Double-β-decay Q values of ^{130}Te, ^{128}Te, and ^{120}Te

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The double-β-decay Q values of ^{130}Te, ^{128}Te, and ^{120}Te have been determined from parent-daughter mass differences measured with the Canadian Penning Trap mass spectrometer. The ^{132}Xe-^{129}Xe mass difference, which is precisely known, was also determined to confirm the accuracy of these results. The ^{130}Te Q value was found to be 2527.01 ± 0.32 keV, which is 3.3 keV lower than the 2003 Atomic Mass Evaluation recommended value and is consistent with another recent Penning trap measurement. The ^{128}Te and ^{120}Te Q values were found to be 865.87 ± 1.31 and 1714.81 ± 1.25 keV, respectively. For ^{120}Te, this reduction in uncertainty of nearly a factor of 8 opens up the possibility of using this isotope for sensitive searches for neutrinoless double-electron capture and electron capture with β^+ emission.

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A definitive observation of neutrinoless double-β-decay ($0\nu\beta\beta$ decay) would have many profound implications, such as revealing the Majorana nature of the neutrino, constraining the neutrino mass hierarchy and scale, and providing a mechanism for lepton-number violation (see Refs. [1–3] for recent reviews). Currently the best $0\nu\beta\beta$-decay half-life limits come from searches for the characteristic energy peak at the Q values of ^{130}Te [4] or ^{76}Ge [5–7]. The ^{76}Ge Q value has been determined several times [8–10] with a precision significantly better than the 1-keV resolution (1 σ) of the enriched HPGe detectors used in these experiments. The ^{130}Te Q value, however, has rested on much shakier ground. The 2003 Atomic Mass Evaluation (AME2003) recommended value [11] has a 1.99 keV uncertainty and is dominated by a single measurement [12]. This uncertainty is comparable to the 2- to 3-keV resolution (1 σ) of the TeO_2 bolometric detectors used in the Cuoricino $\beta\beta$-decay experiment [4]. The ton-scale CUORE TeO_2 bolometer array [13] and the COBRA CdTeZn semiconductor array [14] anticipate 1 σ experimental resolutions (at 2.5 MeV) of approximately 2 keV and 10 keV, respectively. Recent results from a Penning trap mass measurement [15] yielded a Q value that differed from the AME2003 recommended value by 3 keV, an important result for which confirmation is desired.

Experiments typically use natural tellurium and therefore are also sensitive to the signatures of ^{128}Te $\beta\beta$ decay as well as ^{120}Te double-electron capture ($\varepsilon\varepsilon$) and electron capture with β^+ ($\varepsilon\beta^+$) decay processes. The recommended ^{128}Te Q value is also dominated by a single measurement [12]. The situation for ^{120}Te is even worse: the AME2003 recommended Q value has an uncertainty of 10 keV. Thus, a neutrinoless-decay signal could be obscured by or confused with a background line.

To eliminate these concerns, we have determined the $\beta\beta$-decay Q values of ^{130}Te, ^{128}Te, and ^{120}Te by measuring the parent-daughter mass differences using the Canadian Penning Trap (CPT)[1] mass spectrometer [16]. High-precision mass spectrometry was performed by determining the cyclotron frequencies $\omega_c = \frac{qB}{M}$ of ions of mass M and charge q in the homogeneous magnetic field B of a Penning trap. The cyclotron frequencies of the singly charged parent (ω_1) and daughter (ω_2) ions determine the Q values from the relation

$$Q = m_1 - m_2 = (m_2 - m_e)\left(\frac{\omega_2}{\omega_1} - 1\right), \qquad (1)$$

where m_1, m_2, and m_e are the masses of the neutral parent atom, the neutral daughter atom, and the electron, respectively. The valence electron binding energies were 7–12 eV and can be neglected here. The ratios $\frac{\omega_2}{\omega_1}$ were measured to fractional precisions approaching 10^{-9} using the techniques described below. The CPT mass spectrometer has previously been used to measure the masses of short-lived isotopes to fractional precisions of 10^{-7} to 10^{-9} to determine (single) β-decay Q values [17,18] and proton-separation energies [19–21].

The CPT mass spectrometer has been described in detail in several publications [16,19,22,23]. The measurement technique is briefly presented here with details provided for the aspects of the experiment developed for this work.

