First Direct Double-β Decay Q-Value Measurement of ^{82}Se in Support of Understanding the Nature of the Neutrino

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In anticipation of results from current and future double-β decay studies, we report a measurement resulting in a ^{82}Se double-β decay Q value of 2997.9(3) keV, an order of magnitude more precise than the currently accepted value. We also present preliminary results of a calculation of the ^{82}Se neutrinoless double-β decay nuclear matrix element that corrects in part for the small size of the shell model single-particle space. The results of this work are important for designing next generation double-β decay experiments and for the theoretical interpretations of their observations.

The results of recent neutrino oscillation experiments indicate that the mass of the neutrino is nonzero [1–3]. The mass hierarchy and the absolute mass scale of the neutrino, however, are unknown. Furthermore, the nature of the neutrino is also unknown; is it a Dirac or Majorana particle, i.e., is the neutrino its own antiparticle? The only known practical method for determining the nature of the neutrino is through neutrinoless double-β decay ($0\nu\beta\beta$ decay) measurements [4]. Interest in double-β decay ($\beta\beta$ decay) has been increasing since the laboratory verification of the weak, but allowed, two-neutrino double-β decay ($2\nu\beta\beta$ decay) of ^{82}Se [5]. Including laboratory, geochemical, and radiochemical experiments, twelve isotopes have been observed to undergo $2\nu\beta\beta$ decay: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{128}Te, ^{130}Te, ^{136}Xe, ^{150}Nd, ^{238}U, and ^{130}Ba [6,7]. With the exception of the controversial claim in Ref. [8], $0\nu\beta\beta$ decay has yet to be observed. If experiments succeed in observing $0\nu\beta\beta$ decay, we would have evidence that the neutrino is a Majorana particle and that conservation of total lepton number is violated—a situation forbidden by the standard model of particle physics.

An extensive campaign is currently underway to develop next-generation experiments to detect $0\nu\beta\beta$ decay in a number of candidate isotopes (see Ref. [9] for a current review of planned experiments). One such experiment, SuperNEMO, is expected to provide an increase in sensitivity of 3 orders of magnitude over its predecessor, NEMO-III, and is projected to reach a half-life sensitivity at the 90% confidence level of $1–2 \times 10^{26}$ years by observing 100–200 kg of ^{82}Se for five years [9,10].

The defining observable of $0\nu\beta\beta$ decay is a single peak in the electron sum-energy spectrum at the $\beta\beta$ decay Q value, $Q_{\beta\beta}$. Hence, it is crucial to have an accurate determination of $Q_{\beta\beta}$. The Q value is also a key parameter required to determine the phase space factor (PSF) of the decay. The effective Majorana neutrino mass, together with the corresponding PSF and nuclear matrix element (NME) for a $0\nu\beta\beta$ decay candidate, provide the necessary information to determine the $0\nu\beta\beta$ decay half-life, which is given by

$$(T_{1/2}^{0\nu})^{-1} = G_{0\nu}(Q_{\beta\beta}{}^5, Z)|M_{0\nu}|^2(\langle m_{\beta\beta}\rangle/m_e)^2, \quad (1)$$

where M is the relevant NME, $\langle m_{\beta\beta}\rangle$ is the effective Majorana mass of the neutrino, m_e is the mass of the electron, and $G_{0\nu}$ is the PSF for the $0\nu\beta\beta$ decay, which is a function of $Q_{\beta\beta}{}^5$ and the nuclear charge, Z. Thus, to obtain an accurate estimation of the half-life sensitivity needed to detect a given $\langle m_{\beta\beta}\rangle$, or conversely, to determine $\langle m_{\beta\beta}\rangle$ if the half-life is measured, the NME and especially the Q value need to be known to high precision.

Of all the $0\nu\beta\beta$ decay candidates currently employed in experiments, ^{82}Se is the only one whose Q value has not been measured directly through high-precision Penning trap mass spectrometry (PTMS). PTMS has proven itself to be the most precise and accurate method for determining atomic masses and therefore, Q values [11]. In some cases $Q_{\beta\beta}$ values determined prior to direct Penning trap measurements have been found to be off by more than 10 keV [12,13]. Furthermore, careful calculations of the NME for ^{82}Se $0\nu\beta\beta$ decay [14–18] differ from one another by more

than a factor of 2. In this Letter, in anticipation of
SuperNEMO and other possible experiments with ^{82}Se,
we present the results of a direct measurement of $Q_{\beta\beta}$
with the low-energy beam and ion trap (LEBIT) PTMS
facility and results to improve shell model calculations of
the NME.

