Double beta decay of $^{48}$Ca

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$^{48}$Ca, the lightest double beta decay candidate, is the only one simple enough to be treated exactly in the nuclear shell model. Thus, the $\beta\beta(2\nu)$ half-life measurement, reported here, provides a unique test of the nuclear physics involved in the $\beta\beta$ matrix element calculation. Enriched $^{48}$Ca sources of two different thicknesses have been exposed in a time projection chamber, and yield $T_{1/2}^{2\nu} = (4.3^{+1.1}_{-1.0}\,\text{[stat]} \pm 1.4\,\text{[syst.]}) \times 10^{19} \text{years}$, compatible with the shell model calculations.

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Among all candidates for double beta decay, $^{48}$Ca→$^{48}$Ti is unique, since it is the only one which can be treated “exactly” in the nuclear shell model by solving the problem of eight nucleons distributed within the $fp$ shell without truncation. Consequently, this decay has been a favored testing ground of nuclear theories. However, until now only a lower limit of the $2\nu$ decay half-life, $T_{1/2}^{2\nu} \geq 3.6 \times 10^{19} \text{years}$, has been determined experimentally.

In a recent paper it was shown that the nuclear shell model, constrained by the requirement that it describes well the spectroscopy of the $A = 48$ nuclei, restricts the corresponding half-life also from above, $T_{1/2}^{2\nu} \leq 10^{20} \text{y}$. Therefore the experimental observation of the decay acquired added significance; if it turns out that the shell model cannot predict this theoretically tractable rate, we have to wonder about our ability to describe the nuclear matrix elements in the more complex nuclei, including perhaps even the matrix elements responsible for the neutrinoless decay. Here we will present the result from a new experiment using a time projection chamber (TPC).

The search for double beta decay of $^{48}$Ca was among the first to be attempted in live-time experiments beginning in the early fifties (for an extensive chronology see ). With the largest energy release of all $\beta\beta$ candidates $^{48}$Ca ($Q_{\beta\beta} = 4.3 \text{MeV}$) has a $\beta\beta(2\nu)$ sum-energy spectrum that extends to higher energies than most radioactive background. Yet calcium has a tendency to harbor chemically similar radio-impurities such as $^{90}$Sr and $^{226}$Ra, which do intrude on a major fraction of the $^{48}$Ca spectral range.

When the two $\beta$ particles are tracked in a TPC they are seen to both carry negative charge, originate from a common point, and have separately measured energies. Although this distinctive visualization eliminates the bulk of unrelated activity, there remain several well-known mechanisms for production of negative electron pairs that constitute background for $\beta\beta$ decay. The most serious of these are Möller scattering of single $\beta$ particles, and $\beta\gamma$ cascades in which a $\gamma$-ray internally converts or Compton scatters. These processes are fed principally by the primordial decay chains, but also by cosmogenic and man-made radioisotopes. Decay-chain induced background events can often be tagged by $\alpha$ or $\beta$ particles from neighboring links if the source is thin enough to allow the tagging particles escape into the TPC gas.

The miniscule 0.187% natural abundance of $^{48}$Ca makes enrichment both necessary and expensive. Potential exposure to loss of costly isotope is a deterrent to chemical purification or conversion to the lightest stable compound. The material used was supplied by the Kurchatov Institute as finely powdered CaCO$_3$ enriched to 73% in $^{48}$Ca, and relatively free of U and Th (< 0.8 ppb by mass spectroscopic analysis). The speculative assumption of secular equilibrium and the absence of serious amounts of other high Q-value impurities, led to a projected experimental $\beta\beta$ sensitivity in excess of $10^{20}$ years for this material. Accordingly, a relatively thick $\beta\beta$ source was made to maximize the number of exposed $^{48}$Ca nuclei. The CaCO$_3$ powder was injected into a large glass box in bursts of compressed gas, allowed to settle uniformly onto a 4 $\mu$m Mylar substrate, then fixed with a mist of Formvar. Two such deposits, face-to-face, formed the first $\beta\beta$ source, with a total of 42.2 g of CaCO$_3$ (18.5 mg/cm$^2$ total thickness with substrate and binder.)

