Direct Evidence for Two-Neutrino Double-Beta Decay in ^{82}Se

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The two-neutrino mode of double-beta decay in ^{82}Se has been observed in a time-projection chamber at a half-life of $(1.1^{+0.8}_{-0.3})\times 10^{20}$ yr (68% confidence level). This result from direct counting confirms the earlier geochemical measurements and helps provide a standard by which to test the double-beta-decay matrix elements of nuclear theory. It is the rarest natural decay process ever observed directly in the laboratory.

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Double-beta decay was suggested by Wigner in the 1930's as a second-order weak transition between isobars differing by two units in atomic number. Assuming the emission of two electrons and two neutrinos (as required by the theory of Dirac), Geoppert-Mayer[1] in 1935 made the first theoretical estimate of the extremely low rates for this process [$\beta\beta(2\nu)$]. Four years later, Furry[2] invoked the theory of Majorana (in which the neutrino and antineutrino are identical) to propose an alternative mode of double-beta decay having no neutrinos in the final state [$\beta\beta(0\nu)$]. Experimentally the two modes can be distinguished by the spectra of their sum energies; that is, the sum of the kinetic energies of the two emitted electrons. For $\beta\beta(2\nu)$ a broadly distributed spectrum is expected since a portion of the energy is carried off by unseen neutrinos. Essentially all of the transition energy is available to the electrons in $\beta\beta(0\nu)$. The resulting sharp energy spike would be typically 100 times easier to detect. Furry pointed out that because of the greater phase space available to $\beta\beta(0\nu)$, this mode could proceed at a faster rate than $\beta\beta(2\nu)$ by many orders of magnitude. "According to the older theory," he remarked, "it seemed certain that double-beta disintegration could never be observed because of its extremely minute probability, but the Majorana theory indicates that this is by no means necessarily the case."

Ironically, it is $\beta\beta(2\nu)$ that has now been seen while Furry's potentially faster and experimentally much more distinctive $\beta\beta(0\nu)$ is yet to be detected.[3] Possibly neutrinos are indeed Dirac particles, but the Majorana alternative is not excluded by any known evidence. It is recognized today that parity nonconservation exerts a strong inhibiting influence, but need not exclude $\beta\beta(0\nu)$ entirely.

An observation of $\beta\beta(0\nu)$ would have profound consequences for particle physics. The two electrons appearing alone would constitute a violation of lepton-number conservation—a symmetry breakdown expected in some theories of grand unification. A neutrinoless decay would further indicate a nonzero mass for the neutrino. Under some circumstances, $\beta\beta(0\nu)$ would reveal a right-handed component in the weak leptonic current. The large phase-space enhancement for $\beta\beta(0\nu)$ and the unique character of the monoenergetic spectrum make this mode a very sensitive test for these neutrino properties. Intensive searches for $\beta\beta(0\nu)$ are underway.[4]

The neutrino mass and right-handed–current parameters are related to the $\beta\beta(0\nu)$ rate by matrix elements calculated from nuclear theory. Difficulties in making these calculations result in fairly large uncertainties. Unlike $\beta\beta(0\nu)$, the $\beta\beta(2\nu)$ mode is expected in the standard model. The matrix elements for this mode directly predict the $\beta\beta(2\nu)$ decay rate, independent of any assumptions about unknown properties of the neutrino. Thus a measurement of the $\beta\beta(2\nu)$ rate provides a test of the nuclear theory from which $\beta\beta(2\nu)$ and $\beta\beta(0\nu)$ matrix elements are calculated in similar ways. The theory of double-beta decay and the experimental history have been discussed extensively in the literature.[5-10]