Singly charged ions of Te and Sn were produced by laser ablation of solid targets using a Q-switched Nd:YAG laser to deliver up to 0.5 mJ of energy in 5-ns pulses at a 20-Hz

[1]This acronym is not to be confused with the CPT theorem pertaining to charge, parity, and time reversal symmetry.

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repetition rate. Two pressed and lacquer-bound tellurium metal powder targets (one with ^{nat}Te for ^{130}Te and ^{128}Te measurements and one enriched to 37.4% in ^{120}Te) and one ^{nat}Sn foil was used. For the ^{130}Xe and ^{128}Xe measurements, ^{nat}Xe gas was injected directly into a radiofrequency quadrupole (RFQ) ion guide [22] and ionized by a nearby ion gauge.

Ions then entered a 1.5-kV electrostatic beamline. A timed voltage pulse on one of the beamline electrodes allowed only ions with the desired mass number to reach a purification trap. This trap, a cylindrical Penning trap filled with helium buffer gas, accumulated and thermalized the ion bunches. An RF field applied at the appropriate cyclotron frequency centered the ions of interest while the contaminant ions were driven out of the trap [24]. The purified ion bunches were then transported to a linear RFQ ion trap [23] filled with helium buffer gas. This trap accumulated and cooled the captured ion bunches and ensured conditions were identical for all isotopes injected into the CPT mass spectrometer.

Ions loaded in the mass spectrometer were confined radially by a constant magnetic field ($B = 5.9$ T) and axially by a quadrupole electrostatic potential, resulting in motions with reduced cyclotron (ω_+), magnetron (ω_-), and axial (ω_z) eigenfrequencies [25]. An "evaporation pulse" adiabatically reduced the depth of the electrostatic trapping potential for about 10 ms to expel >90% of the ions. Only the coldest ions, which occupied the smallest volume at the trap center, remained. Next, dipole RF fields were applied at ω_+ frequencies to mass selectively drive any remaining unwanted ion species from the trap.

The cyclotron frequency of the trapped ions was determined through a time-of-flight (TOF) measurement technique that locates the sideband frequency $\omega_+ + \omega_-$ [26]. For ions in an ideal Penning trap, $\omega_c = \omega_+ + \omega_-$. To ensure that this relationship is satisfied accurately experimentally, the Penning trap was carefully aligned to the magnetic field axis and its electrodes were designed and tuned to minimize distortions in the electric field taking advantage of the cancellation of the leading effects of trap misalignments [27]. In addition, the $\omega_+ + \omega_-$ excitation power was adjusted to ensure full conversion from one motion to the other, further canceling the effect of any remaining electrostatic imperfections [28]. As prescribed by this TOF technique, the ions were first excited to a magnetron-orbital radius using a dipole ω_- RF field. A quadrupole RF field at a frequency ω_{ex} near the sideband frequency was then applied. On resonance, the RF field fully converted magnetron motion to reduced cyclotron motion. The ions were subsequently ejected from the trap and allowed to drift toward a microchannel plate detector (MCP) located in a region of the lower B field. As ions traversed the B-field gradient, the kinetic energy of the radial motion was converted to linear kinetic energy. Near the MCP, ions were accelerated to 2.4 keV for detection and the TOF recorded. The ion TOF was smallest when the conversion to reduced cyclotron motion was most effective. The resonance shape was determined from repeated measurements of the TOF spectrum at a series of equally spaced ω_{ex} values.

The two-pulse Ramsey method of separated oscillatory fields [29] was applied for the ω_{ex} quadrupole RF-field excitation. The resulting TOF resonance pattern is shown in Fig. 1. The use of two pulses resulted in narrower linewidths (≈40% narrower than for a single pulse applied over the same time) that increased the precision of the measurements [9,30,31]. The central TOF minimum was identified from an initial scan using only one excitation pulse that yielded a single, dominant TOF minimum. Recently, other heavy-ion mass measurements have also applied this Ramsey method [10,30,32].

