New determination of double-β-decay properties in $^{48}$Ca: high-precision $Q_{\beta\beta}$-value measurement and improved nuclear matrix element calculations

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We report a direct measurement of the $Q_{\beta\beta}$-value of the neutrinoless double-β-decay candidate $^{48}$Ca at the TITAN Penning-trap mass spectrometer, with the result that $Q_{\beta\beta} = 4267.98(32)$ keV. We measured the masses of both the mother and daughter nuclides, and in the latter case found a 1 keV deviation from the literature value. In addition to the $Q_{\beta\beta}$-value, we also present results of a new calculation of the neutrinoless double-β-decay nuclear matrix element of $^{48}$Ca. Using diagrammatic many-body perturbation theory to second order to account for physics outside the valence space, we constructed an effective shell-model double-β-decay operator, which increased the nuclear matrix element by about 75% compared with that produced by the bare operator. The new $Q_{\beta\beta}$-value and matrix element strengthen the case for a $^{48}$Ca double-β-decay experiment.

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The discovery of neutrino oscillations represents the first evidence for new physics beyond the Standard Model [1, 2]. The oscillations conclusively demonstrate that neutrinos have mass, that flavor eigenstates are mixtures of mass eigenstates, and that neutrino physics is more complicated than we had thought. The observation of neutrinoless double-β ($0\nu\beta\beta$) decay, extremely rare if it exists, would at once fill multiple gaps in our understanding of the neutrino’s nature and would represent a major breakthrough for particle physics. Since this lepton-number-violating process can occur only if the neutrino is its own antiparticle, its discovery would unambiguously confirm the neutrino as a Majorana particle, while a measured lifetime would provide a value for the neutrino mass scale [3]. In order to extract that value from the $0\nu\beta\beta$-decay half-life, however, two quantities must be accurately determined: a phase-space factor, which depends on the $Q_{\beta\beta}$-value of the decay, and a nuclear matrix element, which is not observable and therefore must be obtained from nuclear structure theory.

The twelve nuclides that have been observed to undergo two-neutrino double-β ($2\nu\beta\beta$) decay [4, 5] are a basis for a number of large-scale experimental $0\nu\beta\beta$-decay searches currently underway. Of these nuclides, $^{48}$Ca possesses the largest $Q_{\beta\beta}$-value of 4.3 MeV [6], giving it several distinct experimental advantages. Because the $Q_{\beta\beta}$-value lies well above the energy of naturally occurring background, a good signal-to-noise ratio is ensured, while the large phase-space factor enhances the $0\nu\beta\beta$-decay rate. The low isotopic abundance of $^{48}$Ca, however, requires enrichment. $^{48}$Ca is currently being measured at NEMO-III [7] and studied at CANDLES [8] and CARVEL [9]. The $Q_{\beta\beta}$-value provides vital input for the simulation of signal and background, the analysis of current data, and the design of future detectors. In order for the uncertainty of the $Q_{\beta\beta}$-value to be negligible in these studies, the required precision has to be better than the intrinsic resolution of the detector.

The deep implications of massive neutrinos have led to a concentrated effort to calculate the nuclear matrix element for $0\nu\beta\beta$-decay candidates. Various predominantly phenomenological many-body calculations for $^{48}$Ca currently agree to within a factor of about three [10, 11]. That uncertainty implies the same factor of three in an extracted neutrino mass; consequently, improved calculations are vital. $^{48}$Ca occupies a unique position among $0\nu\beta\beta$-decay candidates in that its relatively low mass and doubly magic nature make it a near ideal case for several ab-initio many-body methods developed for medium-mass nuclei. Many calculations of ground- and excited-state energies with two- (NN) and three-nucleon (3N)
forces in the calcium region exist and agree with each other \[12–18\], but no attempt has yet been made to calculate the 0\(\nu\)\(\beta\beta\)-decay matrix element in \(^{48}\text{Ca}\) at the same level of sophistication. Here, using methods first applied to \(^{76}\text{Ge}\) and \(^{82}\text{Se}\) \[19–21\], we applied chiral nuclear forces \[22\] and diagrammatic many-body perturbation theory to calculate an effective shell model 0\(\nu\)\(\beta\beta\)-decay operator for \(^{48}\text{Ca}\). We found an increase in the nuclear matrix element of \(\approx 75\%\) compared to that produced by the bare operator alone, and estimated a further increase of \(\approx 8\%\) from moving beyond the closure approximation. To derive the decay rate, the resulting nuclear matrix element is combined with the phase space factor, which depends on the \(Q_{\beta\beta}\)-value to the fifth power. We have determined the \(Q_{\beta\beta}\)-value in a direct measurement at TRIUMF’s Ion Trap for Atomic and Nuclear science (TITAN).

