Experimental Investigation of Double-Beta Decay in ^{82}Se

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A time projection chamber with a selenium double-beta decay source as the central electrode has yielded a lower limit of 1.0×10^{20} yr at 68% confidence level for the two-neutrino half-life of ^{82}Se. This limit is consistent with the results of geochemical measurements, and disagrees with the shorter half-life predictions of nuclear theory. For the neutrinoless mode we find a corresponding lower limit of 7×10^{21} yr, also at 68% confidence level.

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The two most frequently considered modes for double-beta decay are the two-neutrino mode,

$$(Z,A)\rightarrow(Z+2,A)+2e^-+2\bar{\nu},$$

and the neutrinoless mode,

$$(Z,A)\rightarrow(Z+2,A)+2e^-.$$

The two-neutrino mode $[\beta\beta(2\nu)]$ is expected in the standard model as a second-order weak process, whereas the neutrinoless mode $[\beta\beta(0\nu)]$ violates lepton-number conservation. Both decays are considered in the case of even-even nuclei where the single-beta decay to the $(Z+1,A)$ nucleus is highly spin inhibited or energetically forbidden as a result of the nuclear pairing forces, but the transition by the emission of two electrons to the $(Z+2,A)$ nucleus is allowed.

Phase space strongly favors $\beta\beta(0\nu)$ over $\beta\beta(2\nu)$, and a search for the neutrinoless process is a powerful way to test the lepton-number conservation law. An observation of $\beta\beta(0\nu)$ would imply that the neutrino is a Majorana particle (particle = antiparticle), and that it has some mass and/or right-handed interaction. Large phase space notwithstanding, the rate of $\beta\beta(0\nu)$ for ^{82}Se has been limited experimentally to much less than the total decay rate measured by the geochemical technique.[1] It appears that $\beta\beta(0\nu)$, if it exists at all, is greatly suppressed, implying either that the neutrino is a Dirac particle (particle$\neq$antiparticle) or that its mass and any right-handed current admixture are very small.

Upper limits on the Majorana mass, for example, calculated from currently operating ^{76}Ge $\beta\beta(0\nu)$ experiments[2] are as low as 1 or 2 eV.[3] The limits from $\beta\beta(0\nu)$, however, suffer from fairly large uncertainties in the corresponding nuclear matrix elements. The problem can be seen in the disagreement between theory and geochemical experiments for $\beta\beta(2\nu)$, the only mode for which the theory can be tested. Recent reviews discuss these difficulties, and summarize the previous experimental results.[4,5]

There is a need to complement the $\beta\beta(0\nu)$ search with a direct laboratory measurement of $\beta\beta(2\nu)$. Such a measurement would test the geochemical results and provide a benchmark for nuclear physics calculations. The $\beta\beta(2\nu)$ and $\beta\beta(0\nu)$ modes can be distinguished experimentally by the energy spectra of their electrons. For $\beta\beta(2\nu)$, the electrons and neutrinos share the transition energy, and the sum spectrum is a broad distribution.[6] However, in $\beta\beta(0\nu)$ all of the energy is taken by the electrons and the sum spectrum is a narrow spike at the full transition energy.

A third decay mode,

$$(Z,A)\rightarrow(Z,A+2)+2e^-+B,$$

is possible if the massless Goldstone boson known as the Majoron (B) exists.[7] The electron sum-energy spectrum of this mode $[\beta\beta(0\nu,B)]$ is also a distribution, but has a shape distinct from that of $\beta\beta(2\nu)$. The experiment described here is sensitive to all three modes.

