BRIEF REPORTS

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Double beta decay of ^{82}Se

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The two-neutrino double beta decay of ^{82}Se has been measured during a 20 244 h run resulting in a half-life of $1.08^{+0.26}_{-0.06}\times 10^{20}$ years (68% C.L.). No candidate events for the zero-neutrino double beta decay during 21 924 h results in a half-life limit of 2.7×10^{22} years at the 68% confidence level.

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Double beta decay is a second-order weak interaction process that increases the atomic number of a nucleus by two while emitting two beta particles. One possible decay mode of this process, two-neutrino double beta decay [$\beta\beta(2\nu)$], is expected within the standard model and is characterized by the additional emission of two antineutrinos. Since the antineutrinos share the energy, this mode of decay results in a distribution of the sum of the two electron energies. Though this distribution makes a weak signature, recently a number of direct counting experiments have separated the signal from a variety of background processes in a number of isotopes [1–6].

An alternative decay mode, zero-neutrino double beta decay [$\beta\beta(0\nu)$] is an extension to the standard model which requires the existence of massive Majorana neutrinos [7]. Since the detected electrons are the only particles emitted, the sum energy distribution is a peak at the full transition energy. Though this mode of double beta decay has never been observed, the signature is much more distinct than for $\beta\beta(2\nu)$ and thus relatively stringent limits on the half-life have been reported [8].

Interpreting $\beta\beta(0\nu)$ half-life limits to deduce Majorana neutrino mass limits requires the calculation of the nuclear matrix elements for the transition. Unfortunately this is difficult for these large nuclear systems. Although the matrix elements are in principle different for $\beta\beta(2\nu)$ and $\beta\beta(0\nu)$, $\beta\beta(2\nu)$ half-life measurements serve as a guide to the calculation techniques.

The University of California at Irvine (UCI) time projection chamber (TPC) experiment has been studying the double beta decay of several isotopes. This Brief Report presents the final results of the study of ^{82}Se. The TPC has been described elsewhere [9] and only the salient points will be discussed here. The chamber is roughly 80 cm square and 20 cm deep. The source plane, which is also the drift voltage electrode, is a thin Se deposit sandwiched between two aluminized Mylar sheets. This plane splits the TPC into two 10-cm-thick regions which terminate at the wire planes and define the drift regions. The total thickness of the source/electrode is 7 mg/cm^2. The TPC is surrounded by a minimum of 10 cm of lead which in turn is enclosed by a 4π proportional counter cosmic-ray veto shield. This entire setup is situated between Helmholtz coils which provide a magnetic field of roughly 700 G. The TPC records the electron tracks, and the energies and opening angle are determined from the helices fit to each track.

The data presented here come from four separate sets. An initial run of 1680 h used insufficient shielding and thus had a background level too high to be used for $\beta\beta(2\nu)$. However, there were no high energy candidate events for $\beta\beta(0\nu)$ and these data are included in the $\beta\beta(0\nu)$ limit. After the shielding was improved, a 7960 h run was taken in a basement laboratory at UCI and the results were described previously [1]. The TPC then was rebuilt to eliminate known sources of radioactivity and to provide yet additional shielding [9]. The next 8172 h used the new TPC with the same source plane. The resulting improvement in background is most obvious by the 40% reduction in the lone electrons (not members of pairs) over 500 keV emerging from the source.

Finally, the TPC was moved to an underground location at the Hoover Dam in an attempt to decrease background at the higher energies [2]. This location provided a minimum of 72 m of rock overburden and decreased the muon flux traversing the TPC by a factor of 160. At the dam location, all lone-electron events over 2.5 MeV can be attributed to the beta decay of ^{214}Bi (Q value of 3.3 MeV). This final run lasted 4112 h for a total live time of 20 244 h for $\beta\beta(2\nu)$.

