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Search for the double-β decay of ^{76}Ge

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A systematic study of the radioactive background in materials used in Ge-detector fabrication was conducted prior to the construction of an ultralow-background, 135 cm^3 prototype detector. The background from primordial radioactivities in the new system was lower by factors of between 1.5×10^3 and 2.5×10^4 when compared to commercial low-background detectors. Data were collected for 8089 h with the detector located 1438 m underground, resulting in improved lower limits for the half-lives for both two-neutrino and neutrinoless $\beta\beta$ decay of ^{76}Ge to the ground state of ^{76}Se and for the neutrinoless $\beta\beta$ decay to the first excited state of ^{76}Se. The results of four recent theoretical calculations are compared in detail and used to extract limits on $\langle m_\nu \rangle$, the Majorana mass of ν_e, and on the amplitudes of the couplings of right-handed Majorana neutrinos. The best combination of the lowest background data from recent experiments results in a new limit $T_{1/2}^{0\nu} \gtrsim 3\times10^{23}$ yr, corresponding to $\langle m_\nu \rangle < 2.4$ eV neglecting right-handed couplings or 2.8 eV including both right-handed neutrino couplings.

INTRODUCTION

Double beta ($\beta\beta$) decay has the smallest probability ($\lambda \sim 10^{-29}$ sec^{-1}) of any physical process (unless the proton decay candidates from several experiments are confirmed). The classic case is that of ^{130}Te decay observed in geochemical experiments such as those of Kirsten, Richter, and Jessberger,[1] who reported a half-life of 2.49×10^{21} yr. Thus far, there has been no direct laboratory observation of $\beta\beta$ decay; however, Moe, Hahn, and Elliott[2] have reported a number of candidate events from the decay of ^{82}Se in the University of California, Irvine, time-projection chamber (TPC). The importance of the observation of neutrinoless $\beta\beta$ decay stems from its sensitivity as a probe of Majorana neutrino mass and lepton nonconservation. Excellent reviews, including experimental results as well as theoretical details, have been given by Haxton and Stephenson[3] and by Primakoff and Rosen,[4] where the latter is a general review of baryon and lepton conservation. In addition, a comprehensive discussion of $\beta\beta$ decay and neutrino mass has also been given by Shchepkin.[5]

The most interesting connection between 0ν $\beta\beta$ decay and fundamental particle theory is that it can be engendered by Majorana neutrino mass or explicit right handed neutrino couplings to hadrons, or both. The standard electroweak model, as well as the minimal SU(5) grand unified theory (GUT), require neutrinos to be massless while interactions which induce neutrino masses naturally arise in the minimal GUT of SO(10), for example. Models which possess left-right symmetry, as well as lepton-hadron symmetry, in general have massive neutrinos, and SO(10) is but one example. There are many realistic scenarios in which Majorana neutrino masses on the order of tenths to tens of eV arise in this class of models. This entire domain should be accessible to 0ν $\beta\beta$ decay experiments in the near future. The sensitivity of these experiments as probes of grand unification schemes ultimately depends on the level to which background can be reduced and also on a clear understanding of the nuclear structure involved. Both of these subjects are discussed at some length in this article.