TITAN is an ion trap system coupled to the ISAC-TRIUMF rare beam facility. It consists of three traps: a radiofrequency quadrupole (RFQ) beam cooler and buncher \[23\], an electron beam ion trap (EBIT) \[24\], and a measurement Penning trap (MPET) \[25\]; the EBIT was not used in this experiment. Ions were delivered from either ISAC’s Off-Line Ion Source (OLIS) \[28\] or TITAN’s surface-ionization Ion Source (TIS). For the production of \(^{48}\text{Ca}\), an enriched ion source was heated in the TIS whereas \(^{48}\text{Ti}\) and \(^{14}\text{N}^{18}\text{O}^{16}\text{O}^+\) ions were produced with OLIS. The beams from the TIS and OLIS were delivered independently.

The continuous beam from either ion source was accumulated, cooled, and bunched in the RFQ. A fast time-of-flight mass filter \[29\] placed between the RFQ and the MPET and a dynamic capture process in the Penning trap ensured pure isobaric ion bunches in MPET. In addition, dipole cleaning \[31\] was applied to remove any remaining contaminant ions. In a Penning trap, the mass of an ion is measured via the determination of the cyclotron frequency \(2\pi\nu_c = q/m \cdot B\), where \(q/m\) is the charge-to-mass ratio and \(B\) the magnetic field strength. The masses were determined using two excitation schemes: the conventional time-of-flight ion-cyclotron-resonance (TOF-ICR) method \[31, 32\], whereby the ions were excited with a continuous RF field for a time \(T_{\text{RF}}\) (Fig. 1a) and the Ramsey technique \[24, 33\], wherein the oscillatory field was applied in two pulses separated by a waiting period (Fig. 1b). For this, two 200 ms RF pulses were spaced apart by 1553 ms, denoted as 200-1553-200 ms.

The \(\nu_c\) measurements of \(^{48}\text{Ca}^+, {^{48}}\text{Ti}^+,\) and \(^{18}\text{N}^{16}\text{O}^{16}\text{O}^+\) were interleaved; thus, the primary experimental result is the ratio of their cyclotron frequencies, listed in Tab. 1. A statistical uncertainty of \(\delta R/R = 3 \cdot 10^{-9}\) was achieved. Systematic uncertainties were carefully evaluated. These include simultaneous storage of multiple ions, either of the same or different species. To determine the influence of ion-ion-interactions \[38\], we analyzed the data considering only events of one detected ion. Moreover, a count-class analysis \[39\] was applied and, to be conservative, we added the difference in the ratios in quadrature to the statistical uncertainty. In addition, nonlinear decay in the magnetic field may cause shifts in the system of 0.04(11) ppb/h \[40\]; as measurements with \(T_{\text{RF}} \approx 2\) s were separated by approximately 1.5 hours, a 0.23 ppb correction was included. Further off-line studies revealed frequency shifts on the level of 1.3 ppb as a result of unbalanced RF excitation stemming from instabilities in the frequency generator trigger. As all measured ions were isobars, with identical nominal \(m/q\), they followed the same nominal ion trajectory and experienced the same magnetic and electric fields. Thus, relativistic effects and any mass-dependent effects canceled in the ratio. We varied the excitation times (for conventional excitations \(T_{\text{RF}} = 0.457, 1.913, 1.953\) s; for Ramsey 150-653-150 and 200-1553-200 ms) for different data sets to investigate excitation-scheme dependent effects. In addition, the time window allowed for the dynamic capture of the ion bunch in the Penning trap, was varied by -0.5 \(\mu s\) and +0.3 \(\mu s\) from the optimal value to verify the trap compensation (see e.g. \[23\]). No statistically significant differences were observed for any of these variations, and all data sets were included in the weighted average. All

