Masses of ^{130}Te and ^{130}Xe and Double-β-Decay Q Value of ^{130}Te

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The atomic masses of ^{130}Te and ^{130}Xe have been obtained by measuring cyclotron frequency ratios of pairs of triply charged ions simultaneously trapped in a Penning trap. The results, with 1 standard deviation uncertainty, are $M(^{130}\mathrm{Te}) = 129.906\,222\,744(16)$ u and $M(^{130}\mathrm{Xe}) = 129.903\,509\,351(15)$ u. From the mass difference the double-β-decay Q value of ^{130}Te is determined to be $Q_{\beta\beta}(^{130}\mathrm{Te}) = 2527.518(13)$ keV. This is a factor of 150 more precise than the result of the AME2003 [G. Audi *et al.*, Nucl. Phys. **A729**, 337 (2003)].

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The observation of neutrinoless double-β ($0\nu\beta\beta$) decay would imply that neutrinos are Majorana particles, i.e., particles that differ from antineutrinos only by helicity, while the rate of the decay gives information on absolute neutrino mass [1]. The decay rate is proportional to $m_{\beta\beta}^2$, where $m_{\beta\beta}$, the "effective Majorana mass of the electron neutrino," is a linear combination of neutrino mass eigenvalues. Based on constraints from neutrino oscillation experiments $m_{\beta\beta}$ could be larger than 0.05 eV/c^2, allowing the possibility that $0\nu\beta\beta$ decay could be observed by several experiments that are currently planned or under construction. So far the most sensitive limits on $m_{\beta\beta}$ have come from experiments searching for the $0\nu\beta\beta$ decay of ^{76}Ge using germanium semiconductor detectors [2,3], and large-scale ^{76}Ge experiments [4,5] are under development. However, due to uncertainties in the nuclear matrix elements as well as difficulties in interpreting the observations [3,6], searches for $0\nu\beta\beta$ decay in other nuclei are required. ^{130}Te is a favorable candidate, and a competitive, high-resolution experiment seeks to detect ^{130}Te $0\nu\beta\beta$ decay by using cryogenic bolometers consisting of single crystals of TeO_2 bonded to high-sensitivity germanium thermistors. A prototype version, CUORICINO [7], was operated until July 2008 at the Laboratori Nazionali del Gran Sasso (LNGS), while a full-scale version, CUORE [8], which will contain approximately 750 kg of TeO_2, or ~200 kg of ^{130}Te, is under construction.

A crucial datum for all $0\nu\beta\beta$-decay searches is the Q value, the mass-energy difference between the parent and daughter atoms. This defines the location of the expected sharp peak in the sum-energy-spectrum of the two electrons emitted, the signature of the *neutrinoless* decay. For ^{76}Ge, a precision Penning-trap measurement of the ^{76}Ge-^{76}Se mass difference using highly charged ions [9] has been important for the interpretation of the $0\nu\beta\beta$-decay results [2,3], and a recent Penning-trap measurement of ^{136}Xe [10] provides the Q value for future large-scale ^{136}Xe $0\nu\beta\beta$-decay experiments [11]. In the case of ^{130}Te, a 1990 measurement of $Q_{\beta\beta}$ (^{130}Te) by the Manitoba group using a 1 m radius magnetic deflection spectrometer gave 2527.12(2.8) keV. Combining this result with the results of others they obtained 2528.8(1.3) keV [12]. However, the most recent global Atomic Mass Evaluation (AME2003) [13], which includes the results of the Manitoba group and more recent data, gives $Q_{\beta\beta}(^{130}\mathrm{Te}) = 2530.3(2.0)$ keV. This uncertainty in the Q value already impacts the analysis of CUORICINO [7], and would be a serious limitation for the future CUORE experiment, which has an anticipated FWHM energy resolution of 5 keV and absolute energy calibration uncertainty of better than 0.4 keV [7,8]. Here we report a high-precision, cryogenic Penning-trap measurement of the mass-energy difference $[M(^{130}\mathrm{Te})\text{-}M(^{130}\mathrm{Xe})]c^2 = Q_{\beta\beta}(^{130}\mathrm{Te})$ with a 1 standard deviation uncertainty of 13 eV. Since this is more than an order of magnitude less than the uncertainty of the energy calibration of CUORICINO and CUORE, it effectively eliminates uncertainty in the Q value as a limiting factor in the sensitivity of these experiments. We also report precise absolute atomic masses of ^{130}Te and ^{130}Xe for inclusion in a future AME.