The direct $Q_{\beta\beta}$ measurement for ^{82}Se was carried out
at the National Superconducting Cyclotron Laboratory
(NSCL) using the LEBIT facility, a Penning trap mass
spectrometer facility for high precision mass measure-
ments on isotopes produced via projectile fragmentation
[19]. We used the plasma ion source of the LEBIT facility
to simultaneously produce ions of ^{82}Se and of the $\beta\beta$
decay daughter, ^{82}Kr. The source was equipped with a
ceramic charge holder and was filled with ∼200 mg of
granulated selenium which was vaporized by the heat from
the ion source filament. A helium support gas for the
source was mixed with a small amount of krypton to obtain
a similar beam current of ^{82}Kr$^+$ to ^{82}Se$^+$ within a factor
of 3. The extracted ion beam was guided through a radio-
frequency quadrupole (RFQ) mass filter to suppress the
strong accompanying helium current before injection into a
cryogenic RFQ beam cooler and buncher for the creation
of low-emittance ion bunches that are sent to the LEBIT
9.4 T Penning trap [20]. On their path the ions were
purified further by using a time-of-flight mass separation
scheme [21], allowing only ion species of the same mass-
to-charge ratio to be dynamically captured in the trap.

At the LEBIT facility, the cyclotron frequency, $\nu_c =
qB/2\pi m$, of an ion with mass-to-charge ratio, m/q, in a
magnetic field, B, is measured using the time-of-flight
(TOF) ion-cyclotron resonance detection technique
[22,23]. First, isobaric contaminants are removed from the
Penning trap by driving them to large radial orbits with a
radio frequency (rf) azimuthal dipole field. To measure ν_c,
the trapped ions are exposed to an azimuthal quadrupole rf
field at a frequency ν_{rf} near their cyclotron frequency with
the appropriate rf amplitude and excitation time [22,23].
After ejection from the trap, the ions travel through the
inhomogeneous section of the magnetic field, where the
energy of the ions' radial motion is transferred to the axial
direction [24], and are detected on a microchannel plate
(MCP) detector. In resonance, i.e., $\nu_{\mathrm{rf}} = \nu_c$, the energy
pickup of the ions' radial motion is maximized and their
TOF to the MCP is minimized [22]. For a cyclotron fre-
quency determination, this cycle of trapping, excitation,
ejection, and TOF measurement is repeated for different
frequencies. This leads to cyclotron resonance curves, as
shown in Fig. 1, with a centroid at ν_c.

The measurement process for the determination of
$Q_{\beta\beta}(^{82}\mathrm{Se})$ consisted of alternating cyclotron frequency
measurements of ^{82}Kr$^+$ and ^{82}Se$^+$. These measurements
were performed in a series of four runs. The first run con-
sisted of measurements using a 500 ms excitation time.
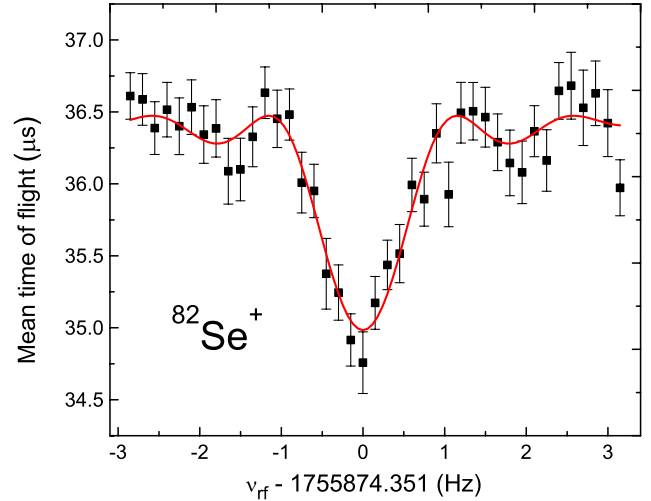For increased precision, we utilized a 750 ms excitation

