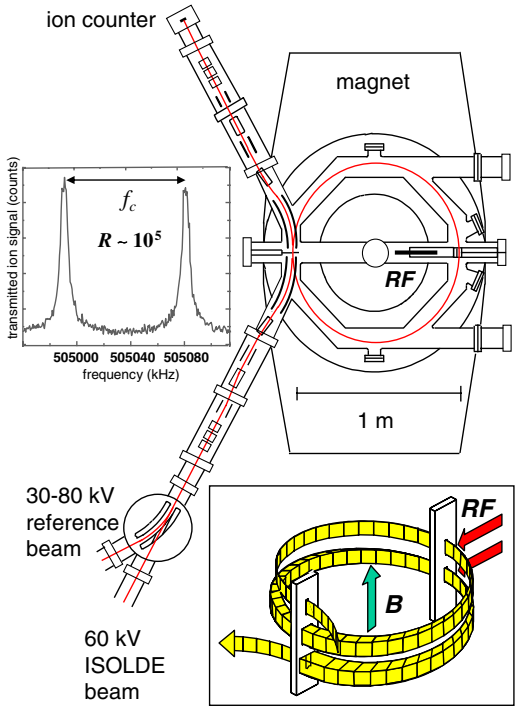

FIG. 1 (color online). Layout of the MISTRAL spectrometer (overhead view). The ion beams (coming from the bottom) are injected either from the ISOLDE beam line (at 60 keV) or from a reference ion source (variable energy). The inset (bottom) shows an isometric view of the trajectory envelope with the 0.4 mm injection slit followed by the first modulator at one-half turn, an opening to accommodate the modulated-ion trajectories at one turn, the second modulator at three-half turns, and then the exit slit. The inset (left) shows the transmitted-ion signal over two harmonics for a reference ion.

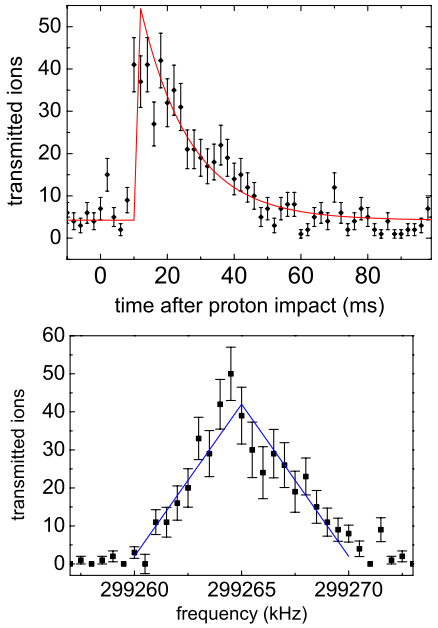

FIG. 2 (color online). (Top) Time profile of the transmitted ^{11}Li ions that shows the release curve of ^{11}Li from the Ta-foil target, dominated by the 8.6-ms half-life. An exponential fit yields a half-life of 10 ± 2 ms, strong confirmation that the measured peak is indeed that of ^{11}Li. (Bottom) Transmitted ^{11}Li ions plotted versus modulation frequency and fit with the theoretically expected line shape [25]. Resolving power is 57 170.

port, resulting in a paucity of statistics. (Note that a preliminary, unpublished result of that experiment was too-hastily communicated for citation in Ref. [1] and included in the 2003 Atomic Mass Evaluation (AME) [21]. The full analysis yielded a result with a much larger uncertainty, making it compatible with the one reported here. These points are detailed in Refs. [22,23].) The experiment was repeated by using the more forgiving general-purpose separator, combined with the powerful technique of laser ionization, which provided a pilot beam of ^{11}Be. These more favorable conditions and statistics are reported here. Note that a preliminary value of this result appeared in a short conference proceedings [24].

Figure 2 (bottom) shows a reconstructed mass peak of the short-lived ^{11}Li nuclide. This spectrum contains 472 ions from 100 scans. The fit to the theoretically expected line shape [25] gives the center position of the 917th harmonic of the cyclotron frequency with a resolving power of over 57 000. A systematic analysis was performed of peak position versus number of channels grouped comparing the resolving power with that of the reference scan. Seven such measurements were made. The proton beam used at the ISOLDE facility is pulsed, which gives rise to a pronounced time structure in the yield, a so-called release curve that is characteristic of the element, and the target matrix [26]. Though lithium has a fast release time from the tantalum-foil target, the ^{11}Li release profile shown in Fig. 2 (top) is dominated by the much-shorter half-life. The fit shown corresponds to a half-life of 10 ± 2 ms. This gives confidence in attributing the mass peak to ^{11}Li. The frequency spectrum is accumulated by using one proton pulse per frequency bin. The order is random so as to avoid any bias in pulse-to-pulse intensity variation. After each complete spectrum, a (continuous) ^{11}B-reference scan is performed to avoid any error due to long-term drift of the magnetic field.