Method.—Most of our techniques and our Penning-trap mass spectrometer, originally developed at MIT [14–16], have been described elsewhere [10,17–20]. Here we give an overview and indicate the developments required for the present measurements. A comprehensive review of precision mass spectrometry is given in Ref. [21], and a review of fundamental single-particle Penning-trap physics is given in Ref. [22]. The Penning trap consists of three hyperboloidal electrodes, the ring and two end caps, which produce a cylindrically symmetric quadratic electrostatic potential. The electrodes are housed inside an ultrahigh vacuum insert, submerged in the liquid-helium-filled bore of a carefully shimmed 8.5 T superconducting magnet. The combination of uniform magnetic field and quadratic electrostatic potential results in three harmonic motions for an ion in the Penning trap: the "trap-modified"-cyclotron, axial, and magnetron modes, with frequencies f_{ct}, f_z, and f_m, respectively. In the limit of small mode amplitudes, and with no other forces on the ion, the "true" cyclotron frequency, defined by $f_c = qB/2\pi m$, is given *exactly* by

the Brown-Gabrielse invariance theorem, $f_c^2 = f_{ct}^2 + f_z^2 + f_m^2$ [23]. In our Penning trap, only the axial motion is detected directly (and also damped), by interaction with a self-resonant superconducting inductor with a Q of 33 000 and center frequency near 213 kHz, coupled to a dc SQUID.

Single $^{129,130,132}Xe^{3+}$ and $^{130}Te^{3+}$ ions were made inside the trap by electron-impact ionization of neutral atoms entering through a small hole in the upper end cap. For the xenon isotopes, small quantities of gas were admitted at the top of the cryogenic insert, approximately 2 m above the trap. In the case of tellurium, we injected vapor using an electrically heated dispenser containing a few mg of ^{130}Te powder. Unwanted ions were removed by exciting their axial motion, and then lowering the potential of the lower end cap until the ions struck it. Making single ions of the desired isotope was facilitated by using samples with more than 90% isotopic enrichment.

The use of higher charge states increases the signal for a given axial amplitude, and also the cyclotron frequency, both of which improve statistical precision. Smaller mode amplitudes reduce systematic shifts to the mode frequencies due to electrostatic and magnetic field imperfections. Further, the fractional precision with which f_z must be measured to obtain a certain fractional precision for f_c using the invariance theorem varies as $(f_z/f_c)^2$, again favoring high f_c. Hence a significant development with respect to our previous work on ^{136}Xe [10] and ^{129,132}Xe [17]—in which multiply charged xenon ions were compared with nonsimultaneously trapped, singly charged reference ions—was to extend to these heavy multicharged ions a ''two-ion technique,'' first demonstrated by the Harvard group in a mass comparison of the antiproton and negative hydrogen ion [24], which we have implemented for singly charged ions with mass number $\sim$30 [18–20]. In this technique, instead of only trapping a single ion at a time, the two ions whose cyclotron frequencies are being compared are simultaneously trapped: one ion is at the center of the trap where its cyclotron frequency is measured, while the other is temporarily ''parked'' in a large radius cyclotron orbit. The ions are then interchanged by using a sequence of rf pulses, the cyclotron frequency of the new inner ion is then measured, and so on. Since the interchange time is typically 5–10 min, this enables many more interchanges in a run time of up to 15 h (limited by the ion lifetime or the need to refill a liquid-N_2 Dewar) than the procedures of Refs. [10,16,17], in which alternation between the ion species required remaking and isolating each ion, every interchange. This advantage of increased rate of interchange, essential for reducing uncertainty in the cyclotron frequency ratio due to variation in the magnetic field, is obviously greater for ions that are difficult to make. Further, particularly for vapor injection, with possible heating of the Penning trap by thermal radiation and worsening of the trap vacuum by other gases released, it ensures uniform trap conditions for repeated measurements on the two different ions, for as long as they survive against collision with background gas. This can be several days for triply charged ions (the tellurium data was obtained with a total of three $^{130}Te^{3+}$ ions) or several weeks for singly charged ions.