**TABLE I.** The \(Q_{\beta\beta}\) value of \(^{48}\text{Ca}\) and the masses of mother and daughter nuclides were found by interleaving cyclotron-frequency measurements of \(^{48}\text{Ca}^+, {^{48}}\text{Ti}^+,\) and \(^{18}\text{N}^{16}\text{O}^{16}\text{O}^+\); the tabulated ratios are the weighted average of seven data sets. The total (statistical and systematic) is listed in parentheses and the statistical uncertainty in square brackets. The last column indicates the precision \(\delta R/R\) achieved.

| Species | Ratio | Precision |
|---------|-------|-----------|
| \(^{48}\text{Ca}^+, {^{48}}\text{Ti}^+,\) | 0.999 904 448 9(46)\[31\] | 5 \(\times\) 10^{-9}\ |
| \(^{48}\text{Ca}^+, {^{18}}\text{N}^{16}\text{O}^{16}\text{O}^+\) | 1.000 930 621 6(61)\[35\] | 6 \(\times\) 10^{-9}\ |
| \(^{48}\text{Ti}^+, {^{18}}\text{N}^{16}\text{O}^{16}\text{O}^+\) | 1.001 026 276 6(47)\[41\] | 5 \(\times\) 10^{-9}\ |
Table II. A comparison of the $Q_{\beta\beta}$ and mass excesses (ME) determined in this work to recent values. ISOLTRAP had determined the mass of TiO using the reference masses $^{87}$Rb and $^{50}$Mn as $-4892.9(1.0)$ and $-4892.5(1.2)$ keV respectively; the weighted average is listed below. All values are in keV.

|       | TITAN | LEBIT | ISOLTRAP | AME 2003 | AME 2012 |
|-------|-------|-------|-----------|----------|----------|
| $Q_{\beta\beta}$ | 4267.98(32) | 4268.121(79) | | 4273.60(4.00) | 4266.98(38) |
| ME($^{48}$Ca) | $-44224.45(27)$ | $-44224.767(194)$ | | $-44214(4)$ | $-44224.750(120)$ |
| ME($^{48}$Ti) | $-48492.70(21)$ | | $-48492.3(8)$ | $-48487.7(8)$ | $-48491.734(358)$ |
| Ref. | this work $^{[34, 35]}$ | | $^{[36]}$ | $^{[37]}$ | $^{[6]}$ |

Systematic uncertainties were added in quadrature to the statistical uncertainty and are included in Table II. The ratios $R$ can be related to the $Q_{\beta\beta}$-value and were used to find the masses of Ca and Ti from that of N$^{18}$O$^0$ by

$$Q_{\beta\beta} = (R - 1)(M_{T_i} - m_{e}) + RB_{T_i} - B_{Ca}$$

(1)

$$M_{Ca,Ti} = R(M_{N^{18}O} - m_{e}) + m_{e} + RB_{N^{18}O} - B_{Ca,Ti}$$

(2)

where $M$ refers to the atomic mass, $m_{e}$ the electron mass, $B$ the electron binding energy of the outermost electron and the subscripts identify the nuclide. Values for $B$ were taken from $^{[11]}$. Table II compares the values achieved in this work with values found in recent literature.

The following results could be extracted: We determined for the first time the atomic mass of $^{48}$Ti directly using Penning trap mass spectrometry and found the mass error to be $-48492.71(21)$ keV; this is a 2.2σ deviation from the Atomic Mass Evaluation (AME) 2012. We also confirm the mass measurement of $^{48}$Ca of $^{[34]}$, which deviates 10.6(4.1) keV from the previous evaluation in 2003 $^{[37]}$. Finally, we measured the $Q_{\beta\beta}$-value, the most relevant parameter for the $0\nu\beta\beta$ decay, to be 4267.98(32) keV from direct frequency ratios. This value disagrees with the $Q_{\beta\beta}$-value as evaluated in AME 2012, which is $-48491.734(358)$ keV. The ratios $R$ can be related to the $Q_{\beta\beta}$-value and were used to find the masses of Ca and Ti from that of N$^{18}$O$^0$ by

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(2)

with $Q_{\beta\beta}$ being the $0\nu\beta\beta$ decay operator. The effect of correlations outside the valence space on the $0\nu\beta\beta$-decay nuclear matrix element thus remains an open question.