Figure 1(a) shows the spectrum of the sum of the energies of all two-electron events over 800 keV for which each electron possessed at least 150 keV of energy. In addition it was required that the two electrons be emitted

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on opposite sides of the source plane, for in this case the TPC angular bias is understood [9]. For energies below 800 keV, MØller scattering dominates the spectrum. The primary backgrounds over 800 keV are the beta decay, internal conversion of ^{208}Tl, and Compton scattering followed by MØller scattering. The beta decay and internal conversion of ^{214}Bi (^{212}Bi) is virtually eliminated by the identification of the alpha decay of the ^{214}Po (^{212}Po) daughter. The other naturally occurring radioactive isotopes either have low Q values or small internal conversion probabilities and therefore do not contribute. Furthermore, the successive emission of particles as a nucleus proceeds through the decay chain is observed. This permits us to measure the level of radioactive contamination contributing to the signal. One of the two events over 3.0 MeV is most likely due to MØller scattering as

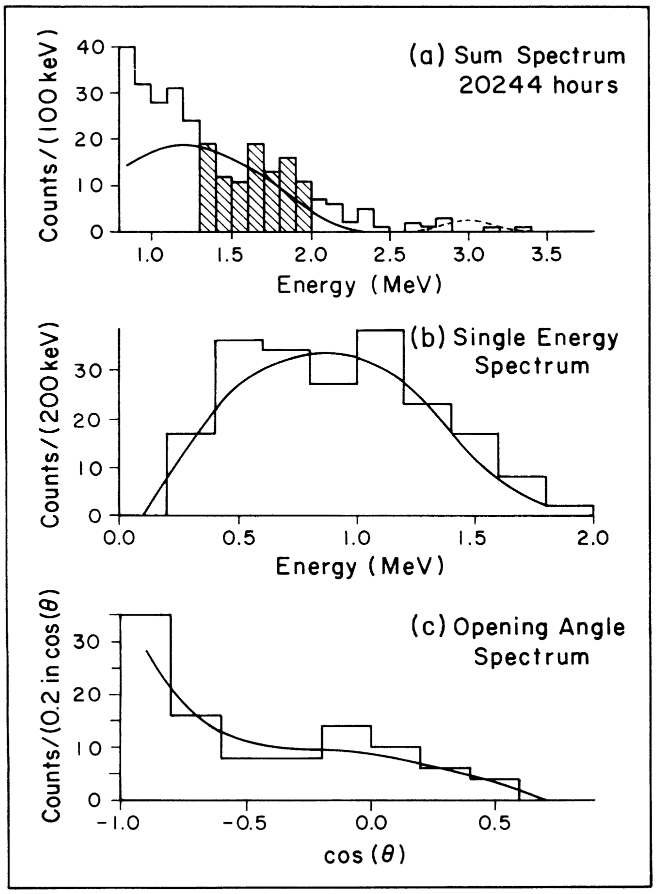

FIG. 1. (a) The spectrum of the sum of the two energies of $\beta\beta(2\nu)$ candidate events. The energy of each electron in these events was at least 150 keV and they were emitted on opposite sides of the source plane. The shaded region identifies the events that were used in the maximum likelihood analysis. The dashed curve is a Gaussian located at the ^{82}Se end point with width appropriate for the TPC resolution. It is arbitrarily normalized to 10 events. (b) The energy spectrum of the electrons taken one at a time for the events from the shaded region and (c) the opening angle distribution of those same events. The solid curves in all 3 plots are the theoretical $\beta\beta(2\nu)$ curves normalized to the best-fit half-life of 1.08×10^{20} yr.

one of the electrons carries most of the energy. The other event at about 3.3 MeV is a good candidate for the beta decay, internal conversion of ^{208}Tl as one of the electrons has an energy consistent with the 2.6 MeV internal conversion line.

The shaded region of Fig. 1(a) is that having the highest signal-to-background ratio. This is the region chosen for further analysis. Figure 1(b) shows the energy spectrum of the electrons from the events in the shaded region taken one at a time. Figure 1(c) shows the opening angle distribution of the same events.