FIG. 1 (color online).   Time-of-flight cyclotron resonance
curve for ^{82}Se$^+$. An excitation time of $T_{\mathrm{rf}} = 750$ ms was used
to obtain a resolving power of 2×10^6. The fit of the theoretical
line shape to the data is represented by the solid line.

time for the final three runs. Each TOF resonance was
the average of 25 to 40 scans over the respective frequency
range with 41 trapping cycles per scan. During the
measurement process the number of ions recorded by the
MCP was limited to an average of 2 ions per trapping cycle,
corresponding to <7 ions in the trap at a time (assuming
30% detector efficiency). This was done to limit the
number of contaminant ions produced via charge-exchange
reactions. Each resonance consisted of ∼500–3000
detected ions, depending on the number of scans per
resonance and the beam current from the ion source. To
determine ν_c, each resonance was fitted using the theoreti-
cal line shape described in Ref. [22]. The average uncer-
tainty in ν_c for each resonance was ∼30 ppb (parts per
billion).

For the frequency ratio determination of ^{82}Kr$^+$ to ^{82}Se$^+$,
drifts in the magnetic field were taken into account by
linearly interpolating two cyclotron frequency measure-
ments of ^{82}Kr$^+$ bracketing a ^{82}Se$^+$ measurement to obtain
$\nu_c^{\mathrm{int}}(^{82}\mathrm{Kr}^+)$. This interpolated cyclotron frequency was used
to obtain the frequency ratio $R = \nu_c^{\mathrm{int}}(^{82}\mathrm{Kr}^+)/\nu_c(^{82}\mathrm{Se}^+)$.
The values obtained from a total of 110 ratio determi-
nations and their weighted average are shown in Fig. 2.
The difference to the reference ratio, $R_{\mathrm{AME2003}} =
[m(^{82}\mathrm{Kr}) - m_e]/[m(^{82}\mathrm{Se}) - m_e]$, is plotted using the
mass values for ^{82}Kr and ^{82}Se from the atomic mass
evaluation AME2003 [25].

In preparation for, and during the measurement process,
great care was taken to minimize possible systematic
effects. By measuring mass doublets, contributions to the
measurement uncertainty arising from mass dependent
systematic effects due to frequency shifts, for example
caused by field imperfections, are already greatly reduced.
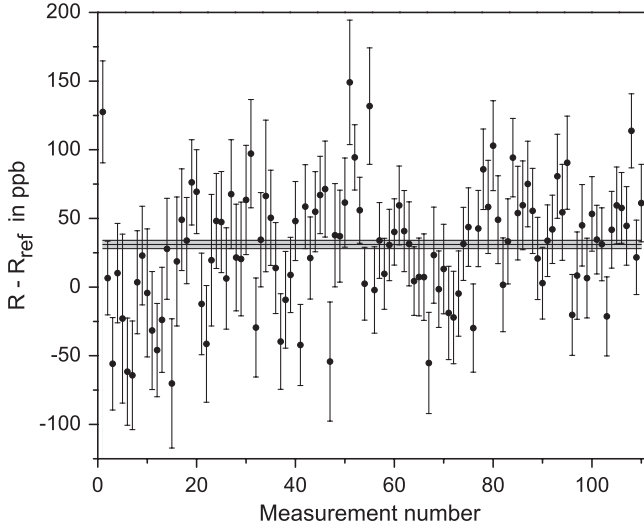Nevertheless, prior to the measurements, imperfections

FIG. 2. Difference between the cyclotron frequency ratio of
^{82}Kr^{+} and ^{82}Se^{+} and the ratio obtained from literature mass data
[25]. The solid lines indicate the weighted average and the 1σ
statistical uncertainty band.

TABLE I. Average cyclotron frequency ratios $R_{\mathrm{run}} =$
$\nu_c^{\mathrm{int}}(^{82}\mathrm{Kr}^{+})/\nu_c(^{82}\mathrm{Se}^{+})$ with their statistical errors as obtained
in four separate runs with N frequency ratio measurements
performed in each run. Also given is the final weighted average
R_{LEBIT} with its statistical and final uncertainty and the ratio
based on the AME2003 atomic mass evaluation [25].