The mass of ^{11}Li is determined by comparison with the reference scans as well as a calibration procedure using other combinations of nuclides with well-known masses. The analysis of previous measurements with MISTRAL [16,17] revealed a systematic deviation of the results proportional to the relative mass-doublet difference accompanied by an offset, due to different magnetic fields seen by ions with different origins that are transmitted at different energies. The calibration for the present measurement was performed by using the stable nuclides ^{10}B and ^{11}B from the off-line ion source compared with ^{9}Li, ^{9}Be, and ^{10}Be from ISOLDE. Measurements were performed over the duration of the experiment, by using different combinations in order to have an overdetermined set. Originally, two methods (detailed in Ref. [22]) were used to correct for this systematic effect. In the so-called ''global'' calibra-

tion, all of the measurements were treated as a whole, and an average corrected ^{11}Li relative mass difference with respect to the tabulated value [27] of $-74.2 \pm 4.6 \times 10^{-7}$ was obtained. In the so-called "local" approach, each of the ^{11}Li measurements is corrected by the calibration scans taken at the closest time interval. The local corrections are derived either from a linear fit (as above), if the doublets differ in mass number, or by using the offset of the $A = 10$ (^{10}B-^{10}Be) doublet to correct the $A = 11$ (^{11}B–^{11}Li) doublet (this procedure was confirmed by using ^{76}Ge–^{76}Rb to calibrate ^{74}Ge–^{74}Rb in Ref. [19]). The average corrected value for ^{11}Li is $-74.0 \pm 5.2 \times 10^{-7}$, consistent with the global approach.

The ^{11}Li resonance shown in Fig. 2 has an uncertainty of 4.1×10^{-7} derived from statistics and magnetic field fluctuations (see [17]). Though reference scans and calibration measurements were performed during the experiment, the corrected ^{11}Li values still showed a nonstatistical scatter. Therefore, an additional error of 9×10^{-7} was added in quadrature to each measurement in order to achieve a Birge ratio of unity for the weighted average. The individual corrected measurements, with the total uncertainty, are plotted in Fig. 3 versus the relative mass difference with respect to the tabulated value [27].

An additional, independent analysis has also been performed [23], by following the prescriptions described in Ref. [17]. It again uses a global fit, but with a different treatment of the uncertainties, and yields a corrected ^{11}Li relative mass difference of $-74.8 \pm 4.6 \times 10^{-7}$. Thus, the three methods give perfectly consistent results, and the final mass obtained for ^{11}Li is 11.043 714(5) u, corresponding to a mass excess of 40 719 ± 5 keV. By using the ^{9}Li mass from Ref. [21], the new S_{2n} for ^{11}Li is 378 ± 5 keV.

We profited from Resonant Ionization Laser Ion Source (RILIS) ionization and also performed a mass measurement for ^{11}Be as a check, given that its tabulated uncertainty is relatively small. Again, the independent analyses of Refs. [22,23] are consistent, and the result for ^{11}Be is 11.021 653(4) u, corresponding to a mass excess of 20 170 ± 3 keV. This value is in excellent agreement with previous results from reaction Q-value measurements of Pullen *et al.* [28]: 20 175 ± 15 keV [^{9}Be(t, p)^{11}Be] and Goosman and Kavanagh [29]: 20 174 ± 7 keV [^{10}Be(d, p)^{11}Be].

The new S_{2n} value for ^{11}Li is shown in Fig. 4, along with those calculated from all previous mass measurements of ^{11}Li. The value from CERN [30] was performed by using a mass spectrometer. The time-of-flight isochronous (TOFI) [31] result is a time-of-flight measurement of a fragmented beam using an isochronous mass spectrometer. The KEK [32] result is a ^{11}B(π^-, π^+)^{11}Li reaction Q value, and the MSU [33] result is derived from the Q value of the ^{14}C(^{11}B, ^{11}Li)^{14}O reaction. The evaluated value is mostly influenced by the MSU result [33] from which the new value deviates by 2.3σ.

In addition to the greatly reduced uncertainty, the new S_{2n} value is considerably higher than the previously accepted one and, as such, has consequences not only for nuclear theory but for other experiments. Two important recent results, in particular, both require the halo binding energy as a critical ingredient: the electric-dipole ($E1$) transition from the ground state, determined by Coulomb dissociation at RIKEN [9], and the mean-square charge radius, determined by laser spectroscopy at TRIUMF-ISAC [11].

