Direct Mass Measurement of the Four-Neutron Halo Nuclide ^{8}He

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A high-precision Penning trap mass measurement of the exotic ^{8}He nuclide ($T_{1/2} = 119$ ms) has been carried out resulting in a reduction of the uncertainty of the halo binding energy by over an order of magnitude. The new mass, determined with a relative uncertainty of 9.2×10^{-8} ($\delta m = 690$ eV) is 13 keV less bound than the previously accepted value. The mass measurement is of great relevance for the recent charge-radius measurement of ^{8}He [P. Mueller *et al.*, Phys. Rev. Lett. **99**, 252501 (2007).]. The ^{8}He mass is the first result from the newly-commissioned Penning trap: TITAN (TRIUMF's Ion Trap for Atomic and Nuclear science) at the ISAC (Isotope Separator and Accelerator) radioactive beam facility at TRIUMF.

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The chart of bound nuclides so far synthesized and studied includes more than 3000 systems, each comprised of only two components: protons and neutrons. As simple as their composition may seem, the complex interactions that bind nuclei together still lack a full theoretical foundation. Despite the fact that between 6000 and 8000 bound nuclides are predicted to exist, it is the lightest that provide the most stringent tests of theory. The reason for this is that properties of small systems can be compared with concrete predictions of *ab initio* calculations (see, for example, [1–5]) and also because the lightest systems demonstrate the most exotic nuclear behavior due to the large imbalance of their components (see, for example, Jonson's review [6]). In this Letter we report on a precision mass measurement of ^{8}He, which has the largest neutron-to-proton ratio of all bound nuclei. This nuclide is particularly exotic since it exhibits a nuclear halo, a diffuse area of nuclear matter that extends farther from the core than normally allowed for by the strong interaction. ^{6}He is known to form a two-neutron halo and the speculation is that ^{8}He has a halo of *four* neutrons. Measurements of the nuclear charge radius of the two-neutron halo cousins ^{6}He [7] and ^{11}Li [8] show the core and halo revolving around a center of mass which increases the mean-square charge radius compared to the lighter isotopes. This leads to a model where the two neutrons are correlated such that they are predominantly on one side of the core. A recent study of ^{8}He [9] shows a *decrease* in charge radius compared to ^{6}He indicating that the four neutrons are more symmetrically distributed. The charge radius in those cases is determined via an isotope shift measurement of atomic transitions and by using atomic structure calculations [10]. However, a precise knowledge of the mass is needed. In fact, the result of the charge-radius determination of ^{8}He is dominated by the uncertainty of the atomic mass. A precision mass measurement is therefore necessary to reduce the error and confirm these observations and conclusions. In general, the binding energy is a central input parameter of nuclear structure theory, and many experimental programs dedicated to mass measurements exist (see [11] for a review and comparisons). The Penning trap technique has emerged as the most precise and reliable, even for short-lived nuclides (see [12]). The new Penning-trap facility at TRIUMF, called TITAN (TRIUMF's Ion Trap for Atomic and Nuclear science [13]) was used to measure the mass of ^{8}He.

The ^{8}He beam was produced at TRIUMF's ISAC facility [14] using a SiC target bombarded by a 25-microampere proton beam, accelerated to 500 MeV by the TRIUMF cyclotron. The exotic helium isotopes were ionized by a newly developed FEBIAD (Forced Electron Beam Ion Arc Discharge) [15] source, mass separated by a dipole magnet and then transported at 20 keV to the TITAN experiment at a rate of ≈ 1500 pps.

The TITAN mass spectrometer is sketched in Fig. 1 and consists of three ion traps: a radio frequency quadrupole (RFQ) cooler and buncher [16], an electron beam ion trap (EBIT) charge breeder [17], and a precision mass measurement Penning trap (MPET) [18]. The ISAC beam is injected into the RFQ, which is floating at high voltage to electrostatically retard the incoming beam to $E_k \approx 20$ eV. For the ^{8}He measurements, the helium buffer gas normally used was replaced with hydrogen in order to avoid resonant charge exchange with the trapped helium ions. The cooled and bunched beam is then transported at $E_k \approx 1$ keV to the precision Penning trap. For the experiment presented here, the EBIT was bypassed and the ions were delivered as singly charged ions to MPET. Here, one determines the cyclotron frequency $\nu_c = q/mB/2\pi$, which depends on q/m the charge-to-mass ratio of the ions of interest. The Penning trap uses the combination of a strong homogenous magnetic field ($B = 3.7$ T) and an electrostatic quadrupole field generated by a hyperbolic electrode configuration.

