Suggestive Evidence for the Two-Neutrino Double-β Decay of ^{76}Ge

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A dramatic reduction in background was achieved in the latest Pacific Northwest Laboratory–University of South Carolina germanium detectors. Two 1.05-kg natural-isotopic-abundance detectors were operated for 1.92 kg yr. The residual spectrum, after straightforward corrections, has a significant region resembling the theoretical spectrum of the two-neutrino $\beta\beta$ decay of ^{76}Ge. A fit to the data yields $T_{1/2}^{2\nu}(^{76}\text{Ge}) = (1.1^{+0.6}_{-0.3}) \times 10^{21}$ yr at the 95% C.L., which agrees with shell-model predictions.

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Double-β decay is a second-order weak process in which two neutrons in a nucleus decay to protons simultaneously. The most interesting modes would violate lepton-number conservation by having two electrons but no antineutrinos in the final state (0ν $\beta\beta$ decay). Such decay modes would require mechanisms not contained in the standard model of electroweak interactions. Zero-neutrino $\beta\beta$ decay is conceivably engendered by Majorana neutrino mass, by the coupling of Goldstone bosons (Majorons) to the neutrino sector, thereby providing a mechanism for generating Majorana neutrino mass, by Higgs-particle exchange, or by the exchange of supersymmetric partners of the photon, Z^0 boson, or gluon. These processes have been recently reviewed.[1-3]

Although 0ν $\beta\beta$ decay nuclear matrix elements are not the same as those governing 2ν $\beta\beta$ decay, experimental measurements of the latter test our theoretical understanding of the pertinent nuclear structure. There are several efforts underway to measure half-lives of 2ν $\beta\beta$ decay;[4-10] however, the only published report claiming direct observation until very recently was by Elliott, Hahn, and Moe.[4] Their result is $T_{1/2}^{2\nu}(^{82}\text{Se}) = (1.1^{+0.8}_{-0.3}) \times 10^{20}$ yr from data taken with the University of California, Irvine, Time Projection Chamber. This apparatus is now being used to search for the $\beta\beta$ decay of ^{100}Mo.[11]

There have been three recent preliminary reports of direct observation of 2ν $\beta\beta$ decay, two involving ^{100}Mo (Refs. 6 and 7) enriched to 96% and one involving ^{76}Ge (Ref. 9) enriched to 85%. Neither constitutes unambiguous evidence for direct observation; however, the sensitivities are close to achieving that goal.

This Letter describes a singles-counting experiment using germanium detectors with natural isotopic abundance (7.76% ^{76}Ge). The backgrounds, however, have been reduced to levels that render their sensitivities superior to those of the current isotopically enriched detectors.

The system consists of two 1.05-kg fiducial-mass crystals mounted in specially constructed "dipstick" cryostats with two 90° bends separating the liquid nitrogen and cryopump material from the crystals. The germanium itself and the cryostat materials were prepared by procedures unique to these detectors[12,13] with dramatic results leading to the present ultralow levels of radioactive backgrounds outlined below.

A major background in germanium crystals is from the decay of ^{68}Ge formed by energetic cosmic-ray neutrons via $^{70}\text{Ge}(n,3n)^{68}\text{Ge}$ and other similar reactions. To minimize this background, the process was begun with germanium ore newly mined from a depth of ~200 m at the Apex mine in St. George, Utah. The ore was milled and the product was returned underground daily until ~200 kg were accumulated. It was then delivered overland to Eagle Pitcher Industries in Quapaw, Oklahoma, for purification and conversion to metal ingots. Air transportation was avoided because the high-energy cosmic-ray neutron flux is approximately 2 orders of magnitude more intense at 9000 m than at sea level. The total cosmic-ray exposure of the material at this point was about 13 d, a short time compared to the half-life of ^{68}Ge (~271 d).