The actual measurement of the cyclotron frequency of the inner ion used the ''pulse-and-phase'' technique [14]. In brief, after damping all three modes, the cyclotron motion is excited with a rf pulse near f_{ct}. Its phase is then allowed to evolve for a variable period of 0.2–58 sec, after which the final phase is coherently mapped onto the axial mode, using a ''pi pulse'' at the cyclotron-to-axial coupling frequency, $f_{cc} = f_{ct} - f_z$ [15]. The evolved cyclotron phase—which by varying the phase evolution time gives f_{ct}—and the axial frequency f_z are then determined from the ring-down signal of the axial motion following the pi pulse. The magnetron frequency f_m is then obtained from f_z and f_{ct} and a measurement of the ''trap-tilt parameter'' θ_{mag} [17,23]; f_c is then determined from f_{ct}, f_z, and f_m using the invariance theorem. For the measurements used to produce the final cyclotron frequency ratios, the radius of the inner ion's cyclotron orbit was approximately 60 μm, while the parking radius was close to 2 mm.

Cyclotron frequency ratio measurements.—The ^{130}Te − ^{130}Xe mass difference can be obtained from the cyclotron frequency ratio $^{130}Te^{3+}/^{130}Xe^{3+}$. However, instead of measuring this ratio directly we chose to obtain it from the ratio of the two ratios $^{130}Xe^{3+}/^{129}Xe^{3+}$ and $^{130}Te^{3+}/^{129}Xe^{3+}$. The reason for this is that, although most systematic errors are reduced when comparing ions of similar mass-to-charge ratio, with two ions in the trap, when their mode frequencies are very close (as is the case for the pair $^{130}Te^{3+}/^{130}Xe^{3+}$ with fractional mass difference $\sim 2 \times 10^{-5}$) the ions can no longer be manipulated independently: as we observed, the radial drives which resonantly interact with the inner ion can also excite the outer ion. The resulting systematics, though expected to decrease rapidly with increasing parking radius, are complicated and require further investigation. On the other hand, when measuring $^{130}Xe^{3+}$ and $^{130}Te^{3+}$ against $^{129}Xe^{3+}$ these particular effects are negligible, while other systematics largely cancel in the ratio of ratios. Additionally, the comparison with ^{129}Xe, whose atomic mass (along with that of ^{132}Xe) we have measured previously to better than 0.1 ppb [17], enables the absolute masses to be determined. Nevertheless, we did perform one run where we directly measured $^{130}Te^{3+}/^{130}Xe^{3+}$ with both ions in the trap; we also took data using the simpler procedure in which there is only one ion in the trap—but consisting of only a single set of three f_c measurements on $^{130}Xe^{3+}$ followed by a set of three f_c measurements on $^{130}Te^{3+}$. To help estimate uncertainties we also measured the ratio $^{132}Xe^{3+}/^{130}Xe^{3+}$ and the previously measured ratio $^{132}Xe^{3+}/^{129}Xe^{3+}$ [17]. Our results for the cyclotron frequency ratios averaged over repeated runs, along with estimated systematic corrections and uncertainties, are

TABLE I. Average cyclotron frequency (i.e., inverse mass) ratios and systematic corrections for each ion pair. N is the number of runs included in the average. Δ_{trap}, Δ_{i-i}, and Δ_{fz} are the estimated systematic corrections in parts per trillion (ppt), with estimated uncertainty in parentheses, due to trap field imperfections, ion-ion interaction, and shifts in f_z due to ion-detector interaction and differential voltage drift, respectively. σ_{syst} is the total systematic error and σ_{stat} is the statistical error (in ppt) for each average ratio. $\langle R \rangle$ is the average ratio after applying systematic corrections, with statistical and systematic uncertainties combined in quadrature, in parentheses. The three entries for $^{130}\mathrm{Te}^{3+}/^{130}\mathrm{Xe}^{3+}$ correspond to results obtained with a single ion in the trap, with two ions in the trap, and from the ratio of the $^{130}\mathrm{Te}^{3+}/^{129}\mathrm{Xe}^{3+}$ and $^{130}\mathrm{Xe}^{3+}/^{129}\mathrm{Xe}^{3+}$ ratios, respectively.