Compelling indirect evidence for the existence of double-beta decay comes from geochemical measurements,[11-13] but until now the process had not been seen in the laboratory. The broad sum-energy spectrum for $\beta\beta(2\nu)$ makes this mode difficult to see without the background-rejecting capabilities of a tracking chamber. At the University of California, Irvine (UCI), a time-projection chamber (TPC) has been employed to search for $\beta\beta(2\nu)$ in ^{82}Se. The experiment is designed to look for the two electrons in the decay

$$^{82}\mathrm{Se} \rightarrow {}^{82}\mathrm{Kr} + 2e^{-} + 2\bar{\nu}.$$

The trajectories of the electrons are recorded by the TPC and are analyzed to measure their kinematic characteristics. The experimental setup and detector performance have been described elsewhere[14-16] and only the essentials will be summarized here. The source is 14 g of 97% enriched ^{82}Se deposited on a thin Mylar foil which forms the central electrode of the TPC. The source thickness is 7 mg/cm^2. The TPC is surrounded by a lead shield 10 to 15 cm thick. This lead house is enclosed within a 4π cosmic-ray veto, and the entire system is immersed in a 700-G magnetic field. The experiment is located in a basement laboratory in the physical sciences building at UCI.

The data reported here represent 7960 h of live time. Figure 1 shows the sum-energy spectrum with an 800-keV threshold. The energy of each individual electron was required to be larger than 150 keV. Also plotted in this figure is the theoretical sum-energy spectrum normalized to our best-fit value for the half-life. It is clear from this figure that the signal-to-background ratio is highest in the region 1.3 to 2.0 MeV.

There are several mechanisms which simulate $\beta\beta(2\nu)$ and thus must be considered as possible contributions to the data of Fig. 1. The most efficient of these are common beta decays which are followed by internal conversion (β+IC), and Moeller scattering. The origin of the electrons which undergo Moeller scattering can be either β rays of Compton electrons arising from γ rays impinging on the source plane.

The β+IC isotopes which cause the most trouble are members of the uranium and thorium series. Two of these isotopes, ^{214}Bi from the uranium series and ^{212}Bi from the thorium series, have daughters which are unstable against α decay. These β-α cascades are very easy to identify in the TPC. Thus, the contribution from most isotopes within these decay chains can be estimated from the observed decay rates of ^{214}Bi and ^{212}Bi. The contributions due to Moeller scattering and any other β+IC isotopes can be estimated by the examination of the spectrum of lone electrons (not members of pairs). A much more rigorous description of the background estimation can be found elsewhere.[15,16]

The result of the background studies shows that the β+IC of ^{208}Tl and Moeller scattering are the only significant background contributions to the data in the 1.3- to 2.0-MeV energy range, contributing 2.8 ± 0.7 and 9.3 ± 2.6 counts, respectively. Thus, we considered these contributions and a possible contribution of $\beta\beta(2\nu)$ as the explanations for the observed events between 1.3 and 2.0 MeV shown in Fig. 1. The histograms in Fig. 2 show the observed events which fall between these two sum-energy levels and which survive the 150-keV single-energy threshold. Furthermore, we required that the two electrons be emitted on opposite sides of the source plane, since the opening-angle bias of the detector was understood in this case. Figure 2 includes the sum- and single-energy spectra along with the opening-angle spectrum for the 46 observed events which survive these cuts. The opening-angle-distribution predictions include the effect of the detector bias.

The superimposed curves in Fig. 2 represent the shapes of the three previously mentioned contributions. The background spectra were all determined from measured data, and the $\beta\beta(2\nu)$ spectra are those determined from the calculations of Doi, Kotani, and Takasugi.[7]

The best fit was determined by a maximum-likelihood procedure for both the cases of a constrained and an unconstrained background. In the unconstrained fit, each of the three components was allowed to vary in integer steps between 0 and 140% of the observed integral number of counts (46). The likelihood value was calculated as follows: First, the admixture of the three components

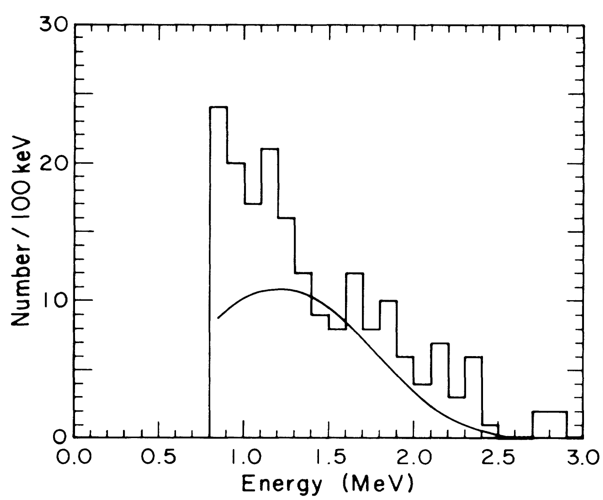

FIG. 1. The observed sum-energy spectrum of two-electron events. A threshold of 800 keV was imposed on the sum energy of the events, and a threshold of 150 keV was imposed on the single energy. The curve is the theoretical $\beta\beta(2\nu)$ sum-energy spectrum normalized to 1.1×10^{20} yr.