The germanium ingots were subsequently transported by surface to Princeton Gamma Tech., Inc., in Princeton, New Jersey, where two germanium diodes of 1116 and 1105 g were fabricated. They are nominally 64 mm in diameter by 67 mm in length. The material was stored 55 m deep in a water well at all times when not actually "in process." The spectrometers were completed and installed in the mine with a total of only two more weeks of cosmic-ray exposure.

The fabrication of high-purity copper parts was accomplished by electroplating from $CuSO_4$ solution onto polished stainless-steel mandrels. The anode was electroformed from the purest available copper stock. Each step of electroplating provides a stage of purification analogous to zone refinement. Further details of this process were recently published.[14]

Prior to the results presented here and in Ref. 9, the strongest bound on the 2ν $\beta\beta$ decay of ^{76}Ge was $T_{1/2}^{2\nu} > 5 \times 10^{20}$ yr claimed by the Caltech–Neuchatel–Paul Scherrer Institute Collaboration.[10] If the half-life is 10^{21} yr, the signal-to-background ratio near the maximum of the theoretical 2ν $\beta\beta$ decay spectrum (between 700 and 800 keV) of our data is approximately 15%; that for the spectrum of Ref. 10 is less than 1%.

Figure 1 shows the raw data with and without corrections for the observed very-low-intensity peaks at 47, 75, 85, 122, 239, 295, 352, 511, 583, 609, 662, 911, 1120, 1173, 1333, 1461, 1765, and 2614 keV and their predicted Compton distributions. All of these are associated with well-known primordial radioactive decay chains or with the decay of ^{57}Co, ^{60}Co, or ^{137}Cs, or are lead x rays.

The intensity of the gallium x-ray peak was used with the known branching ratios to correct for the continuum from ^{68}Ga decay. The response of the detectors to internal positron decay and subsequent annihilation radiation was simulated by two independent well-verified Monte Carlo codes.[15,16] The remaining spectrum appears to be a monotonically decreasing continuum with a small, broad distribution of excess counts centered at about 750 keV superimposed on a low-level, approximately linear continuum extending beyond 3 MeV. The region of this spectrum from 500 to 2800 keV, corrected for the small linear high-energy continuum, is shown in Fig. 2. The source of the dominant continuum below 850 keV has been identified as the bremsstrahlung spectrum from the decay of ^{210}Bi, the equilibrium daughter of ^{210}Pb in the lead shield. In this case, it becomes negligible at 850 keV and has no influence on the pronounced bump in the data between 850 and about 1700 keV. It is important to note that the spectral shape of the corrections cannot generate such a distribution. Overcorrection or undercorrection for the effects of the decay of ^{68}Ge or for the small linear continuum within ranges much larger than allowed by the errors in these components does not create or eliminate this feature. We conclude, therefore, that the suggestive spectral shape from about 850 to about 1700 keV is an intrinsic component of the spectrum and was not introduced by the applied corrections.

In the following it is assumed that the corrected spectrum of Fig. 2 consists of a low-energy continuum that is negligible above 850 keV and the two-neutrino $\beta\beta$ decay spectrum of ^{76}Ge.

The theoretical 2ν $\beta\beta$ decay spectrum was fitted to the data points above 850 keV with the result $n(2\nu)=758 \pm 264$ (2σ). The corresponding half-life is obtained as follows:

$$T_{1/2}^{2\nu}=\ln(2)Nt/n(2\nu)\,, \tag{1}$$

where $\ln(2)Nt=8.589\times10^{23}$ yr corresponds to 1.92 kg yr of data collected with a detector having natural isotopic abundance of ^{76}Ge. The result is

$$T_{1/2}^{2\nu}(^{76}\mathrm{Ge})=(1.13^{+0.61}_{-0.29})\times10^{21}\ \mathrm{yr}\quad(2\sigma)\,, \tag{2}$$

in excellent agreement with the shell-model predictions of Haxton[17] of 1×10^{21} yr and that of Williams and Haxton,[18] 1.15×10^{21} yr, when the contribution of the axial charge operator is included. It also agrees well with the predictions of the quasiparticle random-phase approximation for an experimentally acceptable range of g_{pp}, the neutron-proton, particle-particle coupling parameter.[19-22] The half-life given in Eq. (2) is similar to the experimental result presented recently by the ITEP-Yerevan Collaboration,[9] $(9\pm1)\times10^{20}$ yr, discussed briefly later in this text.

