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First direct determination of the ^{48}Ca double-β decay Q value

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The low-energy beam and ion trap Penning trap mass spectrometer was used for an improved determination of the ^{48}Ca double-β decay Q value: $Q_{\beta\beta} = 4268.121(79)$ keV. The new value is 1.2 keV greater than the value in the 2012 atomic mass evaluation [Chin. Phys. C **36**, 1603 (2012)], a shift of three σ, and is a factor of 5 more precise. Accurate knowledge of this Q value is important for experimental searches to observe neutrinoless double-β decay ($0\nu\beta\beta$) in ^{48}Ca and is essential for extracting the effective mass of the electron neutrino if the ^{48}Ca half-life of $0\nu\beta\beta$ was experimentally determined.

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Neutrinoless double-β decay ($0\nu\beta\beta$) is predicated on the Majorana nature of neutrinos. Thus, an observation of $0\nu\beta\beta$ would confirm that neutrinos are their own antiparticles. Furthermore, if the corresponding phase-space factor $G_{0\nu}$ and the nuclear matrix element $M_{0\nu}$ are computed, a measurement of the half-life $T^{0\nu}_{1/2}$ of $0\nu\beta\beta$ could be used to determine the effective mass of the electron neutrino $\langle m_{\beta\beta}\rangle$ via

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G_{0\nu}(Q_{\beta\beta}, Z)|M_{0\nu}|^2(\langle m_{\beta\beta}\rangle/m_e)^2, \qquad (1)$$

where Z is the nuclear charge and m_e is the electron rest mass.

^{48}Ca, which will be employed in the CANDLES [1] and CARVEL [2] experiments, is a $0\nu\beta\beta$ candidate with both significant challenges and benefits. The low natural abundance of ^{48}Ca, less than 0.2%, makes it difficult to secure a large amount of the isotope for experiments, and the phase-space factor is hampered by the low Z of Ca. On the other hand, ^{48}Ca has the greatest double-β decay Q value $Q_{\beta\beta}$ of all potential candidates. Since $Q_{\beta\beta}$ for ^{48}Ca is higher than typical sources of background, an essentially background-free measurement is possible. The high Q value also boosts the phase-space factor as $G_{0\nu} \propto Q^5$. Finally, of all the $0\nu\beta\beta$ candidates, ^{48}Ca is the only candidate with a doubly closed nuclear shell, which makes its nuclear matrix element the least difficult to compute. The combination of the high Q value and the comparatively simple nuclear structure of ^{48}Ca makes it a promising $0\nu\beta\beta$ candidate, especially with continued improvement in enrichment techniques.

In a previous paper [3], the $Q_{\beta\beta}$ of ^{48}Ca was determined by using an indirect approach. The mass of ^{48}Ca $m[^{48}\mathrm{Ca}]$ was determined by Penning trap measurements of the mass ratios of $m[^{39}\mathrm{K}^+]/m[^{48}\mathrm{Ca}^+]$, $m[^{40}\mathrm{Ca}^+]/m[^{48}\mathrm{Ca}^+]$, and $m[^{41}\mathrm{K}^+]/m[^{48}\mathrm{Ca}^+]$ conducted at the low-energy beam and ion trap (LEBIT) facility. Then the AME2011 [4] value of $m[^{48}\mathrm{Ti}]$ was relied on to calculate the ^{48}Ca double-β decay Q value. In this Rapid Communication, an improved determination of the ^{48}Ca double-β decay Q value is reported, that is based on a LEBIT direct measurement of $m[^{48}\mathrm{Ti}^+]/m[^{48}\mathrm{Ca}^+]$.