Many-body perturbation theory (MBPT) provides a diagrammatic prescription to account for excitations outside the valence space directly from nuclear forces $^{[43, 44]}$. When carried out to sufficiently high order, diagonalization of the resulting effective valence-space Hamiltonian, $H_{eff}$, will reproduce exactly a subset of eigenvalues of the full $A$-body problem (provided the series converges). Despite its long history and recent success in producing ab-initio valence-space Hamiltonians from NN and 3N forces $^{[12, 13]}$, MBPT is only now being extended to calculate effective two-body operators $^{[19–21]}$. We applied this formalism to construct an effective valence-space $0\nu\beta\beta$-decay operator for $^{48}$Ca.

We took as our valence space the standard $pf$ shell, consisting of $f_{7/2}$, $p_{3/2}$, $p_{1/2}$, $f_{5/2}$ orbitals above a $^{40}$Ca core. We first constructed the $X$-box, an object which includes all “unfolded” diagrams containing the $0\nu\beta\beta$-decay transition operator $^{[21]}$. At lowest order, $X$ is the bare $0\nu\beta\beta$-decay operator, and in the current work, we truncated $X$ at second-order in the nuclear interaction. To obtain the final effective $0\nu\beta\beta$-decay operator, we included once-folded $X$-box diagrams and state norms as in Ref. $^{[21]}$. The interaction in these diagrams was the NN force derived from chiral effective field theory (EFT) at order $N^3LO$ $^{[45]}$ and evolved to low momentum (yielding the potential $V_{low-k}$) via renormalization group methods $^{[46]}$. To obtain the nuclear matrix element itself, the following relations hold:

$$M_{0\nu} = M_{0\nu}^{GT} - \frac{g_V^2}{g_A^2} M_{0\nu}^{F} + M_{0\nu}^{T}$$

(3)

where $g_V$ and $g_A$ are the axial and vector coupling constants, and in addition to the usual Gamow-Teller and Fermi terms, we also include the tensor part, which has been shown to be non-negligible in $^{48}$Ca $^{[42]}$. Of the theoretical methods used to calculate this matrix element, only the nuclear shell model provides an exact treatment of many-body correlations, albeit within a truncated single-particle space (valence space) above an inert core. Though nearly all shell-model Hamiltonians to date rely on phenomenological adjustments to mimic correlations outside the valence space, no modifications are made to the $0\nu\beta\beta$-decay operator. The effect of correlations outside the valence space on the $0\nu\beta\beta$-decay nuclear matrix element thus remains an open question.
TABLE III. The $0\nu\beta\beta$-decay matrix elements $M_{0\nu}$ for $^{48}\text{Ca}$ at various approximations in our many-body framework.

| Matrix Element | $M_{0\nu}$ | $\frac{dM_{0\nu}}{dk}$ | $M_{0\nu}^F$ | $M_{0\nu}^B$ | $M_{0\nu}^{\text{Sum}}$ |
|----------------|------------|------------------------|-------------|-------------|------------------|
| Bare matrix element | 0.675 | 0.130 | -0.072 | 0.733 |
| First-order $X$-box, no 3p-1h | 1.340 | 0.225 | -0.064 | 1.501 |
| Full first-order $X$-box | 0.616 | 0.125 | -0.123 | 0.619 |
| Full second-order $X$-box | 1.822 | 0.233 | -0.063 | 1.992 |
| Final matrix element | 1.211 | 0.160 | -0.070 | 1.301 |

we combined our effective operator with wave functions calculated from the GXPF1A interaction [41].

Our results for the $^{48}\text{Ca}$ nuclear matrix element appear in Tab. III where we list the contributions to the different parts of the operator at various orders in $V_\text{low}$.