Run	N	R_{run}
1	53	1.000 039 285(5)
2	2	1.000 039 30(2)
3	7	1.000 039 29(1)
4	48	1.000 039 290(4)
R_{LEBIT}		1.000 039 290(4)(5)
R_{AME2003}		1.000 039 26(3)

were carefully minimized following a tuning procedure
described in Ref. [26].

The effect of a nonlinear magnetic field drift is not
accounted for in the data evaluation and is not mitigated
by using a mass doublet. Therefore the cyclotron frequency
measurements of ^{82}Kr^{+} and ^{82}Se^{+} were alternated with a
period of no greater than 1 hour. Based on an earlier study
[27], this should lead to residual systematic effects of the
cyclotron frequency ratio no larger than 1 ppb. This uncer-
tainty was further minimized by stabilizing the pressure
in the liquid helium dewar to 10 ppm (parts per million)
[28], resulting in an uncertainty well below 1 ppb.
Simultaneously trapped ions of a different m/q value [29]
can cause frequency shifts—this effect was minimized by
verifying that contaminant ions were never present at a
level exceeding a few percent, low enough to not lead to a
significant shift at the desired precision.

The weighted average of the ratios for the individual
runs and the corresponding statistical uncertainty are listed
in Table I together with the weighted average R_{LEBIT} of all
results and the value R_{AME2003} obtained with mass data
from AME2003 [25]. Through evaluation of the entire data
set, with statistical errors as obtained from the fits of
theoretical line shapes to the measured cyclotron resonance
curves, we determined a Birge ratio [30] of 1.27(5). While
close to unity, the significant deviation indicates the pres-
ence of residual systematic effects at the 0.8 ppb level not
discovered in the individual measurements or in the tests
for systematic effects performed. Therefore, to account for
these nonstatistical contributions we multiply the statistical
uncertainty of the weighted average R_{LEBIT} for all data by
the value of the Birge ratio. Both the statistical and total
uncertainty for R_{LEBIT} are given in the table.

The $\beta\beta$ decay Q value is determined from the mass
difference between the mother nuclide of mass m_m and
daughter nuclide of mass m_d through

$$Q_{\beta\beta}/c^2 = m_m - m_d = (R-1)(m_d - m_e), \quad (2)$$

where R is the cyclotron frequency ratio between the singly
charged ions of the daughter and mother nuclides, c is the
speed of light, and m_e accounts for the missing electron
mass of singly charged ions used in the measurement.
Using our final frequency ratio R_{LEBIT} and the AME2003
mass for ^{82}Kr we obtain, $Q_{\beta\beta} = 2997.9(3)$ keV. The new
LEBIT Q value is nearly an order of magnitude more
precise than the previous value of $Q_{\beta\beta} = 2\,996(2)$ keV
based on mass data from Ref. [25], a dramatic improvement
to one of the ingredients needed for a better determination of
the half-life limit for $0\nu\beta\beta$ decay in ^{82}Se.

In addition to a precise $Q_{\beta\beta}$ value, an accurate NME for
the decay is also needed. A number of methods have been
applied to the NME problem, and in ^{82}Se one of the most
prominent methods—the shell model [14,15]—gives
matrix elements that are less than half the size of those
produced by the quasiparticle random phase approxima-
tion (QRPA) [16], the interacting boson model [17], and
the generator coordinate method [18]. Each approach has
its strengths and weaknesses; for instance, the shell model
incorporates complicated correlations but only in a small
single-particle space (the valence shell), while the QRPA is
applied in large single-particle spaces but includes only
simple correlations. Here we report an attempt to correct
for the shell model deficiency by calculating an effective
$0\nu\beta\beta$ decay operator that implicitly includes effects of
single-particle levels that are outside the valence shell.

Our calculation, which will be described in detail in a
forthcoming publication [31], uses diagrammatic perturba-
tion theory to construct an effective two-body $0\nu\beta\beta$ decay
operator that, together with an effective Hamiltonian,
allows the shell model to get around its truncations when
the procedure is carried to completion [32,33]. This frame-
work has been used extensively to determine effective
valence-space interactions, but much less so to construct
other effective operators. The only existing work on an

TABLE II.　^{82}Se $0\nu\beta\beta$ decay matrix elements calculated in QRPA, standard shell model (SM), and with the effective $0\nu\beta\beta$ decay operator discussed in the text.