A schematic of the LEBIT facility is given in Fig. 1; for a more in-depth description of the facility, see Ref. [5]. A Colutron ion source, installed 90° from the main LEBIT beamline, produced singly charged ions of ^{48}Ca via surface ionization. An electrostatic quadrupole deflector bent the continuous ion beam such that the $^{48}\mathrm{Ca}^+$ ions would be directed downstream to the radio-frequency (RF) quadrupole cooler-buncher [6]. Alternatively, the polarity of the electrostatic quadrupole deflector could be reversed such that a pulsed beam of $^{48}\mathrm{Ti}^+$ ions, produced with the newly developed LEBIT laser ablation source, mounted opposite the Colutron ion source, would be sent to the cooler-buncher. When the quadrupole deflector was set to transport $^{48}\mathrm{Ti}^+$ to the cooler-buncher, the $^{48}\mathrm{Ca}^+$ ions were rejected and were sent upstream away from the cooler-buncher and vice versa. After preparation in the cooler-buncher, cooled ion bunches were then ejected, and the microsecond ion pulses were transported to the 9.4-T LEBIT Penning trap [5].

The Penning trap was used in the determination of the ion cyclotron frequency via a time-of-flight (TOF) resonance detection technique [7]. Once an ion bunch of the desired species was captured in the Penning trap, the ions were excited with an applied quadrupole RF electric field. The ion bunch was then ejected from the trap, and the TOF to a downstream microchannel plate (MCP) detector was measured. The RF frequency ν_{RF} is varied, and the process is repeated for a new bunch of ions, which results in a characteristic cyclotron resonance, such as the $^{48}\mathrm{Ti}^+$ resonance shown in Fig. 2. The minimum in the TOF of the central trough corresponds to the ions that are maximally excited with ν_{RF} equal to the cyclotron frequency of the ion $\nu_c = qB/2\pi m$, where q/m is the charge-to-mass ratio of the ion and B is the strength of the magnetic field.

Over a period of 2 weeks, 88 cyclotron frequency measurements were taken. Each resonance lasted approximately 30 min and contained from approximately 400 to 2000 ions where only events with five or fewer detected ions were considered. Of the considered events, on average, two to three ions were detected, which, given the detector efficiency

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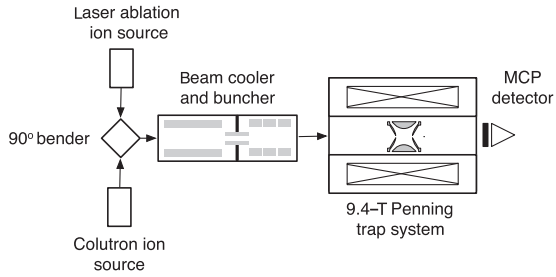

FIG. 1. Schematic of the LEBIT facility.

of approximately 80%, corresponds to a typical number of three simultaneously trapped ions. Two different excitation schemes were used in this measurement; the two data sets are presented in Fig. 3. For the first set of data, consisting of 49 resonances, a Ramsey excitation scheme [8–10] was implemented. A 150-ms burst of RF was followed by a 450-ms wait before an ion bunch was exposed to a second 150-ms burst of RF. In the second set of data, consisting of 39 resonances, a 750-ms traditional quadrupole excitation [11] was applied. The cyclotron resonances were fitted [8,11] to determine the corresponding cyclotron frequency. In order to determine the ratio of cyclotron frequencies of $^{48}Ca^{+}$ and $^{48}Ti^{+}$, $\nu_c(^{48}Ca^{+})/\nu_c(^{48}Ti^{+})$ cyclotron resonances of $^{48}Ti^{+}$ were taken both before and after every $^{48}Ca^{+}$ resonance. The surrounding pairs of $^{48}Ti^{+}$ resonances were then linearly interpolated to determine $\nu_c(^{48}Ti^{+})$ at the time of the $^{48}Ca^{+}$ resonance. The resulting cyclotron frequency (inverse mass) ratios of each data set are presented in Fig. 3. For the Ramsey excitation data set, an average value of $\nu_c(^{48}Ca^{+})/\nu_c(^{48}Ti^{+}) = 0.999\,904\,4458(20)$ was obtained, and for the traditional quadrupole excitation data set, an average value of $\nu_c(^{48}Ca^{+})/\nu_c(^{48}Ti^{+}) = 0.999\,904\,4454(29)$