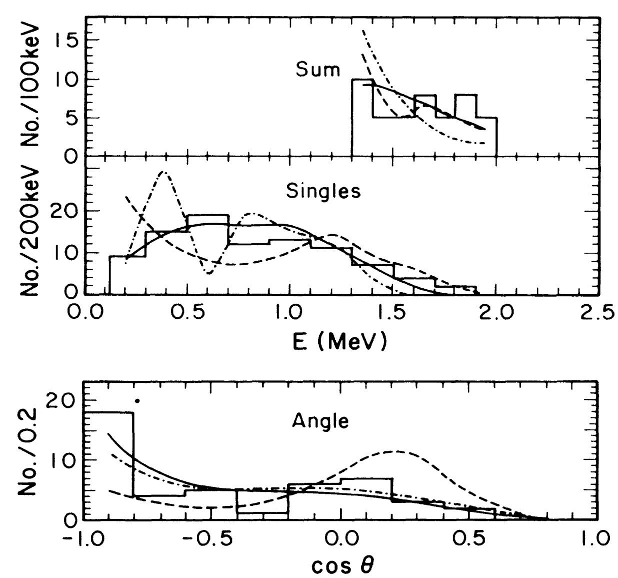

FIG. 2. The histograms are the observed spectra for two-electron events with a sum energy between 1.3 and 2.0 MeV and which have a single-energy threshold of 150 keV. Also these events were required to have the electrons emitted on opposite sides of the source plane. The curves show the shapes of the three assumed contributions to the data: $\beta\beta(2\nu)$ (solid curve), Moeller scattering (dashed curve), and ^{208}Tl (dot-dashed curve).

was normalized to 46 counts. For each bin in each histogram, the number of counts expected was defined as the integral of the predicted spectrum over that bin. The probability of finding the number of counts actually observed in that bin was calculated with Poisson statistics. The product of these probabilities over all bins from all histograms was then multiplied by the probability of observing 46 counts given the predicted integral number before normalization. This then represented the unconstrained probability value for the particular mix of components. The constrained probability value was calculated by multiplication of the unconstrained value by the probability that the particular admixture of backgrounds had fluctuated from the 2.8 ± 0.7 ^{208}Tl and 9.3 ± 2.6 Moeller contributions mentioned earlier.

Figure 3 shows a mesh plot (and a contour plot) from the unconstrained fit for the case where the predicted integral number of counts equaled the observed number. The best fit (which lies in this particular slice) predicts that 78% or 35.9 of the 46 events are due to $\beta\beta(2\nu)$, 10.1 are due to Moeller scattering, and 0 are due to ^{208}Tl. Thus the freely floating ratios in the unconstrained maximum-likelihood fit settled at values closely duplicating the background contributions calculated independently.

In the unconstrained fit, the 68% confidence level allowed the two-neutrino mode to vary between 19 and 54 counts. The constrained fit tightened up the range to between 21 and 47 counts for the 68% confidence level, with the best fit at 35 counts. The efficiency for a $\beta\beta(2\nu)$ event to be detected in the TPC and to survive these cuts is $(6.2 \pm 0.5)\%$, and, hence, the best fit corresponds to a half-life of 1.1×10^{20} yr with a 68%-confidence-level range of $(0.8 \text{ to } 1.9) \times 10^{20}$ yr for the constrained case. As a check of the dependence of this result on the choice of energy range selected for analysis, this procedure was repeated for the much broader sum-energy limits of 0.8 and 2.5 MeV and gave a very similar conclusion.