The soft-dipole resonance is an interesting quantity since it results from the interplay of halo-neutron correlations, the reaction mechanism itself, shell effects (or quenching thereof), and correlations between the neutrons and the core. For loosely bound systems, the excited states are unbound and must be reconstructed from kinematic measurements. This relative energy is equal to the excitation energy minus the S_{2n} and is necessary for extracting the transition probability. The new S_{2n} value reported here was communicated to the authors of Ref. [9], who found an effect of about 6% on their results.

For the charge radius, the S_{2n} is even more critical. The experimental observable is the isotope shift of an *atomic* transition that is influenced by the changing nuclear configuration. The isotope shift has two components: a field shift, resulting from the electric potential distribution of the nucleus and from which the charge radius is determined, and a mass shift resulting from the change in center of mass. For heavy nuclides, the mass shift contributes minimally to the overall isotope shift. Not so for light systems: The ^{11}Li mass shift is ten thousand times the field shift [11], giving the mass capital importance. The present S_{2n} value was likewise communicated to the authors of

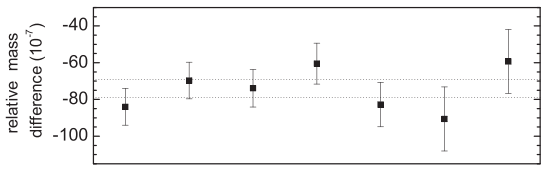

FIG. 3. Individual corrected measurements of the ^{11}B–^{11}Li doublet, including all sources of error. Also shown is the error band of the weighted average.

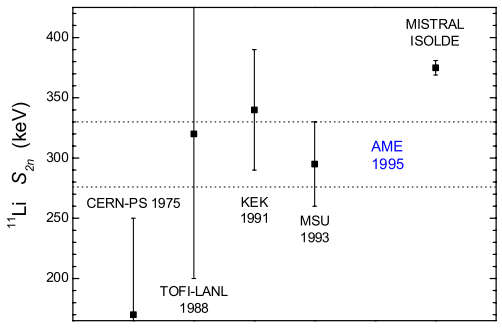

FIG. 4 (color online). ^{11}Li two-neutron separation energies derived from various mass measurements: CERN [30]; TOFI [31]; KEK [32]; MSU [33]; MISTRAL [this work]. The error band is the AME [27].

Ref. [11]. Their interesting results show a ^{11}Li charge radius significantly larger than that of ^{9}Li and have enabled the nascent field of "Borromean halo geometry" [34] in which the opening angles of the halo neutrons can be evaluated. In ^{11}Li, the neutrons are both on one side of the core (an opening angle of 66^{+22}_{-18} degrees is deduced in Ref. [34] and 48^{+14}_{-18} in Ref. [9]), as are the neutrons in the Borromean brother nuclide ^{6}He (opening angle of 83^{+20}_{-10} degrees in Ref. [34]). This is not the case in ^{8}He for which a recent isotope shift measurement by Mueller *et al.* [35] showed that the charge radius is *smaller* than ^{6}He, indicating a more symmetric neutron distribution around the ^{4}He core. In that work, the mass is still the dominating uncertainty.

The isotope shift and dipole strength are elegantly linked by the nuclear polarizability, as discussed by Puchalski, Moro, and Pachucki [36]. They used the new S_{2n} (given in Ref. [24]) and refit the dipole strength data from Ref. [9] to calculate a new polarizability correction for the isotope shift and extract the nuclear volume effect.

The high precision reported here is necessary for constraining nuclear models for two principal reasons: First, the exact value for the S_{2n} has changed considerably—by 25%. Such a change behooves the readjustment of any related interaction. For example, Hesse, Baye, and Sparenberg [37] claim an error on their S_{2n} calculation of less than 10 keV. The sensitivity of a three-body model to the new S_{2n} was indeed examined by Baye, Tursunov, and Descouvemont [38]. Second, there has been great progress recently on the coupled-cluster model [39,40], where the so-called j scheme has now been implemented allowing fast *ab initio* calculations of larger and open (i.e., drip line) systems. Moreover, these models are now including the three-body effects that are necessary for the description of halo systems. Clearly, we have reached the point where more accurate binding energies will be a great importance to constraining the theory of loosely bound nuclear systems.