The extreme rarity of the double-beta decay process and indistinct character of a distributed spectrum put great demands on the background-rejection capabilities of any experiment intended for detection of $\beta\beta(2\nu)$ and $\beta\beta(0\nu,B)$. A time projection chamber (TPC) was selected for its ability to display the two electron tracks individually and thereby discriminate against a host of otherwise indistinguishable backgrounds. 14 g of selenium, 97% enriched in isotope 82, are included in the central electrode or source plane of the TPC. A detailed description of the apparatus has been reported elsewhere.[8,9]

Each electron from double-beta decay would form a helix in the magnetic field of the TPC. Observed helices are analyzed off-line to determine the direction, energy, and opening angle of the event. The energy resolution shows a dependence on the pitch of the helix. In the best cases the two-electron sum-energy resolution is about 4.5% full width at half maximum (FWHM), and averages about 13% FWHM for double-beta decay candidates within the range of acceptance.

Electron energies were calibrated against the internal-conversion lines following beta decay of ^{208}Tl. The thallium was introduced into the TPC by the injection of ^{220}Rn. Potentially troublesome radon daughters all have short half-lives, and decay away in a matter of days.

The measured $\beta\beta(2\nu)$ detection efficiency is 0.154 ± 0.013, which includes loss of 47% of the spectrum[6] due to a sum-energy threshold at 1.1 MeV. Backscattering and helix pitches that are too large or too small for measurement account for most of the remaining losses. Dead time in the system is 10%.

Forty-seven double-beta decay candidates were recorded in the 3164 h of live time since the most recent changes to the detector. The energy spectra shown in Figs. 1(a) and 1(b) include all observed events with two electrons over 1.1 MeV sum energy, originating from a common point on the selenium, and having no further activity at the vertex during the following millisecond. Below 1.1 MeV the sum-energy spectrum is swamped by the beta-decay, internal-conversion sequence in ^{214}Pb. This contaminant is deposited on the outer surface of the source by decaying ^{222}Rn in the TPC gas. Tests have shown that the radon, in turn, comes from the Be-Cu wire used for the grid, cathode, and field wires of the chamber. A sum threshold at 1.1 MeV excludes the ^{214}Pb contribution from spectra (a) and (b) in the figure.

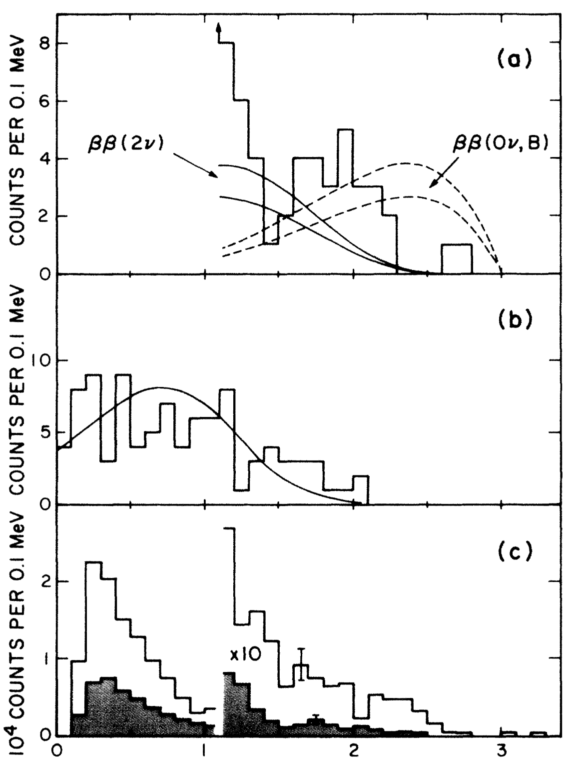

FIG. 1. (a) The sum-energy histogram of the 47 $\beta\beta$ candidates above a 1.1-MeV sum threshold. The theoretical $\beta\beta(2\nu)$ spectrum and $\beta\beta(0\nu,B)$ or Majoron spectrum are normalized to the geochemical rate of $(1.7 \pm 0.3) \times 10^{20}$ years reported by Kirsten (Ref. 10). Identified backgrounds over threshold contribute mostly below 1.5 MeV. Three off-scale events fall between 3 and 6 MeV. (b) The $2 \times 47 = 94$ electrons taken singly, and the normalized theoretical $\beta\beta(2\nu)$ curve. (c) The energy spectrum of single electrons (not members of pairs) from the selenium source before (unshaded) and after (shaded) improvements to the gamma shield. These are thought to be mostly Compton electrons, and contribute to background when they Möller scatter, or are accompanied by a second scattering of the photon. Off-scale events are present up to 9 MeV. Normalized to the same 3164-h live time of (a) and (b).