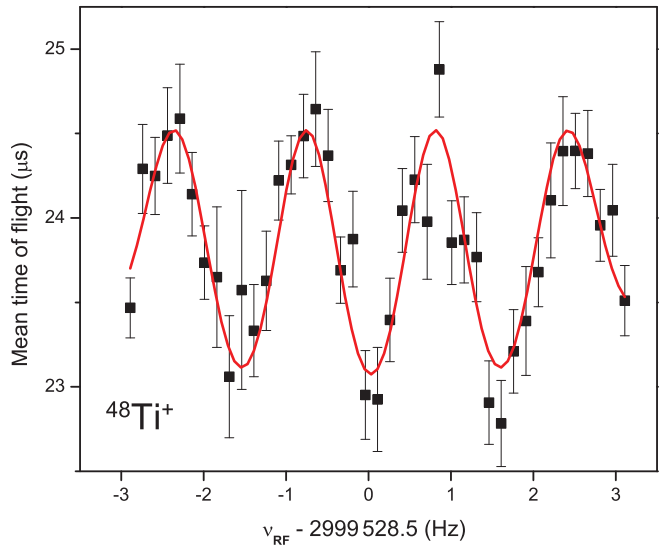

FIG. 2. (Color online) One of 88 time-of-flight cyclotron resonances used for the determination of $\nu_c(^{48}Ca^{+})/\nu_c(^{48}Ti^{+})$. This example resonance is for $^{48}Ti^{+}$ ions obtained with a Ramsey excitation method. The corresponding cyclotron frequency was determined by a fit of the theoretical line shape [8], depicted with the red solid curve.

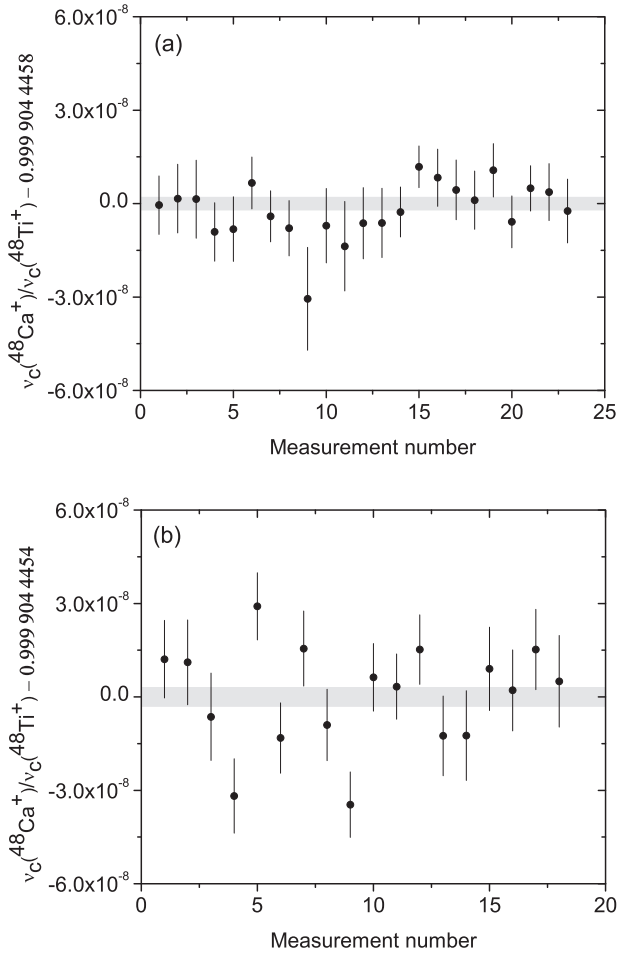

FIG. 3. Data sets of cyclotron frequency ratios of $^{48}Ca^{+}$ and $^{48}Ti^{+}$ ions about the mean value of the data set. A Ramsey excitation method and a traditional quadrupole excitation method were used in data sets (a) and (b), respectively. The statistical uncertainty in an individual cyclotron frequency ratio is represented with the error bars, and the overall 1σ statistical uncertainty of each data set is illustrated with a shaded bar.

was obtained. The Birge ratio [12] of each data set is 0.84 (10) and 1.47 (11), respectively, and the above-listed uncertainty in the cyclotron frequency ratio of each data set is statistical.