We see the same trends as in $^{82}\text{Se}$ and $^{76}\text{Ge}$, namely, at first-order, ladder effects increase the total matrix element by a factor of two, followed by a significant reduction from core-polarization diagrams. Here, however, the effects of second-order diagrams ($\approx 120$ in all) and folding are larger, yielding a final value $\approx 75\%$ larger than that obtained from the bare $0\nu\beta\beta$-decay operator alone. (The increase in $^{76}\text{Ge}$ and $^{82}\text{Se}$ was less than half as much.) We also found that the bare matrix element increased by $8\%$ when we avoided the closure approximation. Although we cannot avoid closure for our effective operator, its matrix element would likely increase by a similar amount.

Though these calculations represent significant progress towards a fully ab-initio calculation and offer our best estimate for the nuclear matrix element with $^{48}\text{Ca}$, the large second-order contributions to $X$ mean that higher-order contributions could also be significant.

Pushing to higher order will be difficult, but we plan other improvements: replacing the phenomenological wavefunctions by those obtained from an ab-initio $H_{\text{dd}}$, including the effects of two-body weak currents in the bare operator [48], investigating the size of induced three-body operators [49], and including 3N forces in intermediate-state $X$-box excitations.

In conclusion, we provided two improved quantities for $^{48}\text{Ca}$ $0\nu\beta\beta$ decay that together are required to extract the effective Majorana neutrino mass from the decay rate. The $Q_{\beta\beta}$ value is now precisely determined in a self-consistent way and confirm a large deviation from separate determinations. The discrepancy with the accepted $^{48}\text{Ti}$ mass value, uncovered in the recent LEBIT $Q_{\beta\beta}$-value measurement, has been resolved by our mass measurement, revealing a shift of $\approx 1$ keV. In addition, we obtained the nuclear matrix element by including the effects of levels outside the valence space in a shell model calculation. These efforts make a $0\nu\beta\beta$ experiment in $^{48}\text{Ca}$ more attractive.

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\[ ^{\text{3}} \text{Y. Fukuda et al. (Super-Kamiokande Collaboration), Phys. Rev. Lett. 81, 1562 (1998)} \]

\[ ^{\text{4}} \text{Q. R. Ahmad et al., Phys. Rev. Lett. 89, 011302 (2002)} \]

\[ ^{\text{5}} \text{P. T. Avignone III, S. R. Elliott, and J. Engel, Rev. Mod. Phys. 80, 481 (2008)} \]

\[ ^{\text{6}} \text{A. S. Barbash, Phys. Atom. Nucl. 73, 162 (2010)} \]

\[ ^{\text{7}} \text{N. Ackerman et al. (EXO Collaboration), Phys. Rev. Lett. 107, 212501 (2011)} \]

\[ ^{\text{8}} \text{G. Audi, M. Wang, A. H. Wapstra, F. G. Kondev, M. MacCormick, X. Xu, and B. Pfeiffer, Chin. Phys. C 36, 1287 (2012)} \]

\[ ^{\text{9}} \text{R. Arnold et al. (NEMO Collaboration), Phys. Rev. Lett. 95, 183202 (2005)} \]

\[ ^{\text{10}} \text{S. Umehara et al., J. Phys.: Conf. Ser. 39, 356 (2006)} \]

\[ ^{\text{11}} \text{Y. G. Zdesenko et al., Astropart. Phys. 23, 249 (2005)} \]

\[ ^{\text{12}} \text{E. Caurier, J. Menéndez, F. Nowacki, and A. Poves, Phys. Rev. Lett. 100, 052503 (2008)} \]

\[ ^{\text{13}} \text{J. Barea, J. Kotíka, and F. Iachello, Phys. Rev. Lett. 109, 042501 (2012)} \]

\[ ^{\text{14}} \text{J. D. Holt, T. Otsuka, A. Schwenk, and T. Suzuki, J. Phys. G 39, 085111 (2012)} \]

\[ ^{\text{15}} \text{J. D. Holt, J. Menéndez, and A. Schwenk, J. Phys. G 40, 075105 (2013)} \]

\[ ^{\text{16}} \text{A. T. Gallant et al., Phys. Rev. Lett. 109, 032506 (2012)} \]

\[ ^{\text{17}} \text{F. Wienholtz et al., Nature 498, 346 (2013)} \]