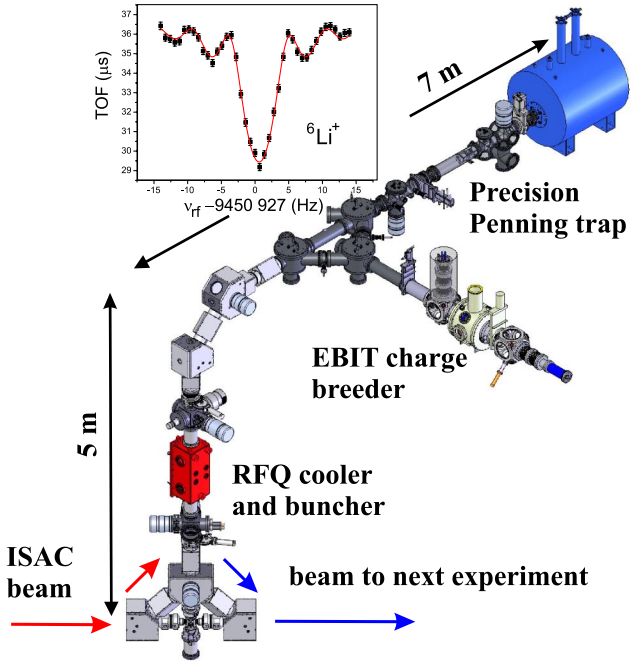

FIG. 1 (color online). The TITAN mass spectrometer setup at the TRIUMF-ISAC radioactive beam facility. The EBIT was bypassed for the experiment presented here. The inset shows a typical off-line TOF resonance curve for $^6Li^+$. The solid line is a fit of the theoretical curve [21] to the data points.

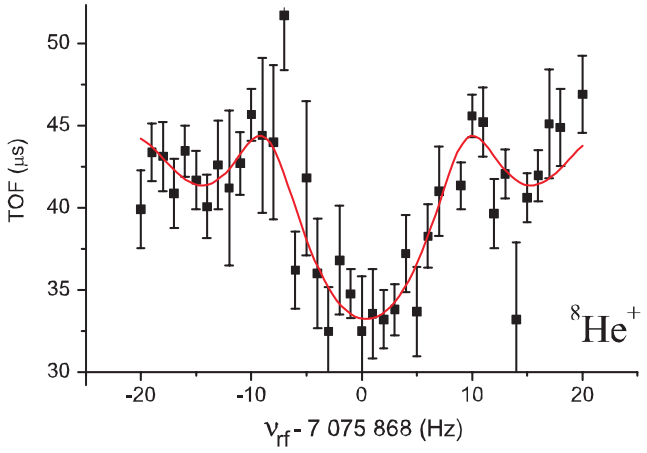

FIG. 2 (color online). Time-of-flight resonances recorded for $^8He^+$. The solid line is a fit of the theoretical curve [21] to the data.

The motion of ions in such configurations is well understood [19]. It is governed by independent eigenmotions with three distinct frequencies: the axial motion at ν_z, the magnetron motion at ν_-, and the reduced cyclotron motion at ν_+. The latter two motions are in the radial plane and are related by $\nu_c = \nu_- + \nu_+$. The ion's cyclotron frequency is measured by exciting the radial motion using an azimuthal quadrupole rf field with frequency ν_{rf}. This field causes conversion of the magnetron and reduced cyclotron motion that depends on ν_{rf}. Scanning ν_{rf} over the expected ν_c produces a characteristic time-of-flight (TOF) resonance curve [20,21]. In resonance ($\nu_{rf} = \nu_c$), and by proper choice of excitation amplitude and duration T_{rf}, a full conversion of magnetron to cyclotron motion can be achieved, which maximizes the energy associated with motion perpendicular to the magnetic field axis. After excitation, the ions are released from the trap and travel out of the magnetic field onto a detector, where the time of flight is recorded. While passing through the inhomogenous section of the magnetic field, the energy associated with motion perpendicular to the magnetic field axis is converted into energy in the motion parallel to the magnetic field axis, with minimal TOF observed at the resonance $\nu_{rf} = \nu_c$.