The spectrum of Fig. 2 was also submitted to a more complex analysis. It was assumed that the region of the

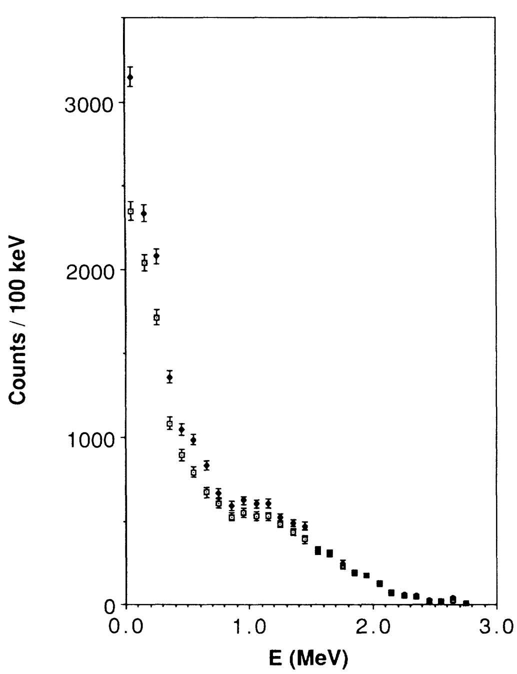

FIG. 1. 1.92 kg yr of raw data (solid diamonds) from the present experiment and corrected (open squares) for the γ-ray peaks and associated Compton distributions.

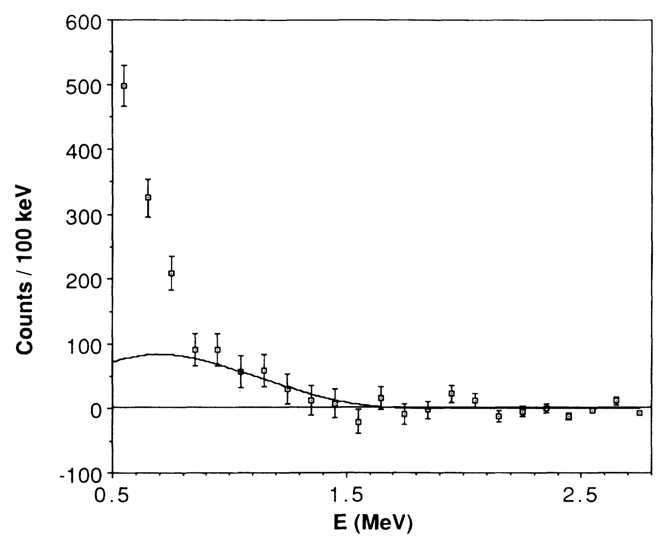

FIG. 2. The γ-ray-corrected spectrum from Fig. 1 further corrected for the decay of ^{68}Ge and a small linear continuum. The solid line is the theoretical shape of the 2ν $\beta\beta$ decay spectrum fitted to the data above 800 keV.

spectrum from 300 to 2100 keV is an admixture of $2\nu\ \beta\beta$ decay and the bremsstrahlung spectrum which can be represented in this energy region by a second-order polynomial of the form

$$f(E)=a+b(E_0-E)+c(E_0-E)^2 \quad (E_0\equiv 850\ \text{keV})\,. \quad (3)$$

The residual spectrum following this correction is shown in Fig. 3.

All of the remaining events were assumed to be from $2\nu\ \beta\beta$ decay with the result $n(2\nu)=765\pm 230\ (2\sigma)$ corresponding to

$$T_{1/2}^{2\nu}(^{76}\text{Ge})=(1.12^{+0.48}_{-0.26})\times 10^{21}\ \text{yr}\quad (2\sigma)\,. \quad (4)$$

The analysis was repeated using various low-energy cutoffs. The results were all consistent until the cutoff was extended down to 200 keV. At this point, the bremsstrahlung is no longer correctly represented by a function of the form of Eq. (3).