Experiments which measure, or place limits on the decay rate, ω, or half-life, $T_{1/2}$, also determine, or place limits on, the composite neutrino mass, $\langle m_\nu \rangle$, or right handed couplings. The process of extracting values of (or limits on) these quantities from half-life information, is clearly nuclear model dependent. It is then very important to measure the continuum of electron energies from 2ν $\beta\beta$ decay as well as the full energy peak at the $\beta\beta$-decay Q value. According to conventional wisdom, the 2ν half-life is an excellent test of 0ν theoretical matrix elements because of the scaling relation first suggested by Primakoff and Rosen[6] and derived theoretically by Haxton and Stephenson.[3] A somewhat different view will be discussed later. On the other hand, the practice of scaling the 0ν matrix elements of the $\beta\beta$ decay of ^{76}Ge, with 2ν matrix elements renormalized to agree with experimental observations of the decay of ^{82}Se, is not reliable because the nuclei involved in both decays have significantly different neutron and proton occupations. There is a strong temptation to do such scaling using the measured total half-life of ^{82}Se from geochronological studies, $(1.45\pm0.15)\times10^{20}$ yr, coupled with shell-model predictions for the 2ν half-lives of both isotopes, using similar calculational techniques. They are $T_{1/2}(^{76}\mathrm{Ge})=4.15\times10^{20}$ yr and $T_{1/2}(^{82}\mathrm{Se})=2.62\times10^{19}$ yr (see Table 9 of Ref. 3). Such scaling between isotopes is risky at best, and resulting conclusions are very suspect. To extract reliable values or limits on $\langle m_\nu \rangle$ from $\beta\beta$-decay data, it will be necessary to measure the 0ν and 2ν half-lives in the same decay. If the scaling relation of Primakoff and Rosen is found not to hold, the 2ν $\beta\beta$-decay data can be used to test the assumptions made in nuclear structure calculations of the 0ν mode. The closure approximation is one such assumption.

For reasons given above, further background reduction efforts using our ultra-low-background prototype Ge detector, in various shielding configurations, in the Homestake gold mine[7] have been continued. One important result is a new limit of $T_{1/2}^{2\nu}(^{76}\mathrm{Ge}) \gtrsim 3\times 10^{20}$ yr. The major contributors to the background in all regions of our spectrum have been identified and steps are being taken to eliminate these to a level which would allow the direct observation of 2ν $\beta\beta$ decay. Further discussion of this and a number of other experiments will be given later.

There are several techniques being used in $\beta\beta$-decay experiments, and it is useful to review their relative strengths and weaknesses. Until very recently the most reliable limit on the Majorana mass of ν_e was that reported by Kirsten and co-workers[1] ($\langle m_\nu \rangle < 5.4$ eV) obtained from the ratio of the $\beta\beta$ decay rates of ^{128}Te and ^{130}Te. The argument was made that the structures of these nuclides should be very similar, so that the nuclear matrix elements would cancel in the ratio. The extensive weak coupling shell model calculations of Haxton, Stephenson, and Strottman predict that these matrix elements differ by less than 1%. (See Table 9 of Ref. 3.) The ratio of the experimental and theoretical half-lives for ^{130}Te is 147; this suggests that there are perhaps very severe cancellations between terms associated with each intermediate state. One should not then assume that these cancellations would be the same in both Te isotopes. It is also true that geochronological experiments are not able to distinguish between ordinary 2ν $\beta\beta$ decay and the exotic lepton nonconserving 0ν process because only the final decay product is measured. The time projection chamber measurements of the electron spectrum from the $\beta\beta$ decay of ^{82}Se can, in principle, distinguish between 2ν and 0ν decay; however, the energy resolution achievable with a source large enough to obtain statistically significant data will be relatively poor (7–10%). The ^{76}Ge experiments, on the other hand, have the distinct advantage of excellent energy resolution ($\Delta E/E \sim 1.8\times 10^{-3}$) at 2041 keV, the vicinity of the decay energy. In addition, the source is the 7.78% abundant ^{76}Ge in the detector itself, and increases in volume will not necessarily affect the energy resolution. Radioactive impurities in the detector and cryostat are readily identifiable and are less prone to be confused with $\beta\beta$-decay events. It is reasonable to conclude that though the TPC technique may prove to be superior for 2ν $\beta\beta$-decay measurements, the ^{76}Ge experiments show the most promise for searching for the exotic 0ν processes. In addition, four independent theoretical nuclear structure calculations discussed below verify that ^{76}Ge is a favorable case.

GENERAL THEORETICAL CONSIDERATIONS

We begin our theoretical discussion by introducing the fundamental quantities in terms of notation used later. Our notation is not specifically that of a single author; however, we use the conventions of Ref. 3.