All known systematic sources of error give rise to a systematic uncertainty that is much less than statistical uncertainty. Since $^{48}Ca^{+}$ and $^{48}Ti^{+}$ have the same mass number, mass-dependent systematic effects are practically eliminated. Furthermore, nonlinear fluctuations in the magnetic field have been shown to give rise to an error well below 1×10^{-9} for measurements where an individual cyclotron frequency measurement is obtained in roughly an hour [13]. Finally, ion production via two independent sources was ideal for ensuring the purity of ion samples in the trap. When the quadrupole deflector was set for $^{48}Ca^{+}$, no $^{48}Ti^{+}$ ions made it to the trap and vice versa. Contaminants with mass numbers other than $A = 48$ were effectively removed prior to the trap with a pulsed electric steerer based on the TOF from the buncher to the steerer. To check that all contaminants were removed during a $^{48}Ca^{+}$ measurement, a dipole electric

TABLE I. Average cyclotron frequency ratios $\nu_c(^{48}Ca^+)/\nu_c(^{48}Ti^+)$ with the excitation method, the statistical uncertainty, and the Birge ratios of each data set. The overall average of the entire collection of data is presented.

Excitation	$\sigma_{stat} \times 10^{-9}$	Birge ratio	Ratio
Ramsey	2.0	0.84 (10)	0.999 904 4458(20)
Quadrupole	2.9	1.47 (11)	0.999 904 4454(42)
Average			0.999 904 4457(18)

RF field was set to drive $^{48}Ca^+$ out of the trap. It was then verified that no ions were detected at the MCP, i.e., no other ions were present in the trap. The purity of the $^{48}Ti^+$ ion bunches was also similarly checked and was verified. Since the samples were pure, there were no frequency shifts from Coulomb interaction with contaminant ions in the trap [14].

Although all known systematic effects give rise to a systematic error much less than the statistical uncertainty, for the traditional quadrupole excitation data set where the Birge ratio was greater than unity, the statistical uncertainty was scaled by the Birge ratio to account for any residual unknown systematic effects and nonstatistical fluctuations. These parameters are listed in Table I. A weighted average of the two data sets was then taken to obtain an average value of the entire collection of data:

$\nu_c(^{48}Ca^+)/\nu_c(^{48}Ti^+) = 0.999\,904\,4457(18)$.

This improved determination of $\nu_c(^{48}Ca^+)/\nu_c(^{48}Ti^+)$ was used to compute the ^{48}Ca double-β decay Q value, which can be expressed as

$$Q_{\beta\beta} = [m(^{48}\mathrm{Ca}) - m_e]c^2\left[1 - \frac{\nu_c(^{48}Ca^+)}{\nu_c(^{48}Ti^+)}\right], \qquad (2)$$

where $m(^{48}$Ca) is the atomic mass of ^{48}Ca, m_e is the mass of the electron, and c is the speed of light. Using the measured value of $\nu_c(^{48}Ca^+)/\nu_c(^{48}Ti^+)$ and the atomic mass of ^{48}Ca in the 2012 atomic mass evaluation (AME) [15] yields $Q_{\beta\beta} =$ 4268.121(79) keV. This value is 1.2 keV greater than the 2012 AME value, a shift of three σ, and is a factor of 5 more precise. Note that, although the value of $Q_{\beta\beta}$ has a strong dependence on the measured cyclotron frequency ratio, for the obtained precision, $Q_{\beta\beta}$ is insensitive to the atomic mass value of ^{48}Ca used in Eq. (2) to within several keV.

By using the new determination of the Q value and a weak interaction axial-vector coupling constant of $g_A = 1.254$, the phase-space factors for both $2\nu\beta\beta$ decay $G_{2\nu}$ and $0\nu\beta\beta$ decay $G_{0\nu}$ have been calculated by following the procedure set forth in Ref. [16] and are listed in Table II. These values of $G_{2\nu}$ and $G_{0\nu}$ are 0.3% and 0.1% different from those in Ref. [3]

TABLE II. Q value based on the direct measurement of $\nu_c(^{48}Ca^+)/\nu_c(^{48}Ti^+)$. Corresponding phase-space factors for $2\nu\beta\beta$ decay and $0\nu\beta\beta$ decay calculated following Ref. [16].