The corrections for the Compton distributions can be questioned because of our assumption that the sources of the γ-ray peaks were located isotropically around the crystal. Their exact location, in fact, is not known. A complete analysis using data uncorrected for the Compton distributions yields 1.0×10^{21} yr with similar errors. Irrespective of where the sources of the γ-ray peaks are located, there will be some continuum, and it was assumed that the analysis including these corrections was more realistic.

These results are very suggestive evidence for the $2\nu\ \beta\beta$ decay of ^{76}Ge. An absolute claim of observation must await similar experiments with a different isotopic enrichment.

The ITEP-Yerevan experiment[9] has two ~0.5-kg Ge(Li) detectors isotopically enriched to ~85% in ^{76}Ge. The detectors are encased in a NaI(Tl) live shield, and

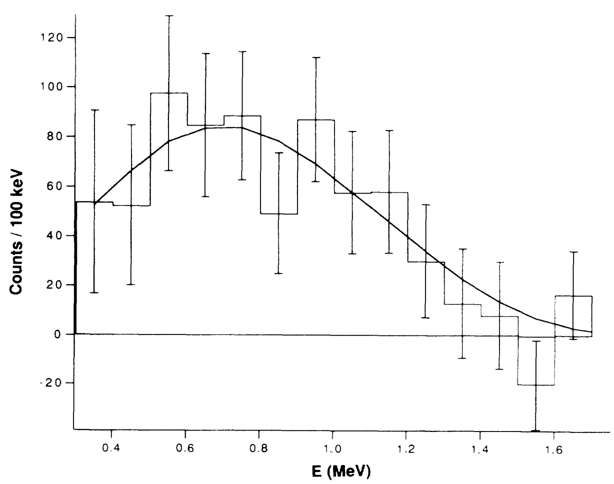

FIG. 3. The residual spectrum from Fig. 2 following final corrections for the bremsstrahlung from ^{210}Bi. The solid line is again the best-fit $2\nu\ \beta\beta$ decay spectrum.

the Compton-suppressed background in the energy range containing most of the $2\nu\ \beta\beta$ decay events is similar to the Caltech-Neuchatel-Paul Scherrer Institute singles spectrum.[10] The apparatus has one natural-isotopic-abundance control detector of similar dimensions mounted alongside the enriched detectors. The data from the control detector were subtracted from those of the enriched detectors after a complicated experimental efficiency correction and normalization to the same value of the product of volume and counting time. For this procedure to be reliable, the background in the control detector must be known to be the same as that of the enriched detectors to very high accuracy, particularly in cases in which the background is so dominant.

An enriched experiment with background levels of the Pacific Northwest Laboratory-University of South Carolina (PNL-USC) detectors would be far superior to either of these current germanium experiments. The PNL-USC and ITEP-Yerevan groups have since collaborated in mounting a ~0.25-kg Ge detector, enriched to 85% in ^{76}Ge, in one of the PNL-USC low-background cryostats in the Homestake gold mine.

A bound on the half-life for $0\nu\ \beta\beta$ decay with the emission of Majorons[23,24] of $T_{1/2}^{0\nu\chi^0}(^{76}\text{Ge})\gtrsim 6\times 10^{21}$ yr can be obtained from the data shown in Fig. 2, corrected for $2\nu\ \beta\beta$ decay. This particle may have been already ruled out by accelerator experiments which measure the width of Z^0.

The present body of data is not sufficiently large to allow bounds more sensitive than previously published to be placed on $0\nu\ \beta\beta$ decay with the emission of electrons only. However, in the final 0.8 kg yr of operation of the new detectors, the raw spectrum contains an average background of 0.3 count/keV kg yr in the energy interval 2000–2100 keV, and it continues to decrease with time.

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