The semileptonic interaction for the β decay of a d quark is written as follows:

$$H = \frac{-G_F\cos\theta_C}{\sqrt{2}}[\,j_L^\mu(J_{L\mu}^+ + \eta_{LR}J_{R\mu}^+) + j_R^\mu(\eta_{RL}J_{L\mu}^+ + \eta_{RR}J_{R\mu}^+)]\ , \tag{1}$$

where j_L^μ (j_R^μ) are the components of left- (right-) handed leptonic currents, $J_{L\mu}$ ($J_{R\mu}$) are the components of the left- (right-) handed hadronic currents, and η_{LR}, η_{RL}, and η_{RR} are the relative weightings of the various current-current contractions in the Hamiltonian density. The Cabibbo angle is θ_C, and the Fermi coupling coefficient G_F is $1.023\times 10^{-5}/M_{\mathrm{p}}^2$, where M_{p} is the proton mass. In the above expression,

$$j_L^\mu \equiv \bar{e}\gamma^\mu(1-\gamma_5)\nu \tag{2}$$

and

$$J_{L\mu}^+ \equiv \bar{u}\gamma_\mu(1-\gamma_5)d\ , \tag{3}$$

where e and ν are the lepton fields and u and d are the quark fields. The corresponding right-handed currents are obtained by use of the projection operator $(1+\gamma_5)$. The left- and right-handed neutrino fields can be expanded in the complete basis of Majorana mass eigenstates $\{\upsilon_i(x)\}$ as follows:

$$\nu_L = \sum_{i=1}^{2n} U_i^L \upsilon_i \quad \text{and} \quad \nu_R = \sum_{i=1}^{2n} U_i^R \upsilon_i\ , \tag{4}$$

where n is the number of ν generations and the transformation matrices U are those which diagonalize the neutrino mass matrices.

It is convenient to introduce the parameters x, y, and z, used by a number of authors, but this will be done in the conventions of Ref. 3 and with *a priori* assumption of CP conservation. Accordingly,

$$x \equiv m_e^{-1}\left|\sum_{k=1}^{2n} \lambda_k^{*c} U_k^L U_k^L (m_\nu)_k\right|\ , \tag{5}$$

where λ_k^c is the relative phase between the Dirac particle and antiparticle pieces when the Majorana neutrino is expressed as an admixture of the Dirac particle and antiparticle fields.[3] The physical quantity to which 0ν $\beta\beta$ decay is sensitive is $\langle m_\nu \rangle_L \equiv x m_e$. A quantity $\langle m_\nu \rangle_R$ can be defined analogous to Eq. (5). The two parameters associated with right-handed neutrino couplings are

$$y \equiv \eta_{RR}\left|\sum_{k=1}^{2n} U_k^L U_k^R\right| \tag{6}$$

and

$$z \equiv \eta_{RL}\left|\sum_{k=1}^{2n} U_k^L U_k^R\right|\ . \tag{7}$$

The $\beta\beta$-decay rate, for the 0ν mode, can be expressed in the following general form:

$$\omega(\mathrm{yr}^{-1}) = \alpha_1(\mathrm{yr}^{-1})\{x^2 + \alpha_2 y^2 + \alpha_3 z^2 + \alpha_4 xy + \alpha_5 xz + \alpha_6 yz\}\ . \tag{8}$$

TABLE I. Numerical values for the parameters α_i in Eq. (8) for the $\beta\beta$ decay of ^{76}Ge.

	Ref. 3	Ref. 18	Ref. 19	Ref. 20
α_1	1.08×10^{-13} yr^{-1}	2.21×10^{-13} yr^{-1}	2.18×10^{-13} yr^{-1}	1.12×10^{-13} yr^{-1}
α_2	1.44	1.46	1.04	0.92
α_3	0.65	0.34	7016	114
α_4	−0.45	−0.44	−0.36	−0.33
α_5	−0.38	−0.36	82.0	−6.68
α_6	−1.34	−1.24	−0.82	−0.68

The quantities $\{\alpha_i\}$ depend on the nuclear and atomic wave functions and relevant matrix elements. The various values of these parameters, from recent calculations discussed below, are given in Table I.

