First Penning-Trap Mass Measurement of the Exotic Halo Nucleus ^{11}Li

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In this Letter, we report a new mass for ^{11}Li using the trapping experiment TITAN at TRIUMF's ISAC facility. This is by far the shortest-lived nuclide, $t_{1/2} = 8.8$ ms, for which a mass measurement has ever been performed with a Penning trap. Combined with our mass measurements of ^{8,9}Li we derive a new two-neutron separation energy of 369.15(65) keV: a factor of 7 more precise than the best previous value. This new value is a critical ingredient for the determination of the halo charge radius from isotope-shift measurements. We also report results from state-of-the-art atomic-physics calculations using the new mass and extract a new charge radius for ^{11}Li. This result is a remarkable confluence of nuclear and atomic physics.

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Perched precariously on the brink of nuclear stability, ^{11}Li has the lowest two-neutron binding energy of all bound nuclear systems [1]. This gives rise to the exotic phenomenon of a nuclear halo that has a wave function extending beyond the range normally allowed for by the strong interaction. The determination of the all-important ^{11}Li binding energy, from a direct mass measurement, is particularly challenging due to its half-life of a mere 8.8 ms.

The abnormal spatial properties of the original, and most famous, halo nuclide ^{11}Li were discovered by Tanihata *et al.* in 1985 [2]. Since then examples of nuclei with one (^{11}Be), two (^{6}He, ^{14}Be, ^{17}B) and even four (^{8}He) neutron halos, have also been found (the mass of ^{8}He was also recently measured by the TITAN group [3]). Nuclei with two neutron halos, such as ^{11}Li, are especially interesting because they form three body systems where none of the composite two body systems are themselves stable. Such nuclei were dubbed Borromean by J. Vaagen after the heraldic symbol of the Borromeo family [4]: three rings linked together in such a way that removal of any one ring leaves the other two disconnected.

The halo phenomena arises because of a very low nucleon binding energy, typically hundreds of keV, more than an order of magnitude smaller than that of stable nuclei. Because halo nuclei are so weakly bound their properties provide stringent tests for nuclear models. As such a large amount of work, both experimental and theoretical, has been carried out on the subject, see, e.g., [5,6] for reviews. Interest in the archetypical halo nucleus ^{11}Li has recently been rekindled due to a number of recent experimental results including the nuclear charge radius, determined with precision laser spectroscopy by Sanchez *et al.* [7] and the soft electric-dipole excitation, measured through invariant mass spectrometry by Nakamura *et al.* [8]; the results of both of which are dependent on the ^{11}Li mass. Reproduction of these results provides a real challenge to models of ^{11}Li; a number of which themselves use the two-neutron separation energy, S_{2n}, to adjust the ^{9}Li-n interaction (see, for example [9–12]).

Of the various techniques used for mass measurements (see, for example, the reviews [13,14]) Penning traps have emerged as the most accurate balances for weighing atomic nuclei, where for stable ions relative uncertainties of about 10^{-11} have been obtained [15]. High precision measurements on radioactive species are much more difficult due to constraints which arise due to short half-lives. Before this work the shortest-lived isotope measured with this technique was ^{74}Rb, $t_{1/2} = 65$ ms, to a precision of $\delta m/m = 6 \times 10^{-8}$ [16].

A precision Penning trap is formed by the superposition of a harmonic electrostatic potential over a homogeneous magnetic field. This results in a trapping potential in which an ion undergoes three independent harmonic eigenmotions: a longitudinal oscillation, ν_z, due to the applied electric field, a fast radial cyclotron motion, ν_+, due to the longitudinal magnetic field and a slow radial magnetron drifting, ν_-, caused by the perpendicular magnetic and electric fields [17]. It can be shown that, for an ideal trap, the sum of the frequencies of these two radial motions is equal to that of the true cyclotron frequency of the ion:

$$\nu_c = \nu_+ + \nu_- = \frac{1}{2\pi}\frac{q}{m}B, \tag{1}$$

where q/m is the charge to mass ratio of the ion and B is the magnetic field strength.