We acknowledge the expert technical assistance of G. Conreur, M. Jacotin, J.-F. Képinski, and G. Le Scornet from the CSNSM. We also express our gratitude to V. N. Fedosseyev and the RILIS group as well as the ISOLDE technical group. The MISTRAL program is supported by France's IN2P3 and by the EU research network NIPNET (Contract No. HPRI-CT-2001-50034). The work at ISOLDE was partially supported by the EU RTD program "Access to Research Infrastructures," under Contract No. HPRI-CT-1998-00018 and by the ISOLDE Collaboration.

*Corresponding author.
david.lunney@csnsm.in2p3.fr

[1] B. Jonson, Phys. Rep. **389**, 1 (2004).
[2] A. S. Jensen, K. Riisager, D. V. Fedorov, and E. Garrido, Rev. Mod. Phys. **76**, 215 (2004).
[3] A. M. Poskanzer, S. W. Cosper, E. K. Hyde, and J. Cerny, Phys. Rev. Lett. **17**, 1271 (1966).
[4] I. Tanihata *et al.*, Phys. Rev. Lett. **55**, 2676 (1985).
[5] N. Vinh Mau and J. C. Pacheco, Nucl. Phys. **A607**, 163 (1996).
[6] C. Forssén *et al.*, Nucl. Phys. **A706**, 48 (2002).
[7] I. Brida, F. M. Nunes, and B. A. Brown, Nucl. Phys. **A775**, 23 (2006).
[8] T. Myo, K. Kato, H. Toki, and K. Ikeda, Nucl. Phys. **A790**, 311c (2007).
[9] T. Nakamura *et al.*, Phys. Rev. Lett. **96**, 252502 (2006).
[10] N. A. Orr *et al.*, Phys. Rev. C **51**, 3116 (1995).
[11] R. Sánchez *et al.*, Phys. Rev. Lett. **96**, 033002 (2006).
[12] E. Kugler *et al.*, Hyperfine Interact. **129**, 23 (2000).
[13] M. de Saint Simon *et al.*, Phys. Scr. **T59**, 406 (1995).
[14] D. Lunney *et al.*, Hyperfine Interact. **99**, 105 (1996).
[15] D. Lunney *et al.*, Hyperfine Interact. **132**, 299 (2001).
[16] D. Lunney *et al.*, Phys. Rev. C **64**, 054311 (2001).
[17] C. Gaulard *et al.*, Nucl. Phys. **A766**, 52 (2006).
[18] D. Lunney *et al.*, Eur. Phys. J. A **28**, 129 (2006).
[19] D. Lunney *et al.*, Int. J. Mass Spectrom. **251**, 286 (2006).
[20] J. R. J. Bennett *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **204**, 215 (2003).
[21] G. Audi, A. H. Wapstra, and C. Thibault, Nucl. Phys. **A729**, 337 (2003).
[22] C. Bachelet, Ph.D. thesis, Université Paris-Sud 11, Orsay, 2004, http://tel.archives-ouvertes.fr/tel-00008223/fr/.
[23] C. Gaulard *et al.* (to be published).
[24] C. Bachelet *et al.*, Eur. Phys. J. A **25**, 31 (2005).
[25] A. Coc *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **271**, 512 (1988).
[26] J. Lettry *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. B **126**, 130 (1997).
[27] G. Audi and A. H. Wapstra, Nucl. Phys. **A595**, 409 (1995).
[28] D. J. Pullen, A. E. Litherland, S. Hinds, and R. Middleton, Nucl. Phys. **36**, 1 (1962).
[29] D. R. Goosman and R. W. Kavanagh, Phys. Rev. C **1**, 1939 (1970).
[30] C. Thibault *et al.*, Phys. Rev. C **12**, 644 (1975).
[31] J. M. Wouters *et al.*, Z. Phys. A **331**, 229 (1988).
[32] T. Kobayashi *et al.*, KEK Report No. 91022, 1991.
[33] B. M. Young *et al.*, Phys. Rev. Lett. **71**, 4124 (1993).
[34] C. A. Bertulani and M. S. Hussein, Phys. Rev. C **76**, 051602(R) (2007).
[35] P. Mueller *et al.*, Phys. Rev. Lett. **99**, 252501 (2007).
[36] M. Puchalski, A. M. Moro, and K. Pachucki, Phys. Rev. Lett. **97**, 133001 (2006).
[37] M. Hesse, D. Baye, and J.-M. Sparenberg, Phys. Lett. B **455**, 1 (1999).
[38] D. Baye, E. M. Tursunov, and P. Descouvemont, Phys. Rev. C **74**, 064302 (2006).
[39] G. Hagen *et al.*, Phys. Rev. C **76**, 034302 (2007); **76**, 044305 (2007).
[40] G. Hagen *et al.*, Phys. Lett. B **656**, 169 (2007).