Q value (keV)	$G_{2\nu}$ ($\times 10^{-17}$ yr^{-1})	$G_{0\nu}$ ($\times 10^{-14}$ yr^{-1})
4268.121(79)	3.936 9(7)	6.509 2(5)

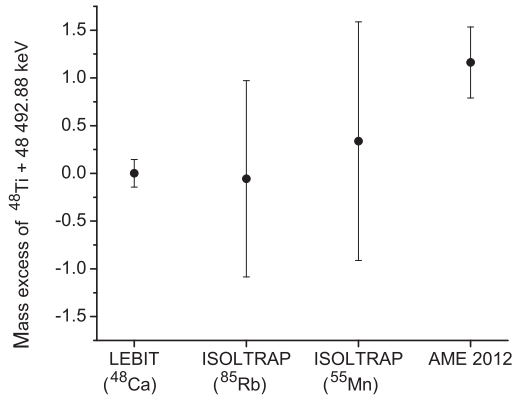

FIG. 4. Comparison of the 2012 AME value of the mass excess of ^{48}Ti with the values obtained by Penning trap mass spectrometry at the LEBIT and ISOLTRAP facilities. The reference mass used for each Penning trap measurement is indicated in parentheses.

that relied on the AME 2011 atomic mass value of ^{48}Ti for calculating the Q value. Through the direct determination of the ^{48}Ca double-β decay Q value, the uncertainty in both $G_{2\nu}$ and $G_{0\nu}$ has been reduced by a factor of 6.

The measured value of $\nu_c(^{48}Ca^+)/\nu_c(^{48}Ti^+)$ provides a direct link between the masses of ^{48}Ca and ^{48}Ti. The atomic mass of ^{48}Ca [3] was recently determined in a LEBIT high-precision Penning trap mass measurement, which is the dominant influence of the 2012 AME value [15]. The 2012 AME value of the atomic mass of ^{48}Ti is based largely on reactions, particularly, ^{47}Ti$(n,\gamma)^{48}$Ti [15,17] from the 1980 paper [18]. The ISOLTRAP Penning trap measurements of $m[^{48}Ti^{16}O^+]/m[^{85}Rb^+]$ and $m[^{48}Ti^{16}O^+]/m[^{55}Mn^+]$ [19] that contribute to the 2012 AME value of $m[^{48}$Ti] yield an average value that differs by over one standard deviation from the overall AME value. To help elucidate the atomic mass value of ^{48}Ti, the measured ratio of $\nu_c(^{48}Ca^+)/\nu_c(^{48}Ti^+)$ and the 2012 AME value of $m[^{48}$Ca] were used to yield a new determination: $m[^{48}\mathrm{Ti}] = 47.947\,940\,75(16)$ u. This value is 1.2 keV less than the 2012 AME value, a change of three σ. The new determination of $m[^{48}$Ti], however, is in excellent agreement with the ISOLTRAP Penning trap measurements of ^{48}Ti as illustrated in Fig. 4. The $m[^{48}$Ti] value presented in this Rapid Communication, which is over a factor of 5 more precise than the weighted average of the ISOLTRAP measurements, strongly supports that the atomic mass of ^{48}Ti be reevaluated.

In conclusion, the direct measurement of $\nu_c(^{48}Ca^+)/\nu_c(^{48}Ti^+)$ enables an improved determination of the ^{48}Ca $\beta\beta$-decay Q value. The newly determined Q value is 1.2 keV greater than the previously accepted value. The phase-space factors for both $2\nu\beta\beta$ decay and $0\nu\beta\beta$ decay have been updated to reflect the improved determination of the Q value. In consideration of the LEBIT Penning trap mass measurement of ^{48}Ca and the ISOLTRAP Penning trap measurements of ^{48}Ti, we conclude that the shift in the Q value is due to an error in the previously accepted value of the atomic mass of ^{48}Ti.

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