A measurement of the cyclotron frequency of an ion in a Penning trap can be made by the application of an azimuthal quadrupolar rf field of frequency ν_{rf} [18]. Such a field causes a periodic conversion between the two radial motions, which is most efficient in resonance, i.e., when $\nu_{\mathrm{rf}} = \nu_c$. For any given excitation time, T_{rf}, the amplitude of the rf can be set such that a full conversion between magnetron and reduced cyclotron motions occurs only in resonance. If an ion is injected into the trap in such a way that it has only an initial slow magnetron motion in the radial plane the application of the rf field at the resonant frequency acts so as to increase the radial energy of the ion up to a maximum achieved when the ion's motion is fully converted into pure reduced cyclotron. The radial energy after the excitation as a function of ν_{rf}, has a characteristic shape with a large peak centered at $\nu_{\mathrm{rf}} = \nu_c$, and a number of successively smaller peaks [see Fig. 1(a)]. A measurement of the radial kinetic energy of the ions can be made using the time-of-flight technique where the ions are extracted from the trap and guided electrostatically toward an MCP detector [19]. During this process the ions traverse an in-homogeneous magnetic field which has the effect of converting their radial kinetic energy into longitudinal kinetic energy. Thus, the ion's time of flight between the trap and the detector is a minimum when the initial radial kinetic energy is a maximum, i.e., when $\nu_{\mathrm{rf}} = \nu_c$. The width of the resonance curve, $\Delta\nu$, and ultimately the resolution of the measurement can be shown to be inversely proportional to the excitation time $\Delta\nu \approx 1/T_{\mathrm{rf}}$. Hence, when extending this technique down to very short-lived isotopes it is important to reduce the amount of time required for the preparation of the ions to a minimum so as to maximize the rf excitation time.

To calculate the mass of an ion from its cyclotron frequency using Eq. (1) the magnetic field must be known. This is found experimentally by measuring the cyclotron frequency of a reference ion, ν_{ref}, whose mass, m_{ref}, is well known. The ratio of the reference frequency to that of the ion of interest, $r = \nu_{\mathrm{ref}}/\nu_c$, can then be used to calculate the new mass as, $m = r(m_{\mathrm{ref}} - m_e) + m_e$, where m_e is the electron mass.

The experiments described were carried out at TRIUMF's ISAC facility. The radioactive lithium beams were produced using a tantalum thin-foil target, bombarded by a 500-MeV, continuous proton beam of 70 μA. The resulting reaction products were surface ionized before being accelerated to a transport energy of 20 keV. The isotopes of interest were selected by passing the beam through a two stage magnetic dipole separator.

The TITAN spectrometer consists of three ion traps [3,20], two of which were used to make the measurements described here. The 20 keV ISAC beam was first electrostatically decelerated to a longitudinal kinetic energy of a few eV before injection into a gas filled radio frequency quadrupole (RFQ) beam cooler [21]. In which it was thermalized via successive interactions with a room temperature gas (H_2), before pulsed extraction.

The cooled ions were then sent directly to a 3.7 T measurement Penning trap. This is in contrast to most other online Penning-trap facilities where an extra step of ion preparation (which can include isobaric purification) is usually carried out in a separate Penning trap. For these measurements this was unnecessary due to the contaminant free lithium beams. Once trapped, ions are conventionally given an initial pure magnetron motion via the application of a dipole excitation. This excitation takes a fixed amount of time, typically on the order of a few milliseconds, thus reducing the time available for the measurement. However, at TITAN an electromagnetic (Lorentz [22]) steering device was used to give the required magnetron orbit. This acts on the ions as they are being injected into the trap avoiding an additional excitation period.

A total of nine separate measurements of the ^{11}Li cyclotron frequency, each taking approximately 30 min, were made over a 14 h period. Reference measurements were made using ^{6}Li at 1 h intervals. During the measurement ^{11}Li ions were delivered at a rate of approximately 3000/s. Taking into account losses due to radioactive decay and assuming 100% transfer efficiency through out the TITAN system this would correspond to a detection rate of approximately 6×10^6 ions per hour. The actual detection rate was much lower, approximately 2000 ions per hour, corresponding to a transfer efficiency of only 0.1%. The majority of this loss was later found to be due to a time dependent drifting of the energy of the ion bunches extracted from the RFQ. This occurred due to a problem with the switch used to pulse the potential applied to a drift tube, which was used to adjust the kinetic energy of the ions.

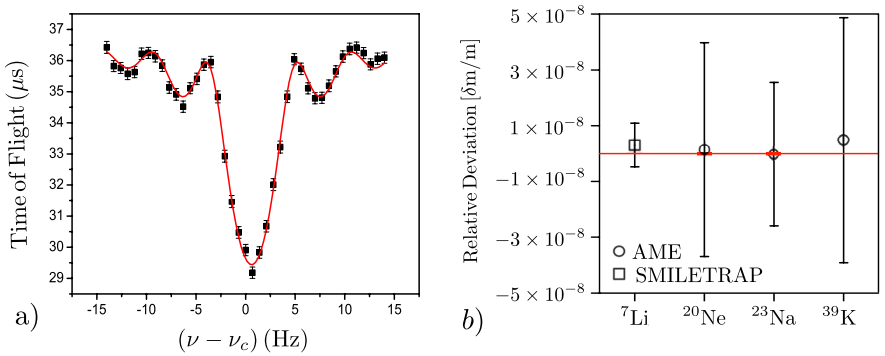

FIG. 1 (color online). (a) A typical ^{6}Li time-of-flight spectrum is shown with a fit of the theoretical line shape, here $\nu_c = 9\,450\,927$ Hz. (b) Results of measurements of a range of masses with respect to that of ^{6}Li. These are compared to literature values, from the AME [23] and SMILETRAP [24]. The error in the literature values is folded into the total error bar shown and is, for all cases except 39 K, negligible.