RELEVANT NUCLEAR STRUCTURE CALCULATIONS

There have been a number of recent nuclear structure calculations of $\beta\beta$-decay matrix elements. The most extensive were the weak-coupling shell model calculations of Haxton, Stephenson, and Strottman,[8] who treated ^{76}Ge, ^{82}Se, ^{128}Te, and ^{130}Te.

In the ^{128,130}Te cases, all p- and n-hole states in the model space ($2d_{5/2}$, $1g_{7/2}$, $3p_{1/2}$, $2d_{3/2}$, $1h_{11/2}$) were included.[8] The two-body interaction used was derived by Baldridge and Vary from the Kuo bare G-matrix elements.[9] The lowest 50 proton and 50 neutron states formed the weak coupling basis. All allowable combinations of these states were included in the p-n interaction matrix. The results exhibited strong coherence in the density matrix, resulting in large Gamow-Teller matrix elements ($M_{\rm GT}\cong1.48$) for both ^{128}Te and ^{130}Te. These disagree by more than an order of magnitude with those derived from geochronological data[1] ($M_{\rm GT}\cong0.12$ for ^{130}Te). The disagreement in the case of ^{128}Te is approximately a factor of 7 ($M_{\rm GT}\cong0.2$). The calculated matrix elements for the decays of ^{128}Te and ^{130}Te are the same to within 1%, and it is tempting to assume that they will cancel in the ratio of decay rates. If the small experimental values are the result of an unpredicted cancellation, this assumption may be totally invalid.[3]

In the cases of ^{76}Ge and ^{82}Se,[10] the valence space included the $1g_{9/2}$, $1f_{5/2}$, $2p_{3/2}$, and $2p_{1/2}$ levels. The assumed closed core was ^{56}Ni, so that the ^{76}Ge ground state consisted of 4p,6n holes, while the ^{76}Se ground state consisted of 6p,8n holes. The wave functions were constructed with all possible combinations of proton and neutron holes. The Kuo matrix elements for the ^{56}Ni core, were adjusted to fit 28 observed energy levels in the region with a rms deviation of 270 keV. An improved update of these calculations appears in Ref. 3.

The Osaka group included the p-wave effect[11] as well as a weak magnetism correction to the nuclear current, which was included in only their most recent report.[12] They found these effects to have approximately equal contributions. It should be pointed out that the Osaka group has used the nuclear matrix elements of Haxton, Stephenson, and Strottman[8,10] so that the differences in their results are attributable to other effects.

Zamick and Auerbach[13] considered the $\beta\beta$ decays of ^{48}Ca and ^{76}Ge in the framework of the Nilsson model with pairing. Their calculations explain the slow decay rate of ^{48}Ca in terms of the K-selection rule ($\Delta K=0,\pm1$). Their result is $M_{\rm GT}=0.18$, in excellent agreement with the earlier shell model calculation of Khodel[14] and the more recent one by Haxton and Stephenson[3] ($M_{\rm GT}=0.19$). The $\beta\beta$ decay of ^{76}Ge is described as a transition of two neutrons in the $K=\frac{1}{2}$ state at $4.71\hbar\omega$ to the $K=\frac{3}{2}$ state at $4.443\hbar\omega$. A value in good agreement with the shell model prediction was obtained for $M_{\rm GT}$, with a realistic value for the deformation parameter $\eta\cong4$, but only when pairing forces are added. For the Bohr-Mottelson value of the pairing gap, $\Delta=1.38$ MeV, the result is $M_{\rm GT}=2.2$. These calculations have been repeated by Haxton and Stephenson[3] using the full Nilsson wave functions with similar results, and are in quantitative agreement with their shell model calculations in an equivalent model space.

