New Limit for Neutrinoless Double β Decay of ^{76}Ge

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A new lower limit of 3.2×10^{22} yr has been obtained for the half-life of neutrinoless double β decay of ^{76}Ge to the ground state of ^{76}Se, by use of a Ge detector of 208 cm^3 active volume running in a salt mine for 2363 h. This is the largest detector used to date in such an experiment. A limit for decay to the first excited state has also been obtained.

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There is considerable interest today in the question of neutrinoless double β decay since it bears on a number of fundamental points of physics. The observation of a solely two-electron decay of a nucleus would be evidence for nonconservation of lepton number and would indicate that the neutrino is to some extent identical with the antineutrino (i.e., has Majorana character). This observation would also imply a nonzero mass for the neutrino and/or the presence of right-handed currents in the weak interaction. As yet there is no conclusive evidence for the existence of this process, which in principle can occur for a fairly large number of "stable" isotopes. One particular isotope, ^{76}Ge, has been of special interest in the search for neutrinoless double β decay[1] because it offers a good compromise among a number of properties making for a sensitive test. It is a reasonably abundant isotope, it has a fairly large Q value for 2β decay, and it lends itself to an especially simple and ultimately sensitive experiment.

The principle of the search for neutrinoless double β decay of ^{76}Ge is that a Ge γ-ray detector comprises both the source of ^{76}Ge and the detector of the decay. The isotope ^{76}Ge is 7.8% abundant and the energy released in a neutrinoless 2β process, now accurately known[2] to be 2040.71 ± 0.52 keV, is carried by the two emitted electrons (neglecting the small nuclear recoil). The range of 1-MeV electrons is quite short (~1 mm) and therefore most often the total energy of the electrons is deposited within the detector. Hence the signal for the 2β decay will be a peak in the spectrum, at 2040.7 keV. Previous searches[3] for this peak give lower limits to the lifetime of $\sim10^{22}$ yr, and therefore a large amount of germanium is required to obtain a detectable signal in a reasonable time.

Apart from the large size of germanium detector needed, another difficulty encountered is background from two sources, viz., naturally occurring radionuclides, especially of the thorium chain, and cosmic-ray–induced background.

In the present experiment a specially constructed high-purity Ge detector was used in an underground site. The detector consists of a 208-cm^3 active volume Ge [47% efficient for ^{60}Co γ rays relative to a 7.6-cm$\times$7.6-cm NaI(Tl) detector] in a J-shaped cryostat assembly made of materials selected for low intrinsic radioactivity. The end cap and crystal mount were made of aluminum with less than 2 ppb of U or Th. Inside the end-cap plastic, Teflon, and small stainless-steel fasteners were used. Vacuum was maintained by activated charcoal in a stainless-steel liquid-nitrogen Dewar. The energy resolution is 3 keV at 2 MeV. The detector was installed in a salt mine near Windsor, Ontario, at a depth of about 330 m. A salt mine has an advantage over a hard-rock cavern or tunnel in that the background from radionuclides is extremely low, perhaps a factor of 1000 less than typical rock, and hence less radiation shielding is needed and holes in the shielding become less important. However, the depth of this particular mine does not give

TABLE I. Counting rates in various peaks and regions of the spectra. The peak rates are given in counts/kh and the regional rates in counts/(keV · kh). The columns are labeled by the shielding; μ means cosmic-ray veto (see text). The region 200–1100 keV includes ^{210}Pb bremsstrahlung.

Peak or region (keV)	Run 1 Pb	Run 2 Pb+Hg	Run 3 Pb+Hg+μ
239 [a]	8620 ± 340	8590 ± 180	8460 ± 190
583 [a]	2770 ± 130	2760 ± 100	2640 ± 110
911 [a]	820 ± 60	930 ± 50	790 ± 60
1460	186 ± 30	178 ± 60	200 ± 30
2615 [a]	960 ± 60	1010 ± 50	890 ± 50
2650–3250	0.79 ± 0.07	0.91 ± 0.07	0.07 ± 0.04
3250–3750	0.40 ± 0.05	0.40 ± 0.04	0.29 ± 0.02
200–1100	900	180	167
1100–2650	8.75	7.78	7.15

[a]From ^{232}Th chain. Peaks from the ^{238}U chain are very much weaker.

as large an overburden of rock as is available in many hard-rock mines or Alpine tunnels, and the cosmic-ray reduction is about a factor of 400 relative to our surface laboratory. No peaks which could be attributed to neutrons in germanium have been observed in the mine.