The shielded UC Irvine TPC containing the $\beta\beta$ source as the central electrode in a magnetic field was located in a tunnel at the Hoover Dam under a minimum of 72 m of rock. Data were recorded on magnetic tape, and subsequently passed through stripping software to select clean $1e^-$ and $2e^-$ events. The $2e^-$ events were individually scanned by a physicist. All unambiguous negative pairs emitted from opposite sides of the source with a common point of origin were fitted with helices, and the parameters written to a $\beta\beta$ candidate file or a $^{214}$Bi file, depending on whether a $^{214}$Po $\alpha$ particle appeared at the vertex within the following millisecond. The far more numerous $1e^-$ events were fitted automatically by software and also written to a parameter file.

The lone electron ($1e^-$) spectrum plotted against ki-
netic energy \( (K) \) in Fig. 1 represents the total beta activity of source contaminants, and can be broken down into the contributions from individual radionuclides by a least squares fit. \(^{90}\text{Sr} \) (2250 \( \mu \text{Bq/g} \)), \(^{226}\text{Ra} \) (530 \( \mu \text{Bq/g} \)) and their daughters account for the bulk of the spectrum. Contributions from \(^{137}\text{Cs} \) (940 \( \mu \text{Bq/g} \)), and daughters of \(^{228}\text{Ra} \) (90 \( \mu \text{Bq/g} \)), are also present. The two Ra activities being much larger than the mass spectroscopic limits on U and Th, indicate severe breaking of equilibrium in the respective series. The daughters of greatest concern (\( Q_{\beta} > 2 \text{ MeV} \)) are \(^{90}\text{Y} \), \(^{214}\text{Bi} \), \(^{212}\text{Ac} \), and \(^{208}\text{Tl} \). As a check of the fitting procedure, the energy spectrum of electrons tagged by \(^{214}\text{Po} \) \( \alpha \)-particles was noted to closely match the fitted \(^{214}\text{Bi} \) component when adjusted for the \( \alpha \) escape probability \( (P_{\alpha} = 0.24 \pm 0.01 \) from an independent measurement.\)

![Graph](https://example.com/graph1.png)

**FIG. 1.** The lone electron spectrum for the thick source, and the most important of the fitted components. From top to bottom at low energy are the total spectrum, \(^{90}\text{Sr} \), \(^{226}\text{Ra} \), and \(^{228}\text{Ra} \). Daughters are assumed in equilibrium, with the exception of \(^{210}\text{Pb} \). Its daughter \(^{210}\text{Bi} \) was fitted separately, then included in the \(^{226}\text{Ra} \) curve.

The activities determined from the lone electron spectrum were used as input to a Monte Carlo calculation of the \( 2e^- \) background. \(^{90}\text{Sr} \) and its daughter \(^{90}\text{Y} \) are essentially pure \( \beta \) emitters, and contribute only through Möller scattering. The other high \( Q_{\beta} \) nuclei have complex decay schemes with multiple gamma rays, all of which were included in the Monte Carlo with their corresponding conversion coefficients. Most of these simulated \( 2e^- \) backgrounds were directly testable against TPC measurements, with good agreement: The measured \(^{214}\text{Bi} \) component was simply the \( 2e^- \) data subset tagged by the \(^{214}\text{Po} \) \( \alpha \), and corrected for the \( \alpha \) escape probability. The \(^{90}\text{Y} \) \( 2e^- \) measurement was provided by a drop of \(^{90}\text{Sr} \) solution applied to a natural isotopic replica of the \(^{48}\text{Ca} \) source, and placed in the TPC. The \(^{212}\text{Bi} \) and \(^{208}\text{Tl} \) \( 2e^- \) measurements were scaled from those produced by an injection of \(^{220}\text{Rn} \), by comparing observed rates of the rapid \(^{212}\text{Bi} \)\(^{212}\text{Po} \), \( \beta-\alpha \) sequence.