Above the threshold, the identified background is less severe, and limits can be set on the amount present (see Table I). Each process contributing is detectable in some other way which can be utilized to find its intensity. For example, a trace of ^{208}Tl produces false counts by beta decay with internal conversion. A multiplicity of conversion lines and finite energy resolution make it impractical to try to remove the thallium events selectively on the basis of these lines. However, the number of thallium events is determined by occurrences of the easily recognized ^{212}Bi-^{212}Po beta-alpha sequence in a competing branch of the series. The distribution of the beta-alpha events on the source plane shows no preference for the region of the selenium deposit. This uniformity is suggestive of ^{220}Rn in the TPC gas. The suspected source of ^{220}Rn under normal operating conditions is the same Be-Cu wire responsible for ^{222}Rn.

Similarly, some background arises from ^{214}Bi. Most can be recognized by the appearance of the 164-μs ^{214}Po alpha particle within the following millisecond, but occasionally the alpha particle is absorbed by the source, and remains hidden. These events also descend from radon.

Another identified background results from Compton scattering of gamma rays incident on the selenium source from without. The second electron comes from a Möller scattering of the Compton electron, or from a second scattering or photoelectric absorption of the photon. The energy spectrum of single electrons (not members of pairs) from the selenium source is shown in Fig. 1(c). From this spectrum, and the assumption[11] that these are Compton electrons, the rate of production of second electrons was calculated. The result agrees with the ratio of two-electron to single-electron events measured when a strong gamma source was placed inside the detector shield. Tests are underway to identify the origin of the residual gamma flux.

Since we are reporting a lower limit for the ^{82}Se half-life, the conservative assumption is the minimum background column of Table I. This leaves 32 ± 7 counts as possible $\beta\beta(2\nu)$ events, from which the ^{82}Se half-life is limited to $> 1.0 \times 10^{20}$ yr at 68% confidence level. This result puts to rest the suggestion of a much shorter half-life by an earlier cloud-chamber experiment.[12] It also disagrees with the relatively short half-life predicted for ^{82}Se by shell-model calcula-

TABLE I. Identified backgrounds between 1.1 and 3.0 MeV.

Source of background		How measured	Rate (per 3164 h) Min.[a]	Max.[b]
β decay with internal conversion				
Thorium series	^{228}Ac	β-α sequence ^{212}Bi-^{212}Po	0	12
	^{212}Bi	β-α sequence ^{212}Bi-^{212}Po	0	0
	^{208}Tl	β-α sequence ^{212}Bi-^{212}Po	4	8
Uranium series	^{234m}Pa	β-α sequence ^{214}Bi-^{214}Po	0	4
	^{214}Bi	β-α sequence ^{214}Bi-^{214}Po	0	4
Möller scattering		Single electrons, Fig. 1(c)	8	15
Two Compton scatterings		Single electrons, Fig. 1(c)	2	11
Compton scatter and photoelectric absorption		Single electrons, Fig. 1(c)	1	5
Total			15	59

[a]Assumes U and Th daughters come from Rn in TPC gas, and that the electrons of Fig. 1(c) are mostly β particles without gamma rays.

[b]Assumes U and Th daughters are imbedded in the Se, and that the electrons of Fig. 1(c) are mostly Compton recoil electrons. "Min." and "Max." are the one-sigma limits accompanying these assumptions.

tions.[4] The proximity to the geochemical half-life of $(1.7\pm0.3)\times10^{20}$ yr reported by Kirsten[10] provides some hope that a clean double-beta decay spectrum is within reach.