The present experiment consisted of several runs. In the first one the detector was enclosed in a lead castle of about 20 cm thickness. Then, in the second run, a 6-mm-thick mercury shield was put inside the lead castle to surround the detector completely. The chief effect of this was to remove from the spectrum much of the bremsstrahlung from ^{210}Pb decay in the lead shield, thus improving the low-energy background in the detector. (It should be pointed out that although the lead was old, approximately 150–200 yr, ^{210}Pb could nevertheless be seen.) Finally, a 0.6-m^2 plastic area scintillator was placed above the castle and used as a cosmic-ray veto detector. The event rate in this detector was about 8/s and the analog-to-digital converter analyzing the Ge pulses was inhibited for 500 μs with each veto pulse. Table I lists the counting rates in various peaks and regions for the three runs and it can be seen that the cosmic-ray veto reduces the high-energy background by about 30%. It was also observed that over runs of several months (the data recorded nearly daily) the 2614.47-keV peak moved by only about 0.4 channel.

Figure 1 shows a portion of a spectrum around the expected 2β-peak position. The energy calibration was determined from background γ rays of 583.14, 1460.75, and 2614.47 keV and the 2614.47-keV single-escape peak, and the system was found to be very linear in this region, having an rms deviation from linearity of about 0.2 keV. The background at the 2β-peak energy was determined from a region comprising the fifteen channels above and below the expected location of the peak. A likelihood function for obtaining the observed number of counts in the 2β region (either three or four channels centered on the centroid location of the 2β peak which was taken to be a Gaussian of 3 keV full width at half maximum) was calculated as a function of the mean 2β-decay rate under the assumption that both background and 2β-decay rates are Poisson probability distributions. The several

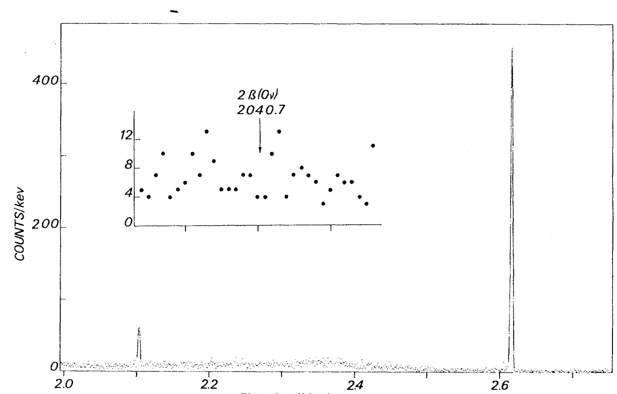

FIG. 1. Energy spectrum in the region from 2 to about 2.8 MeV. Each channel is 1 keV wide. This spectrum was obtained after 1548 h. The large peak at 2615 keV is ^{208}Tl decay and its single-escape peak can be seen at 2104 keV. The region near the expected location of the neutrinoless 2β peak at 2040.7 keV is shown in the inset.

runs were also combined by use of the likelihood method. At a 68% confidence level, $T_{1/2} > 3.2 \times 10^{22}$ yr, and at a 95% confidence level $T_{1/2} > 1.5 \times 10^{22}$ yr. This limit assumes a fiducial volume of 194 cm^3 estimated by excluding a sensitive layer of 1 mm from the outside of the detector. Other recently published limits are 2×10^{22} yr,[4] 1.6×10^{22} yr,[5] and 1.9×10^{22} yr,[6] also at a 68% confidence level. The limit of 3.2×10^{22} yr can be interpreted as an upper limit of 18 eV on the mass of a Majorana neutrino.[7]

The limit we have given is based on the assumption that the only significant neutrinoless 2β branch is to the ground state. However, if there is a significant branch α $(0 < \alpha < 1)$ to the 2^+ state of ^{76}Se at 559.1 keV, then two things would occur. Firstly, there would be a peak at 1481.6 keV which would depend on $T_{1/2}$, the *total* half-life for neutrinoless 2β decay (if we assume that only ground-state and first excited-state decays contribute), α, and on the probability P_e of the 559.1-keV γ ray escaping from the crystal. Secondly, there would be a contribution to the 2040.7-keV peak depending also on $T_{1/2}$, α, and P_a, the probability of total absorption of the 559.1-keV γ ray in the detector. The probabilities P_e and P_a have been estimated with a Monte Carlo code as 0.34 and 0.13, respectively. Hence our results for $T_{1/2}$ and α can be expressed as

$$T_{1/2} > (1-0.87\alpha)\times 3.2\times 10^{22}\ \text{yr}$$

and

$$T_{1/2} > 0.34\alpha \times 1.6\times 10^{22}\ \text{yr},$$

the second limit arising from a search for decay to the first excited state. This limit, equivalent to 1.6×10^{22} yr at 68% confidence level and 7.2×10^{21} yr at 95% confidence level, under the assumption of a γ-ray escape probability of 1, has been obtained in a way similar to that for the ground-state branch.

The present experiment is being continued with three crystals of approximately the same size as the present one mounted in a single cryostat.

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