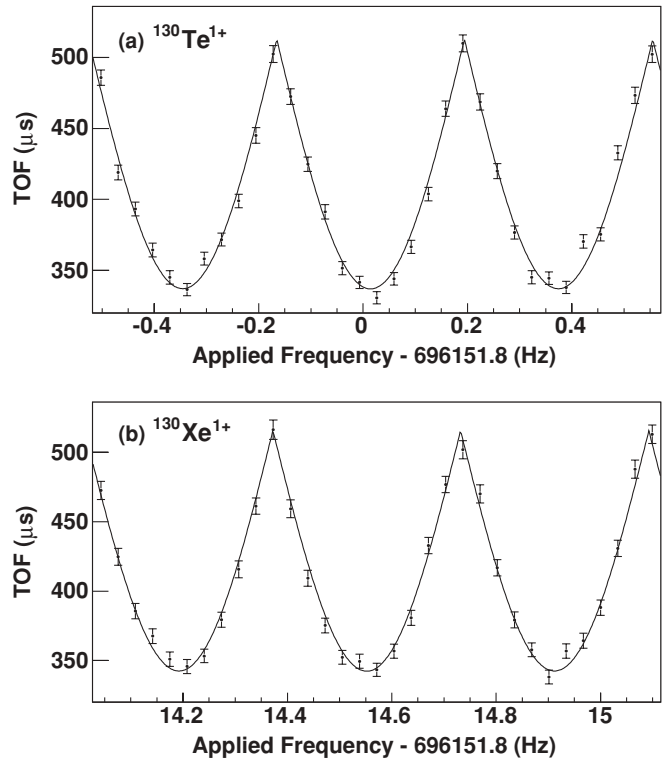

FIG. 1. Time-of-flight spectra of events with ⩽5 detected ions for (a) $^{130}Te^{1+}$ and (b) $^{130}Xe^{1+}$ ions using two-pulse Ramsey excitations over a total time of 3000 ms. The TOF offset was not measured and has no impact on the frequency determination. The curves are the fits to the data.

The ratio of determined cyclotron frequencies and the resulting Q values obtained using Eq. (1) are listed in Table I. The experiments were performed under two sets of measurement conditions. The ^{130}Te-^{130}Xe measurements and initial ^{120}Te-^{120}Sn measurements were performed with a probe time of 3000 ms (two 300-ms excitation pulses separated in time by 2400 ms). The TOF spectra for ^{130}Te and ^{130}Xe measurements with ⩽5 detected ions per shot are shown in Fig. 1.

A second set of measurements (^{128}Te-^{128}Xe and ^{120}Te-^{120}Sn) used a 1000-ms sequence of two 100-ms pulses separated by 800 ms. The use of a shorter probe time was necessitated by a small distortion in the quadrupole electric field of the CPT mass spectrometer that broadened the resonance linewidth. This distortion occurred after the data collection with 3000-ms probe times and did not affect this earlier data.

The technique was experimentally verified to the required accuracy by measuring the ^{132}Xe-^{129}Xe mass difference under the conditions of both the 3000- and 1000-ms measurements.

TABLE I. Summary of frequency ratios ω_2/ω_1 and the resulting mass differences ΔM measured using two-pulse Ramsey method times of 3000 and 1000 ms. The uncertainties include both statistics and systematics, combined in quadrature.

Isotopes	Time (ms)	ω_2/ω_1	ΔM (keV)
^{130}Te-^{130}Xe	3000	1.0000208837(26)	2527.01(32)
^{120}Te-^{120}Sn	3000	1.0000153639(142)	1715.96(159)
^{132}Xe-^{129}Xe	3000	1.0232682365(25)	2793899.12(30)
^{130}Xe-^{129}Xe	3000	1.0077478330(26)	930309.60(32)
^{120}Te-^{120}Sn	1000	1.0000153436(141)	1713.69(157)
^{128}Te-^{128}Xe	1000	1.0000072676(110)	865.87(131)
^{132}Xe-^{129}Xe	1000	1.0232682457(81)	2793900.22(97)

This difference was found to be 2793899.12 ± 0.30 and 2793900.22 ± 0.97 keV for the 3000- and 1000-ms measurements, respectively. These results agree with the value 2793899.180 ± 0.070 keV from Ref. [33] using 931494.028 ± 0.023 keV/c^2 per u [34].

Most systematic effects cancel in the frequency ratios because the measurements were performed for isotopes with nearly identical masses under identical experimental conditions. The results of the ^{132}Xe-^{129}Xe measurements confirmed that mass-dependent systematic effects were $\lesssim$0.3 keV/u. This is consistent with previous measurements using the CPT mass spectrometer [35]. Mass-dependent systematic effects were therefore negligible because the $\beta\beta$-decay mass differences were $\times 10^3$ smaller.