QRPA [16]	SM [15]	Corrected SM
5.19	2.64	3.56

effective $0\nu\beta\beta$ decay operator is an exploratory calculation, as it happens, for ^{82}Se [34]. In that work the starting point was a *G*-matrix interaction [33]. Using a low-momentum interaction [35], $V_{\mathrm{low}\,k}$, derived from nuclear forces in chiral effective field theory [36], we have carried this calculation significantly further. We now include all diagrams to second order in the interaction, state norms, and folds, while expanding the set of high-lying single-particle orbits that we treat.

Our result is shown in Table II, which we compare to values obtained from the QRPA and the standard shell model. The contributions from outside the valence space to the effective operator increase the shell model NME by ~30% to 3.56, narrowing the gap between it and the QRPA.

This calculation represents an important first step in producing a true *ab initio* NME, suggesting that it will be larger than the shell model has indicated. We plan to improve our results by including three-nucleon forces [37–39] and two-body currents [40], by constructing an effective interaction consistent with the effective decay operator, and by investigating the size of induced three-body terms in the effective decay operator.

In conclusion, by using Penning trap mass spectrometry we have performed the first direct *Q*-value measurement of ^{82}Se $\beta\beta$ decay by measuring the cyclotron frequency ratio between singly charged ions of ^{82}Se and the $\beta\beta$ decay daughter, ^{82}Kr. Our result, $Q_{\beta\beta} = 2\,997.9(3)$ keV, is nearly an order of magnitude more precise than the previous value based on the 2003 atomic mass evaluation [25]. Following the procedure in Ref. [41] and using our new *Q* value, we calculate the PSF for the $0\nu\beta\beta$ decay mode of ^{82}Se to be $G_{0\nu} = 2.848(1) \times 10^{-14}$ yr^{-1}, where the uncertainty has also been improved by nearly an order of magnitude. With the corrected shell model NME calculation presented here and the current upper limits of $\langle m_{\beta\beta} \rangle = 140$–380 meV from the EXO-200 experiment [42] we obtain a lower limit range for the ^{82}Se $0\nu\beta\beta$ decay half-life of 5.0×10^{24}–3.7×10^{25} years. Assuming SuperNEMO achieves its projected sensitivity at the 90% confidence level of 1–2×10^{26} years, an effective neutrino mass as low as 60–85 meV could be detected.