Another recent set of nuclear structure calculations of the $\beta\beta$ decays of ^{128,130}Te, ^{82}Se, and ^{76}Ge was published by Grotz and Klapdor.[15] In this work, right handed couplings were neglected and the nuclear matrix elements calculated in the framework of particle number-projected BCS wave functions with a two body interaction including pairing, double Gamow-Teller, and quadrupole-quadrupole terms. The decay rate in this case is expressed as

$$\omega_{0\nu}=(\langle m_\nu\rangle^2/m_e^2)f^{0\nu}\,|1-\chi_F|^2\,|M^{0\nu}R_0|^2\,, \qquad (9)$$

where $f^{0\nu}$ is the phase space factor given by Doi *et al.*[16] as 4.2×10^{-15} yr^{-1} for ^{76}Ge. The Fermi decay branching ratio χ_F was calculated as -0.24 and $R_0|M^{0\nu}|=10.4$ for this decay, where $M^{0\nu}$ is the Gamow-Teller matrix element. The final result is $\langle m_\nu\rangle^2=2.5\times10^{23}$ yr$/T_{1/2}^{0\nu}$ (^{76}Ge) in eV squared. Earlier, Klapdor and Grotz[17] found that strong cancellations, from Gamow-Teller and quadrupole-quadrupole correlations, reduced the 2ν decay matrix elements of the Te isotopes by more than a factor of 10. These cancellations were not found to effect 0ν decay significantly; hence, they explain the discrepancy between the shell model predictions[3] and the geochronological half-lives[1] while strongly supporting the existence of large matrix elements in the case of $0+\to0+$, 0ν $\beta\beta$ decay. This phenomenon challenges the scaling principle of Primakoff and Rosen and makes the measurement of 2ν $\beta\beta$ decay all the more important. More recent work by

Vogel and Fisher[17] includes the effects of pairing, static quadrupole deformation, spin-isospin polarization and the Δ_{33} isobar admixtures. For example, their 2ν $\beta\beta$-decay rate for ^{76}Ge is 4 times larger than the shell model value,[3] while they also predict faster than observed rates for ^{82}Se, ^{130}Te, and ^{150}Nd.

Finally, there have been two recent papers by Tomoda, Faessler, Schmid, and Grümmer[18,19] which discuss neutrinoless $\beta\beta$ decay of ^{76}Ge. They describe the initial and final nuclear states by angular-momentum- and particle-number-projected Hartree-Fock-Bogoliubov wave functions. In this approach the energy was minimized after projection. The model space included the $1g_{9/2}$, $1f_{5/2}$, $2p_{3/2}$, and $2p_{1/2}$ levels. The p-wave contribution was included as well as relativistic corrections to the nuclear current including weak magnetism. In an earlier attempt, short range correlations were not included. The decay rate was extremely sensitive to η_{RL}, the coupling of the right handed leptonic current to the left handed hadronic current. The inclusion of short range correlations reduced the nuclear recoil term by a factor of 40 while it had little effect on the usual contributions.[18] In their later report Tomoda *et al.*[19] included relativistic corrections including weak magnetism. They have also accounted for the fact that the associated two-body operator acquires a finite range due to the finite dimensions of the nucleon. The proper accounting for this effect, in the short range NN correlations, results in only a moderate reduction in the matrix element.[19] The earlier reported cancellation is not evident.[18]

The values of the parameters α_i from Refs. 3 and 18–20 are given in Table I. The large value of α_3 calculated in the work of Doi *et al.*[20] reflects a severe enhancement of the coupling of left handed neutrinos to right handed hadrons. This is due to the inclusion of the p-wave contribution. This enhancement was also seen in the calculation of Tomoda *et al.*;[19] however, the inclusion of short range correlations[18] alone seemed to cause a cancellation between the p-wave and recoil effects, resulting in a reduction of α_3 by more than 2 orders of magnitude. While these large differences do not appear in the Majorana mass term, characterized by α_1, a large interference from α_3 could make a sensitive extraction of $\langle m_\nu \rangle$ difficult. This is where a $0+ \to 2+$ measurement (or limit) will be extremely valuable because this transition is driven only by right handed currents. In this regard, the ^{76}Ge $\beta\beta$ decay experiments are unique in that they have excellent energy resolution and sensitivity for the $0+ \to 2+$ 0ν peak at 1481.6 keV.