Ion pair	N	Δ_{trap}	Δ_{i-i}	Δ_{fz}	σ_{syst}	σ_{stat}	$\langle R \rangle$
$^{130}\mathrm{Xe}^{3+}/^{129}\mathrm{Xe}^{3+}$	5	1(18)	1(11)	−18(31)	38	73	0.992 311 669 329(82)
$^{130}\mathrm{Te}^{3+}/^{129}\mathrm{Xe}^{3+}$	3	−5(17)	1(11)	−11(30)	36	75	0.992 290 942 332(83)
$^{132}\mathrm{Xe}^{3+}/^{130}\mathrm{Xe}^{3+}$	5	−5(34)	2(22)	−35(34)	53	83	0.984 832 390 737(98)
$^{132}\mathrm{Xe}^{3+}/^{129}\mathrm{Xe}^{3+}$	6	−8(45)	2(33)	−22(38)	68	65	0.977 260 673 493(94)
$^{130}\mathrm{Te}^{3+}/^{130}\mathrm{Xe}^{3+}$ (1 ion)	1	−7(26)	0(0)	34(15)	30	252	0.999 979 112 310(254)
$^{130}\mathrm{Te}^{3+}/^{130}\mathrm{Xe}^{3+}$ (2 ion)	1	2(6)	0(60)	0(16)	62	182	0.999 979 112 415(192)
$[^{130}\mathrm{Te}^{3+}/^{130}\mathrm{Xe}^{3+}]$ $(^{129}\mathrm{Xe}^{3+})$		−6(11)	0(2)	7(13)	17	97	0.999 979 112 412(98)

given in Table I. As can be seen, the three different methods for obtaining the $^{130}\mathrm{Te}^{3+}/^{130}\mathrm{Xe}^{3+}$ ratio gave results consistent within their errors.

Systematic corrections and error estimates.—Under the heading Δ_{trap} in Table I we list estimates of the small corrections that we apply to the observed cyclotron frequency ratios to allow for imperfections in the quadratic electrostatic potential and the uniform magnetic field of the trap [17,22]. The main contribution to the uncertainty is in determining the lowest-order electrostatic field imperfection. Under Δ_{trap} we also include the effect of uncertainty in the trap-tilt parameter, $\theta_{\mathrm{mag}} = 0.57(5)°$. Under Δ_{i-i} we list estimates of the shifts to the ratios from perturbation of f_{ct} and f_z of the inner ion due to Coulomb interaction with the outer ion [18]. Although the estimated shifts are negligible, we assigned larger uncertainties using measurements of the $^{132}\mathrm{Xe}^{3+}/^{129}\mathrm{Xe}^{3+}$ ratio at different ρ_{ck}. For $^{130}\mathrm{Te}^{3+}/^{130}\mathrm{Xe}^{3+}$ (2 ion) we have also included an estimate of the shift (in fact small due to cancellations) due to the drives applied at f_{ct} or f_{cc} of the inner ion exciting the outer ion, hence affecting the ion-ion interaction. Under Δ_{fz} we give the (significant) systematic corrections we applied to our measured ratios to allow for shifts to the axial frequency due to the "frequency-pushing" interaction of the ion with the resonant detection circuit [17], and due to small ion-differential drifts in the trap voltage [25]. Systematic shifts to the ratio due to the ions' image charges in the trap electrodes, and also due to a possible m/q dependence of the ions' equilibrium positions, are both estimated to be negligible. Overall, the largest contribution to the uncertainty in the ratios was the statistical error of the simultaneous fits to the f_c measurements, which was mainly due to magnetic field variation.

Atomic masses of ^{130}Te, ^{130}Xe, *and* $Q_{\beta\beta}(^{130}\mathrm{Te})$.—We first convert the cyclotron frequency ratios into mass differences between neutral atoms. To do this we account for the mass of the missing electrons, and the ionization and chemical binding energies, which we obtained from Refs. [26–28]. The mass differences corresponding to the ratios in Table I are given in Table II. We note our value for the $^{132}\mathrm{Xe} - {}^{129}\mathrm{Xe}$ mass difference is in excellent agreement with the value 2.999 374 228(6) u (statistical error only), obtained from measurements of $M(^{129}\mathrm{Xe})$ and $M(^{132}\mathrm{Xe})$ using single ions in Ref. [17].