Since the Monte Carlo \( 2e^- \) rates were derived from intrinsic activity levels in \( \mu \text{Bq/g} \), their agreement with direct measurements also confirms the Monte-Carlo predicted \( 2e^- \) efficiency of the TPC. A Monte-Carlo generated background spectrum was essential only for \(^{226}\text{Ac} \). In our \( 2e^- \) background model we elected to use the smoother, better-statistics Monte Carlo spectra for the other contributions as well.

An alternative determination of \( 2e^- \) background was carried out by a separate subgroup of the collaboration, and included independent Monte Carlo calculations and a greater reliance on the above-mentioned TPC measurements as opposed to lone-electron fits. We refer to this direct measurement method as analysis "A", and the lone-electron based method as analysis "B". To eliminate events with the poorest energy resolution, analysis B included a cut on electrons making the smallest angles with the magnetic field, \( |\cos(\theta)| < 0.9 \).

The \( 2e^- \) sum spectrum from the \(^{48}\text{Ca} \) source, after event-by-event removal of the \( \alpha \)-tagged \(^{214}\text{Bi} \), is shown in Fig. 2a with a singles threshold of 400 keV. The various remaining background spectra as determined by analysis A are superimposed. The residual spectrum following background subtraction, appears in Fig. 2b.

![Graph](https://example.com/graph2.png)

**FIG. 2.** (a) The measured \( 2e^- \) sum-energy spectrum and background spectra for the thick source with a 400 keV singles threshold. From top to bottom at low energy are the total measured spectrum, Möller events, \(^{214}\text{Bi} \), and daughters of \(^{228}\text{Ra} \). (b) Residual \( \beta\beta \) candidates and Monte Carlo \( \beta\beta \) spectrum at the corresponding \( T_{1/2} = 4.1 \times 10^{19} \) y obtained at this threshold (dashed line).

The above procedure was repeated for a series of singles thresholds and one relatively high sum threshold, with consistent results. The corresponding half-lives were calculated in each case, as shown for two of the threshold combinations in Table 1. The 2 MeV sum threshold was accompanied by an additional singles spectrum cut on
the strong $^{214}$Bi conversion line at 1.3 MeV. Quoted errors in the table are statistical. The calculated half-life is independent of threshold and analysis A or B within errors.

Since the half-life precision was degraded by the unexpectedly large Ra and Sr contamination, the 42.2 g source was replaced after 2440 hours exposure, with one containing only 10.3 g of enriched CaCO$_3$, and total thickness 5.4 mg/cm$^2$. The thinner source was exposed 4001 hours, and these results are also included in Table I. The source mass for the $^{214}$P$_0$ from 0.24 to 0.69, and the $^{90}$Y component was weakened by the large reduction in target mass for Möller scattering.

In view of these significant improvements, the relatively small increase in signal-to-background ratio observed for the thin source was disappointing. We now understand that multiple Coulomb scattering caused a nonlinear dependence of total Möller cross section on source thickness. In addition, the thick source degraded a larger percentage of electrons to sub-threshold energies, and thereby suppressed background more effectively than the generally more energetic $\beta\beta$ events. Nevertheless, it is encouraging that despite different dependence on source mass for the $^{48}$Ca signal and the background rates (particularly $^{214}$Bi), the half-lives derived from thick and thin sources agree within statistics.

The thick and thin source residual spectra were each corrected for energy loss and efficiency distortion, then combined for the Kurie plot shown in Fig. 2. Including the singles threshold $\epsilon$ in an integration of the Primakoff-Rosen spectral approximation $^6$ produced a Kurie formula that retains the linear energy dependence of a transformed $\beta\beta(2\nu)$ spectrum in the presence of a single threshold cut. The resulting formula is then

$$
\left[ \frac{dN}{dK} / \left( (K - 2\epsilon)(f_0(K) + f_\epsilon(K)) \right) \right]^{1/5} \propto (Q_{\beta\beta} - K)
$$

where

$$f_0(K) = K^4 / 30 + K^3 m / 3 + 4K^2 m^2 / 3 + 2K m^3 + m^4$$

and

$$f_\epsilon(K) = \epsilon (K - \epsilon) (K^2 / 15 + 2K m / 3 + 2m^2 / 3 + \epsilon (K - \epsilon) / 5) .$$