Recorded TOF resonance curves are shown in Fig. 1 (inset) for the ^6Li reference ion and in Fig. 2 for $^8He^+$. The cyclotron frequency, indicated by the minimum time of flight, is obtained by a fit of the theoretical line shape [21] to the data points. The linewidth $\Delta\nu$ is mainly determined by the excitation time T_{rf} ($\Delta\nu \approx 1/T_{rf}$). A resolving power $R = \nu/\Delta\nu$ of about 5×10^5 was obtained since an excitation time of 90 milliseconds was used. The magnetic field calibration is performed by measuring the cyclotron frequency, ν_{ref}, of reference ions having well-known mass m_{ref}. The ratio of the two frequencies is $r = \nu_{ref}/\nu_c$ with ν_c being the cyclotron frequency of the ion under investigation. For singly charged ions, the atomic mass m is derived via $m = r(m_{ref} - m_e + b_1) + m_e - b_2$, where m_e is the mass of the electron and b_1 and b_2 are the first ionization energies of the reference ion and the ion of interest, respectively. The ionization energies used are given in [22] for He and in [23] for Li. Magnetic field calibrations were performed before and after each ^8He measurement. Reference scans were taken with excitation times of $T_{rf} = 400$ ms and $T_{rf} = 900$ ms using stable ions from an off-line ion source. The frequency measurements of the reference ions required approximately 9 min apiece and were performed immediately before and after each ^8He measurement. The isobaric contamination ^8Li could be clearly resolved with the ISAC mass separator and was produced in approximately the same quantity as ^8He. By narrowing the slits after the separator no ^8Li was present in the delivered beam. In addition, only 1–2 detected ions per measurement step were used throughout the experiment to avoid frequency shifts due to simultaneous storage of different species [24].

The measurement of the unknown frequency is interpolated between the reference scans assuming a linear drift of the magnetic field. We investigated off-line the magnetic field decay which we determined to be consistent with a linear rate of $\delta B/B = 2.5 \times 10^{-9}/h$, and it was found to be stable over many days. The data analysis and error treatment of the on-line measurements followed as much as possible the well-established procedure of the

TABLE I. The frequency ratios $r = \frac{\nu_{\mathrm{ref}}}{\nu_c}$ of the three individual scans of $^8He^+$. Shown is also the averaged ratio, together with the statistical and systematic uncertainty. The number of ions per scan is also given. $^6Li^+$ delivered from an off-line ion source with $m(^6\mathrm{Li}) = 6.015\,122\,808(15)$ u, derived from the weighted mean of [26,27] was used as the reference ion.

Ion	$r = \nu_{\mathrm{ref}}/\nu_c$	Number of ions in scan
$^8He^+$	1.335 653 449 (90)	201
$^8He^+$	1.335 653 711 (120)	192
$^8He^+$	1.335 653 447 (80)	220
Average	1.335 653 480 (54) (107)	

ISOLTRAP experiment, described in [25]. Three separate TOF resonances of $^8He^+$, each taking 70 min, were recorded. The frequency ratios r and their uncertainties, including statistical as well as a final systematic error, are given in Table I. The mass of the ^{6}Li reference ion is derived from a weighted average of the high-precision masses measured by SMILETRAP [26] and by JILATRAP [27]: 6.015 122 808 (15) u. Figure 3 (left) shows the three individual results for ^{8}He with respect to the AME2003 [28] value, plotted as a difference of their mass excesses defined by (M(atom)-A) in atomic mass units which are then converted to keV. Only the statistical error is included in the figure, and all three results are consistent with each other.

Mass measurements of stable ions were carried out to establish the level of systematic error due to difference in masses between the ion of interest (^{8}He) and reference ion (^{6}Li). Such systematic effects include, for example, a frequency shift due to electric field imperfections [19,29]. These systematic measurements of masses of ^{4}He and ^{6}Li were compared to their published values (see Fig. 3). Deviations of 7×10^{-9} in the case of ^{4}He (see Fig. 3, center) and 1.6×10^{-8} for ^{6}Li (see Fig. 3, right) were observed. It should be noted that in the case of ^{6}Li our measurement is in good agreement with a recent SMILETRAP [26] datum, that was published after AME03. In this Letter we, however, adopt a conservative estimate of 1.6×10^{-8} for the mass-dependent systematic error. It includes the frequency shift due to electric field imperfections, and accounts for the deviation between TITAN measurements of the ^{6}Li mass and its AME03 value. This estimate is well below our statistical error. We plan to address the issue of ^{6}Li mass value in the near future. Other sources of systematic error, such as magnetic field instabilities, are at least an order of magnitude smaller and are neglected. A transport energy offset was introduced by the pulsed RFQ drift tube, which varied when operated for different excitation time cycles, leading to a systematic error, when taking the reference measurements with different cycle times then those for the ions of interest. We estimated this off-line to be 8×10^{-8}. All errors are added in quadrature to the relative uncertainty of the frequency ratio determination, 4.1×10^{-8}, and yields a final relative mass uncertainty for ^{8}He of 9.2×10^{-8}. The ^{8}He atomic mass is then determined to be 8.033 935 56 (74) u, corresponding to a mass excess value of: 31 610.77 ± 0.69 keV using ^{6}Li as the reference ion, as described above.