The best fit to the data was determined by maximizing the likelihood function (L). L is defined by the product over the bins in all three spectra of the Poisson probability of observing the number of counts in that bin given the number expected for a given hypothesis. An hypothesis is defined by the number of counts due to each of three processes that may make up the spectra: $\beta\beta(2\nu)$, MØller scattering, or ^{208}Tl beta decay and internal conversion. The combination of these three processes that maximizes L is taken as the best fit. The theoretical $\beta\beta(2\nu)$ spectral shapes were taken from [10].

The MØller curves were determined from the lone-electron spectrum by folding it with the known cross section. This determines the shape only. The absolute flux requires knowledge of the origin (e.g., Compton scatter or beta decay) of the initial electron as the Compton scattering cross section is a function of angle and the source is very thin. The ^{208}Tl spectra were determined by encoding the decay scheme [11] in a Monte Carlo calculation. The predicted beta decay spectrum compares favorably to that measured during tests of the TPC with injected ^{220}Rn.

To estimate the uncertainty in the best fit value for each of the contributions, L is integrated from zero to infinity over the other two contributions to derive a likelihood function of only one variable. This function was then convoluted with a Gaussian to incorporate the 8% uncertainty in the efficiency. The region of minimum range which possesses 68% of the area under this one-dimensional likelihood function defines our quoted uncertainties. In the previous report [1] we took the extremes of the contour of the three parameter L which included 68% of the volume. This overestimates the uncertainties and we now follow the more traditional technique (see, for example, [12]).

The solid curves in Figs. 1(a)–1(c) show the $\beta\beta(2\nu)$ theoretical curves for the best fit result of 89.6 events assigned to $\beta\beta(2\nu)$ of the 101 observed events. For an efficiency of 6.2% and 9.77×10^{22} ^{82}Se atoms, we deduce a half-life of $1.08^{+0.26}_{-0.06}\times 10^{20}$ yr with the quoted uncertainty at the 68% confidence level. The best fit MØller and Thallium contributions are $11.4^{+5.2}_{-4.9}$ events and 0.0 (<7.2) events, respectively. By observing the ^{212}Bi, ^{212}Po cascade, we can estimate the number of ^{208}Tl decays contributing to the sample. The result is 7.1 events which falls just within the 68% confidence region. The χ^2 for the fit is 21.3 for 21 degrees of freedom.

Several systematic checks of the fit were tried and all resulted in conclusions similar to that described above. These checks included varying the sum energy thresholds and analyzing the three groups of $\beta\beta(2\nu)$ data separately but simultaneously by requiring that the signal be the same for the three sets but allowing the backgrounds to vary. A fit was also done to a sample of ^{214}Bi beta decay, internal conversion events. For this fit ^{214}Bi spectra deduced from the decay scheme were used in place of those due to ^{208}Tl. The resultant fit assigned the bulk of the events to ^{214}Bi. This analysis serves as a null data set.

The spectrum in Fig. 1(a) shows a lack of events near the end-point energy of 3.0 MeV although a number of events are crowding in on that locale. The dashed curve is Gaussian centered at 3.0 MeV, with its width determined by the TPC resolution for two-electron events and normalization arbitrarily chosen to be 10 events. There are no events within a 300 keV window centered on 3.0 MeV chosen to select candidates for $\beta\beta(0\nu)$. Although this window was chosen *a priori,* it does maximize the lower limit deduced for the $\beta\beta(0\nu)$ half-life as it provides virtually the highest efficiency without accepting any candidate events. Using 1.14 events as a 68% upper limit on the number of $\beta\beta(0\nu)$ candidates, the 21 924 h of live time, and the 18.5% efficiency for observing a 3.0 MeV event within this energy window, we deduce a lower limit on the half-life of 2.7×10^{22} yr.

Using the matrix elements of [13] this limit places an upper limit on the Majorana neutrino mass of 5 eV. Using the results of the UCB-LBL ^{76}Ge $\beta\beta(0\nu)$ experiment of half-life $>6\times10^{23}$ yr [8], and the same matrix elements one places a limit of 2 eV. The $\beta\beta(2\nu)$ results agree well with recent calculations (see, for example, [14]).

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