with electron mass ($m$). The Kurie plot energy intercept at 4.2 \pm 0.1 MeV is consistent with the $^{48}$Ca $Q_{\beta\beta}$ value of 4.271 \pm 0.004 MeV $^6$. The small error bars resulting from the Kurie transformation, have been omitted in the figure. By comparison, the $\alpha$-tagged $^{214}$Bi $2e^-$ events produce a distinctly bowed Kurie plot, and the plot for measured $^{208}$Tl ($Q_\beta = 5.0$ MeV) events is grossly nonlinear.

Since the thick and thin sources were exposed separately, corresponding pairs of columns in the table can be combined as independent measurements. For example, combining thick and thin $\beta\beta$ events for 0.400/0.800 MeV singles/sum thresholds, analysis A, yields $T_{1/2}^{2\nu} = (4.3^{+2.4}_{-1.1}) \times 10^{19}$ y. Either of the other two thick-thin pairs would combine to give an equally valid result. However, since the other two results would not be statistically independent from the first, we do not attempt a grand average. Rather we choose the above number, since it includes a broader range of the spectrum than the higher sum threshold, and we include the A-B analysis difference in the systematic error. The remainder of the systematic error is largely in the detector efficiency. Thus we quote a final result of $T_{1/2}^{2\nu} = (4.3^{+2.4}_{-1.1}[\text{stat.}] \pm 1.4[\text{syst.}]) \times 10^{19}$ y.
TABLE I. Breakdown of counts from the two sources for two energy thresholds.

|                  | Thick Source (0.0775 mol·y) | Thin Source (0.0310 mol·y) |
|------------------|-----------------------------|---------------------------|
|                  | Analysis A                  | Analysis B                |
| Singles threshold (MeV) | 0.400                      | 0.200                     |
| Sum threshold (MeV)    | 0.800                      | 2.000                     |
| $^{214}\text{Bi}$ 1.3 MeV line cut | No                         | Yes                       |
| Small polar angles cut | No                        | No                        |
| With $\alpha$ tag    | 55                         | 50                        |
| Without $\alpha$ tag | 500                        | 472                       |
| Backgrounds $^b$     |                            |                           |
| $^{214}\text{Bi}$    | 189.1 ± 25.5               | 186.3 ± 35.7              |
| Møller events $^c$   | 191.5 ± 4.6                | 163.4 ± 5.6               |
| $^{228}\text{Ac}$, $^{212}\text{Bi}$, $^{208}\text{TI}$ $^d$ | 42.8 ± 7.5                | 29.4 ± 5.6                |
| Total background     | 423.3 ± 27.0               | 379.1 ± 36.6              |
| $\beta\beta$ events | 76.7 ± 35.0                | 92.9 ± 42.5               |
| Efficiency $^e$      | 0.0973                     | 0.0902                    |
| $T_{1/2}^{\beta\beta}$ ($10^{19}$ y) | 4.1$^{+3.5}_{-1.3}$        | 3.2$^{+2.7}_{-1.0}$       |
| Signal/Background    | 0.18                       | 0.25                      |
| Kurie plot intercept (MeV) | 4.1 ± 0.1                 | 4.4 ± 0.1                 |

$^a$Scaled from counts at lower threshold by the ratio observed in a larger $^{214}\text{Bi}$ data set.
$^b$See text.
$^c$Exclusive of $^{214}\text{Bi}$ which is included in the row above.
$^d$Exclusive of Møller, which is included in the row above.
$^e$From Monte Carlo simulation.

consistent between two $\beta\beta$ sources of different thickness, and among various energy thresholds. The corresponding Kurie plots all intercept the energy axis near the $^{48}\text{Ca}$ $Q_{\beta\beta}$ value, unlike plots made from measured samples of the various backgrounds. We believe these results constitute strong evidence for $^{48}\text{Ca}$ double beta decay at a half-life supporting the relatively rigid shell model calculations for this lightest double beta decay nucleus.

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