The time and ion-number dependence of our results were investigated in detail. Parent and daughter measurements were interleaved in time to minimize effects such as B-field drift. Over the course of the experiment, the measured sideband frequencies showed no evidence of drifts. Upper limits on the drifts were 2.5 ppb/day for the ^{130}Te-^{130}Xe pair and 7 ppb/day for the other isotopes. These limits are consistent with our previous studies [21]. We assign uncertainties of 0.08 and 0.2 keV for the 3000- and 1000-ms measurements, respectively, to account for the average time difference between measurements.

The ion detection rate was intentionally kept low (typically $<$10 ions detected per bunch) to limit frequency shifts that can arise from the trapped-ion space charge. The data was sorted into different spectra according to the number of ions detected per trap ejection. Sideband frequencies were determined for each of these binned spectra. Any shift caused by the trapped-ion populations was expected to be identical for parent and daughter measurements and this was verified in the analysis. For the 3000-ms measurements, linear shifts were consistent with zero with a value of -0.05 ± 0.05 keV (-0.4 ± 0.4 ppb) per detected ion observed. For the 1000-ms measurements, resolved linear shifts were observed. For each isotope, the measured slope was consistent with 1.5 ± 0.2 keV (13 ± 2 ppb) per detected ion. These shifts canceled in the frequency ratios and the Q value obtained for each ion-number spectrum was identical within statistics. To be conservative, we used only data with $\leqslant$5 detected ions per bunch (resulting in an average of $\approx$2 detected ions per bunch in each case) to determine the frequency ratios and Q values. Because the MCP detection efficiency was $<$100%, we have imperfect knowledge of the number of ions held in the trap and therefore each ion-number bin contains data from a distribution of trap populations. We assign systematic uncertainties of 0.1 and 0.4 keV for 3000- and 1000-ms measurements, respectively. These values are based on both the consistency of the frequency shifts and on Monte Carlo estimates of the impact from extreme differences in trap-population distributions. In each case, the total uncertainty was dominated by statistics. The results of these measurements are discussed below and displayed in Table I and Fig. 2.

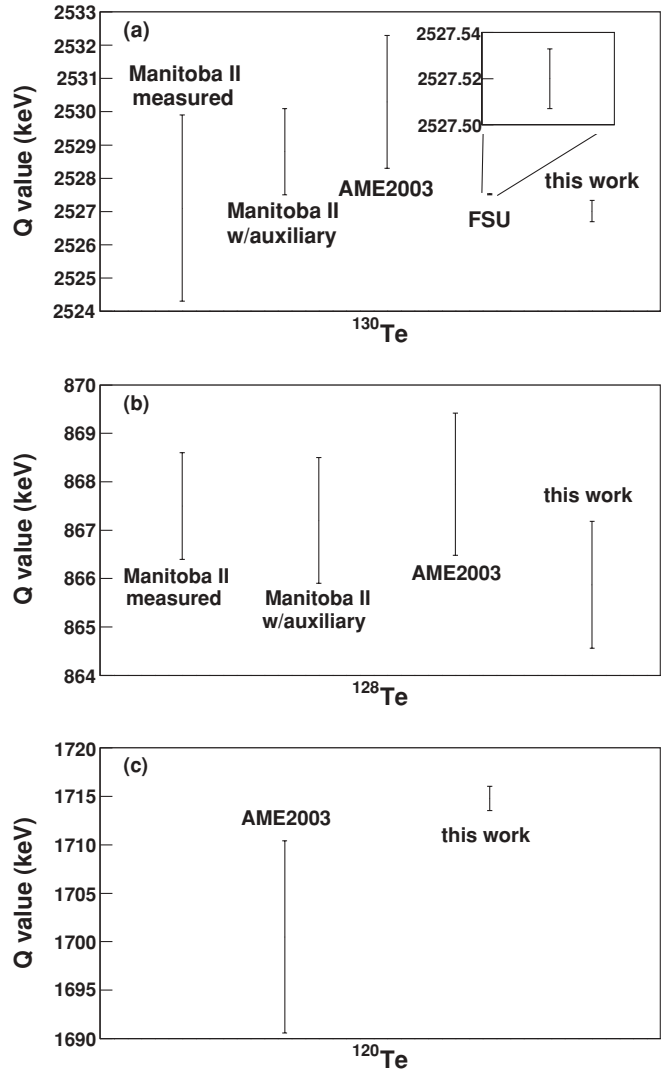

FIG. 2. Q values for (a) ^{130}Te, (b) ^{128}Te, and (c) ^{120}Te determined from recent measurements and evaluations. The values shown are from the Manitoba II deflection-type mass spectrometer (Manitoba II measured) [12], the Manitoba II result supplemented with auxiliary mass data (Manitoba II w/auxiliary) [12], the 2003 Atomic Mass Evaluation (AME2003) [11], the Florida State University Penning Trap (FSU) [15], and the Canadian Penning Trap (this work). Note the different scale in the inset displaying the FSU result.