^{76}Ge DOUBLE BETA DECAY EXPERIMENTS AND RESULTS

The clever introduction of Ge detectors to search for 0ν $\beta\beta$ decay was due to Fiorini and co-workers.[21] Since then a number of improved experiments have been initiated, but only the most recent ones described in the literature[7,22–27] will be discussed. All of these experiments have a common goal: to reduce the background so as to be sensitive to a Majorana neutrino mass of about 1 eV or less. The experiment described by Ejiri *et al.*[26] is a coincidence experiment, somewhat more elegant than our earlier effort,[22] and has as its main goal the detection of $0+ \to 2+$, 0ν $\beta\beta$ decay. The others are single counting experiments with ultimate goals of reducing the background and increasing the volume of Ge so as to increase the sensitivity. Our prototype has been operating in the Homestake goldmine in Lead, South Dakota for more than 2 yr in a variety of shielding configurations. The details of our background reduction are given elsewhere,[28] and this direction will be pursued until the crucially important observation of 2ν $\beta\beta$ decay can be achieved.

The design of our spectrometer evolved from several prior generations of low-background spectrometers. The background in our original 135 cm^3 detector was traced step by step. The aluminum end cap, diode cup, support hardware, and electronic parts close to the detector were found to contain primordial and manmade radioactivity. The isotopes ^{228}Ac, ^{212}Pb, and ^{208}Tl from the ^{232}Th chain, ^{234}Pa^m from the ^{238}U chain, ^{235}U, and ^{40}K were the significant primordial contributors, with ^{137}Cs and ^{60}Co being the only discernible manmade radionuclides. Prospective construction materials, in quantities of 10–100 times that actually used in the detector, were assayed for radionuclide contamination as described in Ref. 28. Aluminum was found to be the major source of primordial radioactivity, with capacitors, resistors, field-effect transistors, and rubber O rings being smaller contributors. Stainless steel screws were found to contain ^{60}Co.

Samples from three types of copper were analyzed, and the one with the least radioactivity (<0.00003 dis/min per kg was selected to replace the aluminum and stainless steel in the cryostat. Brass screws replaced the stainless steel screws, and an indium O ring was used for the vacuum seal. The field-effect transistor was modified to exclude the contaminated component, and the preamplifier was placed outside the shield. An abbreviated list of construction materials and their radionuclide concentrations is given in Table II below. A more extensive list appears in Ref. 28.

The experiment was run underground for nine months with no shielding between the low background lead and the copper cryostat. A large low-energy bremsstrahlung background resulted from the β decay of ^{210}Bi, which follows the β decay of ^{210}Pb present in the lead shielding bricks themselves. An inner shield of pre–World War II steel was tried but was found to be contaminated with radioactive isotopes of thorium and radium, albeit at levels which would be undetectable in previous low-background experiments. Later, a copper inner liner, shown in Fig. 1, was installed which is 7.3 cm thick on the sides and 7.6 cm thick on the ends. This reduced the background in the 250 keV region by about a factor of 13. It is interesting to note that the experiment is sensitive enough to detect the 1124 keV line from the decay of ^{65}Zn present in the crystal due to the cosmic-ray–neutron-generated reaction, ^{70}Ge(n,α2n)^{65}Zn. This line is the sum of the 1115.5 keV transition in ^{65}Cu, following the electron capture of ^{65}Zn, and the Cu x rays. In addition, cosmogenically produced isotopes of Mn, Fe, and Co are also observed in the Cu liner. They were formed by energetic cosmic ray neutrons while the Cu was above ground. The relevant reactions

TABLE II. Primordial radionuclide concentrations in various materials used in fabrication of radiation detector systems.