The data in Table II are intended for use in global, least-squares mass evaluations. Here, for simplicity, we obtain the absolute masses of ^{130}Te and ^{130}Xe using only the mass differences in the first three rows, together with the masses of ^{129,132}Xe in Ref. [17] which we treat as reference masses. For ^{130}Xe we obtain two values from the ratios

TABLE II. Mass difference equations corresponding to the ratios given in Table I. The statistical, systematic, and total errors are shown in parentheses.

Ion pair	Mass difference	Result (u)
$^{130}\mathrm{Xe}^{3+}/^{129}\mathrm{Xe}^{3+}$	^{130}Xe-^{129}Xe	0.998 728 483(10)(5)(12)
$^{130}\mathrm{Te}^{3+}/^{129}\mathrm{Xe}^{3+}$	^{130}Te-^{129}Xe	1.001 441 885(10)(5)(12)
$^{132}\mathrm{Xe}^{3+}/^{130}\mathrm{Xe}^{3+}$	^{132}Xe-^{130}Xe	2.000 645 724(11)(7)(14)
$^{132}\mathrm{Xe}^{3+}/^{129}\mathrm{Xe}^{3+}$	^{132}Xe-^{129}Xe	2.999 374 229(9)(9)(13)
$^{130}\mathrm{Te}^{3+}/^{130}\mathrm{Xe}^{3+}$ (1 ion)	^{130}Te-^{130}Xe	0.002 713 416(33)(4)(34)
$^{130}\mathrm{Te}^{3+}/^{130}\mathrm{Xe}^{3+}$ (2 ion)	^{130}Te-^{130}Xe	0.002 713 402(24)(9)(26)
$[^{130}\mathrm{Te}^{3+}/^{130}\mathrm{Xe}^{3+}]$ $(^{129}\mathrm{Xe}^{3+})$	^{130}Te-^{130}Xe	0.002 713 402(13)(3)(14)

TABLE III. Atomic masses of ^{130}Xe and ^{130}Te obtained from the different ratios, and their weighted averages, compared with previous values.

Atom	Source	Atomic mass (u)
^{130}Xe	$^{130}Xe^{3+}/^{129}Xe^{3+}$	129.903 509 342(16)
	$^{132}Xe^{3+}/^{130}Xe^{3+}$	129.903 509 362(17)
	Average	129.903 509 351(15)
	AME2003 [13]	129.903 508 0(8)
^{130}Te	$^{130}Te^{3+}/^{129}Xe^{3+}$	129.906 222 744(16)
	AME 2003 [13]	129.906 224 4(21)

$^{132}Xe^{3+}/^{130}Xe^{3+}$ and $^{130}Xe^{3+}/^{129}Xe^{3+}$. We take the weighted average, linearly propagating the systematic uncertainty and the uncertainties in the reference masses. These are compared with values from the AME2003 in Table III.

Using the mass difference given in the last row of Table II only, i.e., from the ratios with respect to $^{129}Xe^{3+}$, and 1 u = 931.494 043(80) MeV/c^2 [29], we determine the ^{130}Te − ^{130}Xe double-β-decay Q value to be 2527.518(13) keV. Because their uncertainties are larger (and uncertain), we let the other two values for this mass difference remain as checks.

Using precision cryogenic Penning-trap techniques with two simultaneously trapped, triply charged ions we have measured the atomic masses of ^{130}Te and ^{130}Xe to better than 0.2 ppb fractional precision. The mass-energy difference $[M(^{130}\text{Te})\text{-}M(^{130}\text{Xe})]c^2$, equal to the Q value for the double-β decay of ^{130}Te, has been obtained with a 1σ uncertainty of 13 eV. The individual masses of ^{130}Xe and ^{130}Te improve upon results in the AME2003 [13] by factors of 50 and 130, respectively. Our new value for $Q_{\beta\beta}$ (^{130}Te) agrees with that of the AME2003, but is a factor of 150 more precise. Compared to the energy calibration uncertainty of the CUORICINO and CUORE ^{130}Te neutrinoless double-β-decay experiments, the result provides the necessary order of magnitude improvement for a reliable determination of the location of the peak in the total-electron spectrum, with a further order of magnitude available for possible future developments.

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Note added in proof.—A ^{130}Te double-β-decay Q value of 2527.01(0.32) keV has been recently reported by Scielzo *et al.* [30].

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