After the completion of this work, we became aware of additional Te and Xe mass measurements performed using

triply charged ion pairs held simultaneously in a Penning trap [15]. The results of that work yielded precise mass differences for the ^{130}Te-^{130}Xe and ^{130}Xe-^{129}Xe pairs of 2527.518 ± 0.013 and 930309.618 ± 0.026 keV (using the conversion to keV/c^2 from Ref. [34]), respectively, that are consistent with the results presented here.

^{130}Te-^{130}Xe. The Q value we determine (2527.01 ± 0.32 keV) agrees with the mass difference measured using the Manitoba II deflection-type mass spectrometer [12,36] (see Fig. 2). In Ref. [12], an evaluation of the data incorporating auxiliary ^{124,126,128}Te and ^{128}Xe measurements increased the central value by 1.7 keV. In the AME2003 [11], the incorporation of modern auxiliary data further increased the recommended Q value to 2530.30 ± 1.99 keV. Our result is $6\times$ more precise and 3.3 keV smaller than the AME2003 recommended value and is consistent with another recent Penning trap measurement [15]. This lower value for the Q value will impact the $0\nu\beta\beta$-decay limit obtained from the Cuoricino experiment by shifting the decay energy closer to the ^{60}Co sum peak background at 2505.7 keV and out of a valley presumably caused by a statistical fluctuation [4]. The only isotope in any natural decay chain that emits a γ ray within 5 keV of this Q value is ^{214}Bi, which may have a weak transition at 2529.7 ± 0.8 keV [37].

Using the ^{129}Xe mass in Ref. [33] to set the absolute scale for our 3000-ms measurements, the masses of ^{130}Te and ^{130}Xe were determined to be 129906222.18 ± 0.48 μu and 129903509.32 ± 0.34 μu, respectively. The Q-value shift results from the ^{130}Te mass being 2.22 μu smaller than the AME2003 value of 129906224.399 ± 2.067 μu and the ^{130}Xe mass being 1.32 μu larger than the value of 129903508.007 ± 0.805 μu. Recent ^{129,130,132}Xe results [15,33] were also $\approx$1.5 μu larger than the AME2003 values.

^{120}Te-^{120}Sn. Measurements of the ^{120}Te Q value were performed with both 3000- and 1000-ms timings. The results agree (see Table I) and a weighted average yields a Q value of 1714.81 ± 1.25 keV. This value is 15 keV larger than the AME2003 value of 1700.49 ± 9.92 keV [11] where the uncertainty is dominated by the uncertainty in the ^{120}Te mass. This value provides guidance for experimental searches for $\varepsilon\varepsilon$ and $\varepsilon\beta^+$ decay in ^{120}Te [38–40]. The uncertainty is smaller than the 1 σ detector resolution of any fielded or anticipated experiment. The Q-value energy fortunately lies between the background lines at 1684.0, 1693.1 (single-escape line), and 1729.6 keV that are common in low-background experiments from the decay of ^{214}Bi (a ^{222}Rn daughter). The sensitivity of upcoming $0\nu\beta\beta$-decay experiments should be sufficient to place the most stringent limits (achieved with any isotope) for $\varepsilon\varepsilon$- and $\varepsilon\beta^+$-decay processes.

^{128}Te-^{128}Xe. The AME2003 recommended Q value (867.95 ± 1.47 keV) has remained nearly unchanged from the Manitoba II measurement (867.5 ± 1.1 or 867.2 ± 1.3 keV with auxiliary data) [12]. Our result (865.87 ± 1.31 keV) confirms the accepted value.

In summary, we have measured the Q values for the three naturally occuring tellurium isotopes for which double-β-decay processes are energetically allowed. We confirm the recent finding that the ^{130}Te Q value is 3 keV lower than the value recommended in AME2003. The ^{128}Te Q value was also remeasured and found to be consistent with the AME2003 recommended value. Our ^{120}Te Q-value result reduces the uncertainty by nearly an order of magnitude and will allow $\varepsilon\varepsilon$- and $\varepsilon\beta^+$-decay searches to be performed with greater sensitivity.