Materials	Radionuclide concentration in dis/min per kg		
	^{208}Tl	^{214}Bi	^{40}K
Aluminum	7–200	<4–2000	<20–1000
Copper (grade 101)	<0.03	<0.05	<0.5
Epoxy	50–4000	80–53 000	<1000–72 000
Indium	<1	<3	<20
Lead	<0.02	<0.04	<0.1
Molecular sieve	400–500	1000–3000	8000–9000
Mylar, aluminized	100	200	<2000
Printed circuit board	2000	4000	4000
Solder	<0.3	<0.8	<10
Steel, stainless	<2	<6	<200
Steel, pre–WW II	<0.5	<0.9	<10
Teflon	<0.3	<1–7	<20
Wire, Teflon coated	<4	<1	<20

and the equilibrium concentrations are given in Table III. The existence of detectable levels of these isotopes demonstrates that experimentalists involved in ultra-low-background measurements must be cognizant of cosmogenic radionuclide production in their construction materials. Furthermore, ^{68}Ge will likely be present in Ge crystals from similar reactions. These will be the limiting factors for low background experiments above ground. The effects on the background of different cryostat configurations, and of the copper liner added later, are shown in Fig. 2.

The impact of the present level of background on the 2040.71 ± 0.52 keV region of interest[29] is given in the second column of Table IV, along with the background rates from other experiments. All of the published data through mid 1985 have been reviewed in an attempt to examine various combinations to obtain a "world limit." The data from other experiments came from the recent publications of the Milano,[23] Cal Tech,[24] Guelph-Aptec-Queens,[25] and the UC Santa Barbara–Lawrence Berkeley[27] (UCSB-LBL) groups. The published spectra in the region of 2041 keV were all adjusted to the scale of 1 keV per channel before the individual spectra and various combinations, formed by adding spectra channel by channel, were analyzed. Either the quoted energy resolution, or one calculated from background peaks, was used in each case. The full width at half maximum resolution of the present experiment was 3.7 keV at 2041 keV. The effective resolution for combined spectra was computed by weighting each Gaussian by its corresponding product of ^{76}Ge atoms and counting time, Nt.

The data were analyzed with a maximum likelihood technique rather than the Monte Carlo method[30] used in our earlier work.[22] The likelihood function was calculated by assuming a Gaussian $\beta\beta$-decay peak consisting of λ hypothesized counts. This peak was superimposed on the mean background, and the probability of occurrence of each experimentally observed data point was calculated using Poisson statistics. The likelihood function $L(\lambda)$ is the product of these probabilities and was maximized by varying λ. The confidence level was calculated by numerically integrating $L(\lambda)$. The results of these analyses appear in the last column of Table IV. Our analyses of the

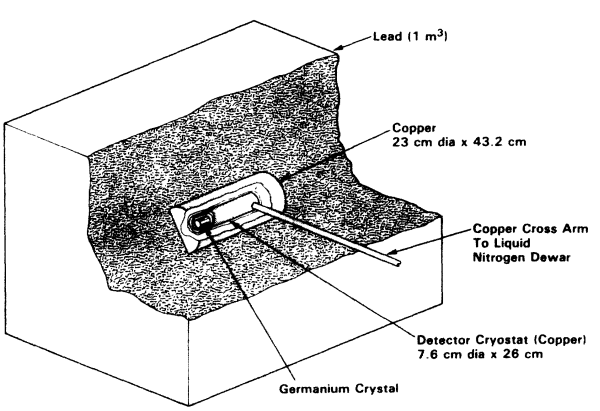

FIG. 1. Ultra-low-background, 135 cm^3 prototype Ge detector with copper inner shield.