A warning has surfaced, however. The predicted opening-angle distribution for $\beta\beta(2\nu)$ is of the form $1-\alpha\cos\theta$, where α is close to unity.[6] This distribution would distinguish double-beta decay from background processes having isotropic electron emission, or some distinctive character such as for Möller scattering. However, as shown in Fig. 2, the distribution measured in the TPC for false $\beta\beta$ pairs from ^{208}Tl closely resembles the expected $\beta\beta(2\nu)$ shape. It is evident that a preference for large opening angles in a collection of electron pairs from a ^{82}Se source is not a sufficient condition to demonstrate the existence of double-beta decay. Once a real $\beta\beta(2\nu)$ spectrum is in hand, ruling out alternative explanations will require some care.

All of the backgrounds in Table I have energy spectra that are far stronger near 1 MeV than near 2 MeV. When the composite spectrum from the "Min." column of the table is subtracted from the spectrum of $\beta\beta(2\nu)$ candidates in Fig. 1(a), the result is a harder spectrum than expected for $\beta\beta(2\nu)$. This technique will be useful as statistics improve, but for the present, the result cannot be regarded as significant.

Very little of the predicted sum-energy spectrum for $\beta\beta(2\nu)$ survives beyond 2.1 MeV. However, the spectrum predicted for the Majoron mode is at its strongest in this region. If we attribute the seven events between 2.1 and 3.0 MeV to $\beta\beta(0\nu,B)$ we find the half-life for this mode to be $>4.0\times10^{20}$ yr at 68%

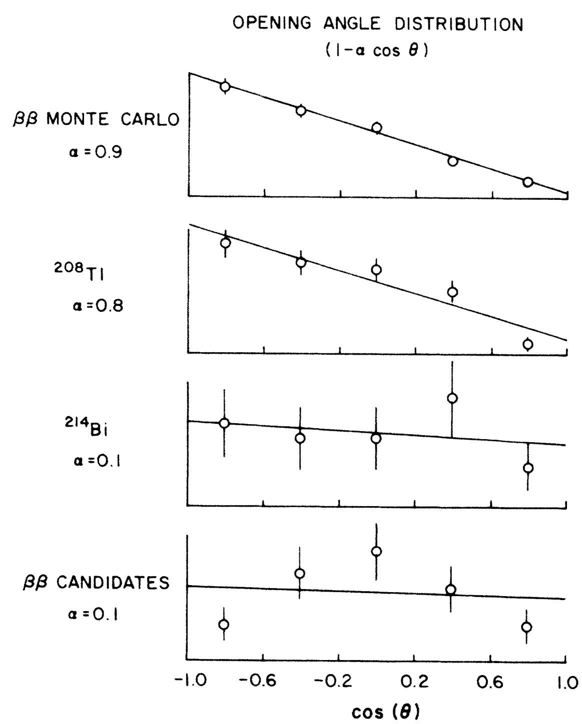

FIG. 2. Least-squares fit to various opening-angle distributions. From top to bottom, a Monte Carlo simulation of the distribution expected from analysis of TPC data for $\beta\beta(2\nu)$, the measured distribution for false $\beta\beta(2\nu)$ events from ^{208}Tl and ^{214}Bi, and the distribution measured for the $\beta\beta(2\nu)$ candidates. The thallium bears an ominous resemblance to the expected $\beta\beta(2\nu)$. The poor resemblance of the $\beta\beta$ candidates to the expected opening-angle distribution is not surprising, in view of the presence of Compton-related background discussed above.

confidence level.