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[1] F. T. Avignone III, S. R. Elliott, and J. Engel, Rev. Mod. Phys. **80**, 481 (2008).
[2] S. R. Elliott and P. Vogel, Annu. Rev. Nucl. Part. Sci. **52**, 115 (2000).
[3] S. R. Elliott and J. Engel, J. Phys. G: Nucl. Part. Phys. **30**, R183 (2004).
[4] C. Arnaboldi *et al.*, Phys. Rev. C **78**, 035502 (2008).
[5] L. Baudis *et al.*, Phys. Rev. Lett. **83**, 41 (1999).
[6] C. E. Aalseth *et al.*, Phys. Rev. D **65**, 092007 (2002).
[7] C. E. Aalseth *et al.*, Phys. Rev. D **70**, 078302 (2004).
[8] G. Douysset, T. Fritioff, C. Carlberg, I. Bergstrom, and M. Bjorkhage, Phys. Rev. Lett. **86**, 4259 (2001).
[9] M. Suhonen *et al.*, J. Instrum. **2**, P06003 (2007).
[10] S. Rahaman *et al.*, Phys. Lett. **B662**, 111 (2008).
[11] G. Audi, A. H. Wapstra, and C. Thibault, Nucl. Phys. **A729**, 337 (2003).
[12] G. R. Dyck *et al.*, Phys. Lett. **B245**, 343 (1990).
[13] C. Arnaboldi *et al.*, Nucl. Instrum. Methods Phys. Res. A **518**, 775 (2004).
[14] K. Zuber, Phys. Lett. **B519**, 1 (2001).
[15] M. Redshaw, B. J. Mount, E. G. Myers, and F. T. Avignone III, Phys. Rev. Lett. **102**, 212502 (2009).
[16] G. Savard *et al.*, Nucl. Phys. **A626**, 353C (1997).
[17] G. Savard *et al.*, Phys. Rev. C **70**, 042501(R) (2004).
[18] G. Savard *et al.*, Phys. Rev. Lett. **95**, 102501 (2005).
[19] J. A. Clark *et al.*, Phys. Rev. Lett. **92**, 192501 (2004).
[20] J. A. Clark *et al.*, Phys. Rev. C **75**, 032801(R) (2007).
[21] J. Fallis *et al.*, Phys. Rev. C **78**, 022801(R) (2008).
[22] G. Savard *et al.*, Hyperfine Interact. **132**, 223 (2001).
[23] J. Clark *et al.*, Nucl. Instrum. Methods Phys. Res. B **204**, 487 (2003).
[24] G. Savard *et al.*, Phys. Lett. **A158**, 247 (1991).
[25] L. S. Brown and G. Gabrielse, Rev. Mod. Phys. **58**, 233 (1986).
[26] G. Gräff, H. Kalinowsky, and J. Traut, Z. Phys. A **297**, 35 (1980).
[27] G. Gabrielse, Int. J. Mass Spectrom. **279**, 107 (2009).
[28] G. Bollen, R. B. Moore, G. Savard, and H. Stolzenberg, J. Appl. Phys. **68**, 4355 (1990).
[29] N. F. Ramsey, Rev. Mod. Phys. **62**, 541 (1990).
[30] S. George *et al.*, Int. J. Mass Spectrom. **264**, 110 (2007).
[31] M. Kretzschmar, Int. J. Mass Spectrom. **264**, 122 (2007).

[32] S. George *et al.*, Phys. Rev. Lett. **98**, 162501 (2007).
[33] M. Redshaw, B. J. Mount, and E. G. Myers, Phys. Rev. A **79**, 012506 (2009).
[34] P. J. Mohr, B. N. Taylor, and D. B. Newell, Rev. Mod. Phys. **80**, 633 (2008).
[35] J. V. F. Vaz, Ph.D. thesis, University of Manitoba (2002).
[36] R. C. Barber *et al.*, Rev. Sci. Instrum. **42**, 1 (1971).
[37] L. P. Ekström and R. B. Firestone, Table of Radiactive Isotopes, http://ie.lbl.gov/toi/index.htm.
[38] T. Bloxham *et al.*, Phys. Rev. C **76**, 025501 (2007).
[39] A. S. Barabash *et al.*, J. Phys. G: Nucl. Part. Phys. **34**, 1721 (2007).
[40] N. Scielzo, APS Meeting Abstracts (October 2008), p. 63.