Backgrounds in the regions above and below the 1.3–2.0-MeV range, although higher with respect to the signal, are also largely understood. A new radioactively cleaner TPC has been operating for a few months, and preliminary indications are that most of this background has disappeared, while the counting rate in the 1.3–2.0-MeV region is nearly unchanged.

We believe that the similarity of the measured spectra and angular distributions to the predicted shapes for $\beta\beta(2\nu)$, the agreement of the maximum-likelihood fit with background contributions calculated independently, the independence of the conclusion on the energy range of analysis, and the persistence of these counts in the

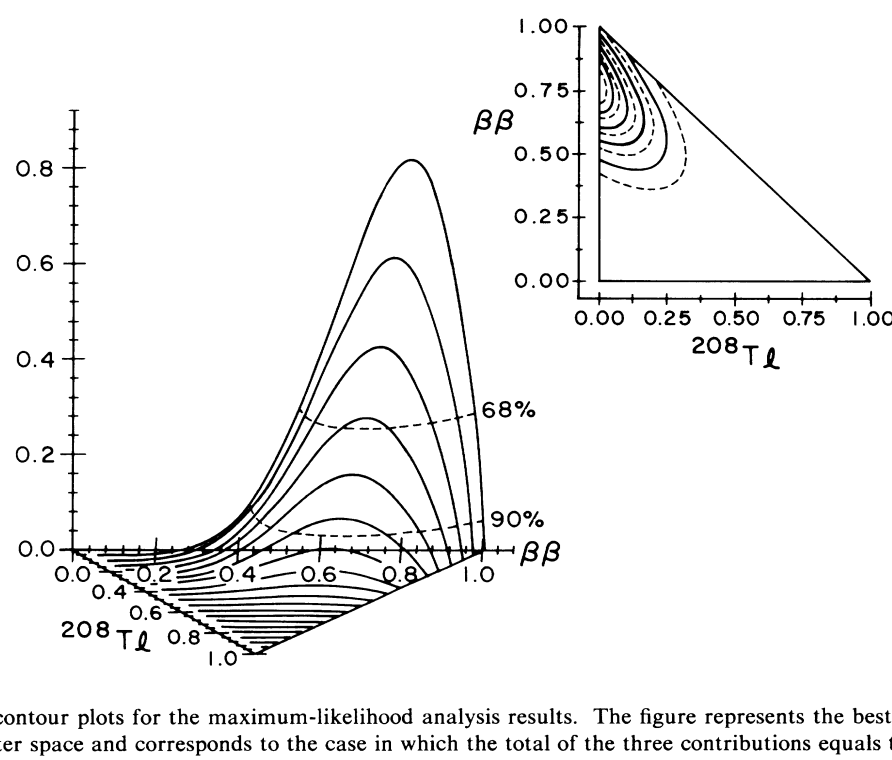

FIG. 3. Mesh and contour plots for the maximum-likelihood analysis results. The figure represents the best-fit slice through the unconstrained parameter space and corresponds to the case in which the total of the three contributions equals the number of events observed. The vertical scale in the mesh plot is the relative probability of that particular combination of the three contributions giving the observed data. The probability is shown as a function of the fractions of ^{208}Tl and $\beta\beta(3\nu)$. The fraction due to Moeller scattering can be deduced by the requirement that the sum of the three fractions be unity. The 68% and 90% curves indicate the regions which contain those percentages of the volume under the surface. The contour plot is of the same function.

face of reduced backgrounds in the new chamber constitute strong evidence for the observation of $\beta\beta(2\nu)$. This result is consistent with the geochemical measurements of Kirsten,[11] $(1.30\pm0.05)\times10^{20}$ yr, and Manuel,[12] $(1.0\pm0.4)\times10^{20}$ yr, and the cosmochemical (meteorite) measurement of Marti and Murty,[13] $0.97^{+0.36}_{-0.45}\times10^{20}$ yr.

We hope that the other mode(s) of double-beta decay will ultimately be detected, and that this direct laboratory observation of $\beta\beta(2\nu)$ will contribute to the theoretical understanding of future results. The TPC experiment continues to operate in an attempt to reduce the uncertainty in the $\beta\beta(2\nu)$ half-life and to extend the search for neutrinoless decay in ^{82}Se.

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