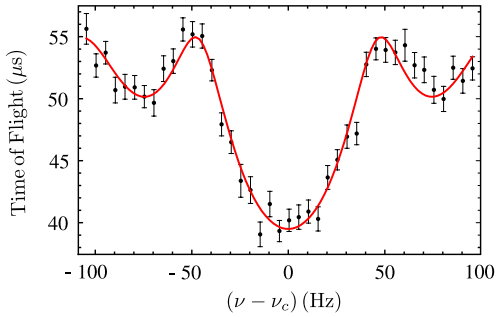

FIG. 2 (color online). A typical ^{11}Li resonance collected over 30 min, containing approximately 1000 ions. Here $\nu_c =$ 5 147 555 Hz. The solid line is a fit of the theoretical curve [18] to the data.

A typical ^{11}Li resonance is shown in Fig. 2. The data were analyzed following as closely as possible the well established procedure of the ISOLTRAP experiment [16] and the central frequency was found from a fit of the theoretical line shape (as illustrated) [18]. To obtain this resonance an excitation time of two half-lifes (18 ms) was used. The theoretical line width of the ^{11}Li resonance is given as $\Delta \approx 1/T_{\mathrm{rf}} = 56$ Hz. The resonance shown in Fig. 2 has a line width of approximately 60 Hz which is close to this theoretical limit. Measurements of the masses of ^{8,9}Li were also made, using a 48 ms excitation time. The results for the frequency ratios for these lithium isotopes are shown in Table I. From these ratios new values for the mass excess of these isotopes were derived using the recent SMILETRAP measurement of the mass excess of ^{6}Li, $\Delta(^6\mathrm{Li}) = 14\,086.882(37)$ keV [24]. The quoted values include a systematic error which takes into account both linear ($\delta m/m = 2 \times 10^{-9}$) and nonlinear ($\delta m/m = 7 \times 10^{-9}$) drifts of the magnetic field which where added in quadrature to the statistical uncertainty. The effects of deviations from the ideal electric and magnetic fields were also explicitly probed by measurement of a range of nuclei ($4 < m < 39$ u), with respect to ^{6}Li, in all cases agreement, within error bars, was obtained between the TITAN measurements and the literature values [see Fig. 1(b)]. An upper limit on these effects was then derived from the uncertainty in the TITAN measurements as $\delta m/m = 1.5 \times 10^{-9}$ per mass unit difference between the measured and reference ions (i.e., 7.5×10^{-9} for ^{11}Li). This was added linearly into the final error budget.

TABLE I. Frequency ratios, $r = \nu_{\mathrm{ref}}/\nu_c$, for ^{8,9,11}Li and the derived mass excesses, Δ. Also shown are the AME03 values for the mass excesses for comparison [23]. The ^{8}Li literature value is derived by adding the average Q value for the ^{7}Li$(n, \gamma)^8$Li reaction (as given in [23]) to the recent SMILETRAP measurement of the mass of ^{7}Li [24].

Isotope	r	Δ_{TITAN} (keV)	Δ_{Lit} (keV)
^{8}Li	1.333 749 862(18)	20 945.80(11)	20 945.799(65)
^{9}Li	1.500 728 256(34)	24 954.91(20)	24 954.3(19)
^{11}Li	1.836 069 26(11)	40 728.28(64)	40 797(19)

Using these mass measurements the two-neutron separation energy, S_{2n}, of ^{11}Li was calculated to be 369.15 (65) keV. Figure 3 shows this new value along with those calculated from all previous mass measurements of ^{11}Li. The value from CERN-PS [25] was obtained using a magnetic dipole mass spectrometer. The TOFI-LANL [26] result is a time-of-flight measurement of a fragmented beam using an isochronous mass spectrometer. The KEK [27] result is a ^{11}B$(\pi^-, \pi^+)^{11}$Li reaction Q value and the MSU [28] result is derived from the Q value of the ^{14}C$(^{11}$B, ^{11}Li$)^{14}$O reaction. The previous best result was achieved at ISOLDE by the transmission spectrometer MISTRAL [29]. The MAYA experiment (also carried out at TRIUMF) used an active target to study the ^{11}Li$(p, t)^9$Li reaction [30]. The new ^{9}Li value can be seen to be ten times more accurate than the literature value and both the values for ^{8,9}Li show good agreement with previous measurements.