The sum energy for a $\beta\beta(0\nu)$ ground-state transition in ^{82}Se is 3.00 MeV. The probability that a neutrinoless event would be detected in a 300-keV window centered on 3 MeV is estimated to be 0.21 ± 0.02. The absence of counts[13] in this window during 4844 h[14] corresponds to a $\beta\beta(0\nu)$ half-life of $> 7\times 10^{21}$ yr at 68% confidence level, or about 2 times the previous published limit for ^{82}Se.[1]

The present experiment and the geochemical experiments now agree that the ^{82}Se half-life exceeds 10^{20} y. Progress in understanding this result theoretically would increase our confidence in the quantitative implications of double-beta decay experiments for neutrino mass and right-handed currents.

Our $\beta\beta(0\nu)$ sensitivity has been compromised temporarily by the desire to keep the background down for the $\beta\beta(2\nu)$ measurement. Enough enriched ^{82}Se is on hand to triple the source mass, but a thicker source would aggravate the Compton-related background. (The double scattering involved is proportional to the source thickness squared). For the present, the intention is to reduce the background by replacing the radioactive wire and other sources, and continue to emphasize the search for $\beta\beta(2\nu)$.

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[8]M. K. Moe, A. A. Hahn, and H. E. Brown, in *The Time Projection Chamber,* edited by J. A. Macdonald, AIP Conference Proceedings No. 108 (American Institute of Physics, New York, 1984), p. 37.

[9]M. K. Moe, A. A. Hahn, and S. R. Elliott, in *Proceedings of the Conference on Neutrino Mass and Low Energy Weak Interactions, Telemark, Wisconsin, 1984,* edited by Vernon Barger and David Cline (World Scientific, Singapore, 1985).

[10]T. Kirsten, in *Proceedings of the Eleventh International Conference on Neutrino Physics and Astrophysics,* edited by K. Kleinknecht and E. A. Paschos (World Scientific, Singapore, 1984).

[11]The Compton assumption follows from the ratio of electron counts from two regions of different thickness, namely the region of the selenium deposit, and the much thinner surrounding area consisting only of Mylar. The electron ratio was approximately equal to the thickness ratio both before and after the shielding change shown in Fig. 1(c). Some percentage of these electrons, of course, are not Compton, but beta particles from uranium, thorium, etc., whose contribution to background is studied separately.

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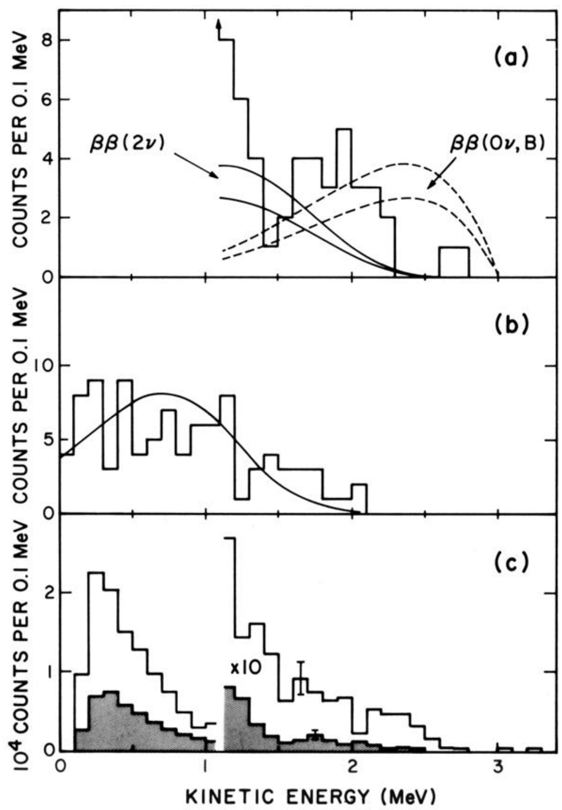
[13]A single count reported earlier was shifted out of the window when the energy calibration was reconciled to the conversion lines following beta decay of ^{208}Tl.

[14]Includes 1680 h with the unimproved shield.



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