The mass of ^{8}He has been measured several times in the past. The AME2003 [28] gives a ME of 31 598 ± 7 keV, shown in Fig. 4 with past data, and the new mass value from TITAN. The uncertainty of the TITAN mass value for ^{8}He is more than a factor 10 smaller than that given in the AME2003. The deviation is just over 2σ. However, a close look at Fig. 4 shows that the new value is compatible with the older measurements [30–34] taken individually [ex-

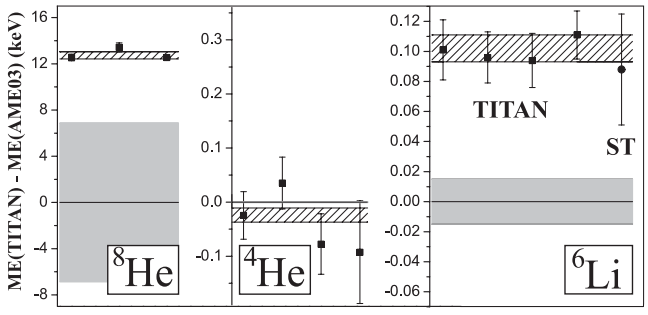

FIG. 3. Deviation of the TITAN mass excess (ME) results with respect to the Atomic Mass Evaluation AME2003 [28]. Left: the three individual ^{8}He measurements. Center: ^{4}He measurements with $^6Li^+$ as reference. Right: verification of accuracy by measurements of $^6Li^+$ with $^7Li^+$ as reference. The TITAN results with statistical error are given as squares, and the hashed area represents their weighted mean and statistical error. The AME2003 value is given as the zero line with the error shown by the shaded area. The SMILETRAP [26] measurement for ^{6}Li is indicated with "ST". Note the different scales.

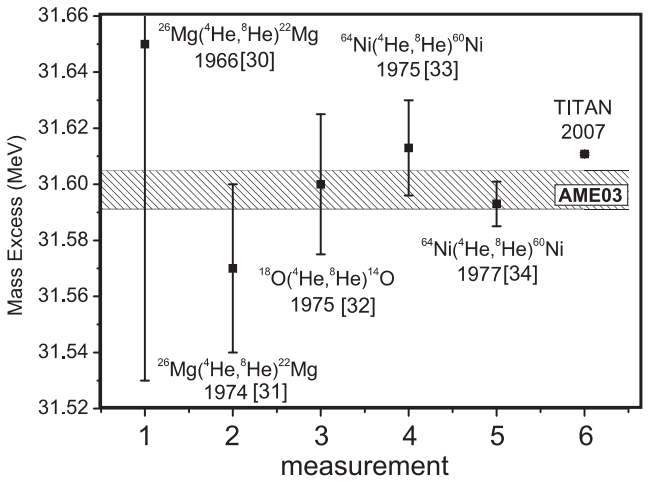

FIG. 4. Previous mass measurements of ^{8}He (references are given in the figure), as compared to the new TITAN Penning-trap result. The hashed area shows the mass resulting from the evaluation of all prior data as a two-sigma error band [28].

cepting the deviation from the 1977 ^{64}Ni(^{4}He, ^{8}He)^{60}Ni reaction [34], which is 2.3σ].

When examining the ^{8}He charge-radius result derived from an isotope shift measurement by Mueller *et al.* [9], the uncertainty of the atomic mass dominates the overall uncertainty of the charge-radius determination. The isotope shift $\delta\nu_{A,A'}$ of a transition between two isotopes A and A' is given by

$$\delta\nu_{A,A'} = \delta\nu^{\mathrm{MS}}_{A,A'} + K_{\mathrm{FS}}\delta\langle r^2\rangle_{A,A'}, \quad (1)$$

where $\delta\nu^{\mathrm{MS}}_{A,A'}$ is the mass shift and K_{FS} is the field shift constant. $\delta\langle r^2\rangle_{A,A'}$ is the change in the mean-square charge radius between the two isotopes. It is extracted from the experimental isotope shift and the calculations of $\delta\nu^{\mathrm{MS}}_{A,A'}$ and K_{FS}. Present calculations [10] reach the necessary accuracy. However, they rely on precise mass values, which are especially important for light nuclides, where the relative influence of the mass shift is more significant. In fact, for the case of ^{8}He the mass shift is a factor of $\approx$70 000 larger than the field shift. With the new TITAN value for the mass, the uncertainty is now considerably reduced and shows ^{8}He to be less bound, thus reducing the charge radius with respect to ^{6}He. This means that the overall effect between the two isotopes should be much more significant. However, the detailed atomic calculation will have to be performed.

In summary, we have made a precision mass measurement of ^{8}He. The precision reached with the TITAN spectrometer is 9.2×10^{-8}. The uncertainty has been reduced by a factor of over 10 and the new value is 13 keV less bound than the previously accepted value. The ^{8}He mass presented the largest source of uncertainty in the recent charge-radius measurement [9]. Therefore the mass reported here will improve the charge-radius result as well. This achievement is the first from the newly commissioned TITAN facility at TRIUMF-ISAC.

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