Although in good agreement with the TOFI-LANL and KEK results the MISTRAL measurement shows over two sigma deviation from the MSU result. Analysis of recent measurements of both the soft-dipole excitation, via invariant mass spectrometry, and the charge radius, via isotope shifts, of ^{11}Li requires the mass. However, due to this uncertainty in the mass the invariant mass spectrometry data were analyzed using the AME03 value whereas the isotope-shift measurements used the MISTRAL result. It was reported in [8] that using the MISTRAL result for the ^{11}Li mass would enhance the total E1 strength by 6%. Using the AME mass value for ^{11}Li (11.043 798(21) u) in the analysis of the isotope-shift measurement results in a charge radius of 2.465(19)(30) fm, where the first uncertainty comes from the isotope-shift measurement, and the second from the ^{7}Li reference radius of 2.39(3) fm [31].

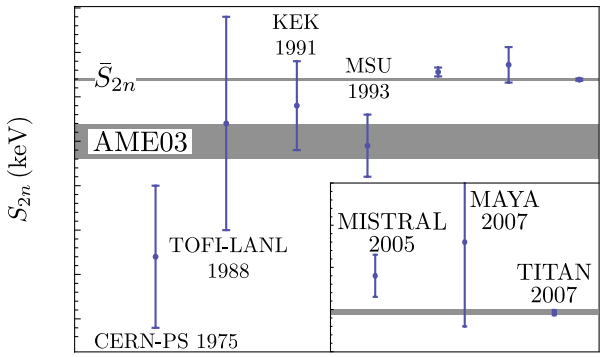

FIG. 3 (color online). ^{11}Li two-neutron separation energies derived from previous mass measurements: CERN-PS [25]; TOFI-LANL [26]; KEK [27]; MSU [28]; MISTRAL-ISOLDE [29]; MAYA [34] and TITAN [this work]. All shown with respect to the 2003 atomic mass evaluation [23]. The second gray line shows the weighted average of all the values (which is essentially identical to the TITAN result). The three most recent results are shown inset on an expanded scale for better comparison.

This is significantly increased from the value reported in Sanchez *et al*, 2.423(17)(30) fm [32], which was calculated using the MISTRAL value for the mass (11.043 715 7(54) u). A good test for nuclear theory would be its ability to reproduce the results of both these experiments. However, a meaningful comparison is only possible if the two results are analyzed using a consistent value for the ^{11}Li mass. With 1.5 sigma agreement with the MISTRAL result the new TITAN measurement shows that the MSU value for the ^{11}Li mass significantly underbinds the two-neutron halo. The impact of this new measurement is then clear. The results from the charge radius measurements and the soft-dipole excitation can now both be recalculated using the new mass, furnishing a more consistent experimental picture of ^{11}Li. Reproduction of these and all other measured ground state properties of ^{11}Li, sets a real, but very rewarding, challenge for nuclear theory.

The nuclear charge radius obtained from laser spectroscopy of the $2s$-$3s$ isotope shift represents a remarkable confluence of correlation effects from atomic theory on the one hand and nuclear theory on the other. The total isotope shift is the sum of a nuclear volume effect that is (nearly) independent of nuclear mass, and a variety of atomic structure effects that depend linearly and even quadratically on the nuclear mass [32]. Relativistic and quantum electrodynamic corrections must be fully taken into account with electron correlation in order to achieve sufficient accuracy in the atomic structure part. With a sufficiently accurate nuclear mass, the atomic structure part can then be accurately calculated and subtracted from the isotope shift in order to derive a value for the nuclear charge radius [32]. Using the TITAN value for the ^{11}Li mass (11.043 723 61(69) u) results in a nuclear charge radius of 2.427(16)(30) fm. The improved accuracy in the nuclear mass effectively eliminates this as a source of uncertainty in the interpretation of the isotope shift in terms of a nuclear charge radius, and so the nuclear charge radius provides a rigorous test of neutron correlations on the nuclear physics side. (The residual uncertainty of ± 0.016 fm comes from the uncertainty in the isotope-shift measurement itself.) As discussed by Sanchez *et al.* [7] and Puchalski *et al.* [33], the result shows that the ^{9}Li core is significantly perturbed by the presence of the two halo neutrons.

In summary we have performed a mass measurement on the exotic halo nucleus ^{11}Li using the newly commissioned TITAN Penning-trap mass spectrometer. This measurement sets a new record for the shortest-lived isotope ever measured using this technique with a half-life, 8.8 ms, over 7 times shorter than the previous record (^{74}Rb, $t_{1/2} =$ 65 ms) held by ISOLTRAP. Using the new measurements a value for the two-neutron separation energy of ^{11}Li was calculated, $S_{2n} = 369.15(65)$ keV with a precision over 7 times better than the best previous result.

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