\[ ^{\text{18}} \text{G. Hagen, M. Hjorth-Jensen, G. R. Jansen, R. Machleidt, and T. Papenbrock, Phys. Rev. Lett. 109, 032502 (2012)} \]

\[ ^{\text{19}} \text{R. Roth, S. Binder, K. Vobig, A. Calci, J. Langhammer, and P. Navrátil, Phys. Rev. Lett. 109, 052501 (2012)} \]

\[ ^{\text{20}} \text{H. Hergert, S. K. Bogner, S. Binder, A. Calci, J. Langhammer, R. Roth, and A. Schwenk, Phys. Rev. C 87, 034307 (2013)} \]

\[ ^{\text{21}} \text{J. Engel and G. Hagen, Phys. Rev. C 79, 064317 (2009)} \]

\[ ^{\text{22}} \text{E. Epelbaum, H. W. Hammer, and U. G. Meiβner, Phys. Rev. C 87, 064315 (2013)} \]

\[ ^{\text{23}} \text{J. Engel et al., Phys. Rev. Lett. 110, 012501 (2013)} \]
[23] M. König, G. Bollen, H.-J. Kluge, T. Otto, and J. Szeryp, Int. J. Mass Spectrom. 142, 95 (1995)
[24] M. Kretzschmar, Int. J. Mass Spectrom. 264, 122 (2007)
[25] T. Brunner et al., Nucl. Instrum. Meth. A 676, 32 (2012)
[26] A. Lapierre et al., Nucl. Instrum. Meth. A 624, 54 (2010)
[27] M. Brodeur et al., Int. J. Mass Spectrom. 310, 20 (2012)
[28] K. Jayamanna et al., Rev. Sci. Instrum. 79, 02C711 (2008)
[29] T. Brunner et al., Int. J. Mass Spectrom. 97 (2011)
[30] G. Bollen et al., Nucl. Instrum. Meth. A 68, 4355 (1990)
[31] G. Gräff, H. Kalinowsky, and J. Traut, Z. Phys. A-Hadron Nucl. 297, 35 (1980)
[32] G. Bollen, R. B. Moore, G. Savard, and H. Stolzenberg, J. Appl. Phys. 68, 675 (1996)
[33] S. Naimi et al., Phys. Rev. C 86, 014325 (2012)
[34] G. Audi, A. Wapstra, and C. Thibault, Nucl. Phys. A 729, 337 (2003)
[35] G. Bollen, H. J. Kluge, M. König, T. Otto, G. Savard, H. Stolzenberg, and G. Audi, Phys. Rev. C 46, R2140 (1992)
[36] A. Kellerbauer, K. Blaum, G. Bollen, F. Herfurth, H. J. Kluge, M. Kuckein, E. Sauvan, C. Scheidenberger, and L. Schweikhard, Eur. Phys. J. D 22, 53 (2003)
[37] M. Brodeur et al., Phys. Rev. C 80, 044318 (2009)
[38] R. A. Dragoset, A. Musgrove, C. W. Clark, and W. C. Martin, “NIST periodic table: Atomic properties of elements,” (February 2012), national Institute of Standards and Technology, Gaithersburg, MD, Available at [http://www.nist.gov/pml/data], http://www.nist.gov/pml/data/
[39] J. Menéndez, A. Poves, E. Caurier, and F. Nowacki, Nucl. Phys. A 818, 139 (2009)
[40] T. T. S. Kuo and E. Osnes, Folded-Diagram Theory of the Effective Interaction in Nuclei, Atoms and Molecules (Lecture Notes in Physics) (Springer-Verlag, 1991)
[41] M. Hjorth-Jensen, T. T. S. Kuo, and E. Osnes, Phys. Rev. C 68, 044316 (2003)
[42] S. K. Bogner, R. J. Furnstahl, and A. Schwenk, Prog. Part. Nucl. Phys. 65, 94 (2010)
[43] M. T. Homma, T. Otsuka, B. A. Brown, and T. Mizusaki, Phys. Rev. C 69, 034335 (2004)
[44] J. Menéndez, D. Gazit, and A. Schwenk, Phys. Rev. Lett. 107, 062501 (2011)
[45] D. Shukla, J. Engel, and P. Navrátil, Phys. Rev. C 84, 044316 (2011)