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[1] S. Abe *et al.* (KamLAND Collaboration), Phys. Rev. Lett. **100**, 221803 (2008).
[2] P. Adamson *et al.* (MINOS Collaboration), Phys. Rev. Lett. **101**, 131802 (2008).
[3] B. Aharmim *et al.* (SNO Collaboration), Phys. Rev. C **81**, 055504 (2010).
[4] F. T. Avignone, III, S. R. Elliott, and J. Engel, Rev. Mod. Phys. **80**, 481 (2008).
[5] S. R. Elliott, A. A. Hahn, and M. K. Moe, Phys. Rev. Lett. **59**, 2020 (1987).
[6] A. S. Barabash, Phys. At. Nucl. **73**, 162 (2010).
[7] N. Ackerman *et al.* (EXO Collaboration), Phys. Rev. Lett. **107**, 212501 (2011).
[8] H. V. Klapdor-Kleingrothaus, A. Dietz, H. L. Harney, and I. V. Krivosheina, Mod. Phys. Lett. A **16**, 2409 (2001).
[9] A. S. Barabash, Phys. Part. Nucl. **42**, 613 (2011).
[10] R. Saakyan (NEMO3 and SuperNEMO Collaborations), J. Phys. Conf. Ser. **179**, 012006 (2009).
[11] D. Lunney, J. M. Pearson, and C. Thibault, Rev. Mod. Phys. **75**, 1021 (2003).
[12] D. Fink *et al.*, Phys. Rev. Lett. **108**, 062502 (2012).
[13] M. Redshaw, G. Bollen, M. Brodeur, S. Bustabad, D. L. Lincoln, S. J. Novario, R. Ringle, and S. Schwarz, Phys. Rev. C **86**, 041306(R) (2012).
[14] E. Caurier, J. Menéndez, F. Nowacki, and A. Poves, Phys. Rev. Lett. **100**, 052503 (2008).
[15] J. Menéndez, A. Poves, E. Caurier, and F. Nowacki, Nucl. Phys. A**818**, 139 (2009).
[16] F. Šimkovic, A. Faessler, H. Müther, V. Rodin, and M. Stauf, Phys. Rev. C **79**, 055501 (2009).
[17] J. Barea and F. Iachello, Phys. Rev. C **79**, 044301 (2009).
[18] T. R. Rodríguez and G. Martínez-Pinedo, Phys. Rev. Lett. **105**, 252503 (2010).
[19] G. Bollen *et al.*, Phys. Rev. Lett. **96**, 152501 (2006).
[20] S. Schwarz, G. Bollen, D. Lawton, A. Neudert, R. Ringle, P. Schury, and T. Sun, Nucl. Instrum. Methods Phys. Res., Sect. B **204**, 474 (2003).
[21] P. Schury, G. Bollen, M. Block, D. J. Morrissey, R. Ringle, A. Prinke, J. Savory, S. Schwarz, and T. Sun, Hyperfine Interact. **173**, 165 (2006).
[22] M. König, G. Bollen, H.-J. Kluge, T. Otto, and J. Szerypo, Int. J. Mass Spectrom. Ion Process. **142**, 95 (1995).
[23] G. Bollen, R. B. Moore, G. Savard, and H. Stolzenberg, J. Appl. Phys. **68**, 4355 (1990).
[24] G. Gräff, H. Kalinowsky, and J. Traut, Z. Phys. A **297**, 35 (1980).
[25] G. Audi, A. H. Wapstra, and C. Thibault, Nucl. Phys. A**729**, 337 (2003).
[26] M. Brodeur *et al.*, Int. J. Mass Spectrom. **310**, 20 (2012).
[27] R. Ringle *et al.*, Phys. Rev. C **75**, 055503 (2007).
[28] R. Ringle, G. Bollen, A. Prinke, J. Savory, P. Schury, S. Schwarz, and T. Sun, Nucl. Instrum. Methods Phys. Res., Sect. A **604**, 536 (2009).
[29] G. Bollen, H.-J. Kluge, M. König, T. Otto, G. Savard, H. Stolzenberg, R. B. Moore, G. Rouleau, and G. Audi (ISOLDE Collaboration), Phys. Rev. C **46**, R2140 (1992).
[30] R. T. Birge, Phys. Rev. **40**, 207 (1932).
[31] J. D. Holt and J. Engel (to be published).

[32] T. T. S. Kuo and E. Osnes, *Folded-Diagram Theory of the Effective Interaction in Nuclei, Atoms and Molecules*, Lecture Notes in Physics Vol. 364 (Springer-Verlag, Berlin, 1990).

[33] M. Hjorth-Jensen, T. T. S. Kuo, and E. Osnes, Phys. Rep. **261**, 125 (1995).

[34] J. Engel and G. Hagen, Phys. Rev. C **79**, 064317 (2009).

[35] S. K. Bogner, R. J. Furnstahl, and A. Schwenk, Prog. Part. Nucl. Phys. **65**, 94 (2010).

[36] E. Epelbaum, H.-W. Hammer, and Ulf-G. Meißner, Rev. Mod. Phys. **81**, 1773 (2009).

[37] T. Otsuka, T. Suzuki, J. D. Holt, A. Schwenk, and Y. Akaishi, Phys. Rev. Lett. **105**, 032501 (2010).

[38] J. D. Holt, T. Otsuka, A. Schwenk, and T. Suzuki, J. Phys. G **39**, 085111 (2012).

[39] A. T. Gallant *et al.*, Phys. Rev. Lett. **109**, 032506 (2012).

[40] J. Menéndez, D. Gazit, and A. Schwenk, Phys. Rev. Lett. **107**, 062501 (2011).

[41] J. Suhonen and O. Civitarese, Phys. Rep. **300**, 123 (1998).

[42] M. Auger *et al.* (EXO Collaboration), Phys. Rev. Lett. **109**, 032505 (2012).