TABLE III. Primary reactions of cosmic ray neutrons with the copper liner and the equilibrium concentrations of daughter isotope decays in dis/min per kg.

Reaction	Specific activity dis/min per kg
^{63}Cu(n,α2n)^{58}Co	0.05
^{63}Cu(n,2α2n)^{54}Mn	0.02
^{63}Cu(n,α)^{60}Co	0.01
^{63}Cu(n,α4n)^{56}Co	0.006
^{63}Cu(n,αp)^{59}Fe	0.004
^{63}Cu(n,α3n)^{57}Co	<0.002

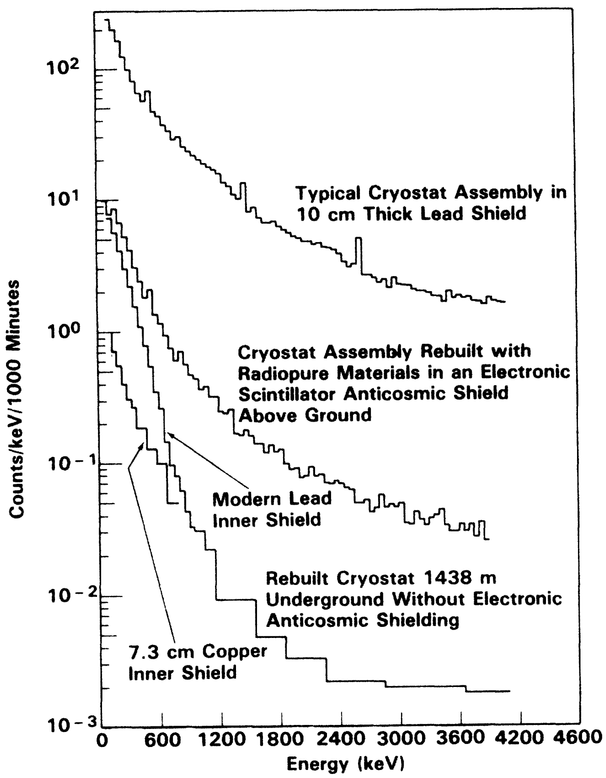

FIG. 2. Background spectra for the 135 cm^3 prototype Ge spectrometer in three different cryostat configurations.

Milano[23] and Cal Tech[24] data yield essentially the same results given by the authors, which implies that the data compression procedure does not change the result significantly.

The number given in the second column of Table IV in counts/keV/yr/10^{23} ^{76}Ge atoms, provides a figure of merit of the radiopurity of each experiment. The impact of the background reduction was seen by noting that the PNL-USC (PNL denotes Pacific Northwest Laboratory; USC, University of South Carolina) experiment after 6075 h yielded a limit of 1.40×10^{23} yr (1σ), while the Milano Total experiment yielded only 1.25×10^{23} yr (1σ), even though the product Nt is larger in the Milano experiment. The best overall limit is obtained by adding the PNL-USC, Milano-2, and the new UCSB-LBL spectra. All other combinations lead to less sensitive results, clearly demonstrating that low background is the key to ultimate sensitivity.

The rebinned data from these experiments are shown in Fig. 3. Several spectra have channels with high numbers just above the arrows corresponding to 2041 keV, but most are not statistically significant. In the low background PNL-USC spectrum collected after only 3763 h, there were eight counts in the four-channel bin 2043–2046 keV. A binomial analysis yielded a probability of <0.01 for having the 18 events, which appear in the 20 keV interval beginning at 2031 keV, distributed as they were for a random, flat, background. We concluded in our earlier paper[7] that a peak exists at 2044.72 keV with a level of confidence of $>99\%$. After twice the counting time there are still eight counts in this bin, while the other bins have increased. A maximum likelihood analysis now shows that there is still a positive peak, but at a level of confidence of slightly less than 68%. The background is

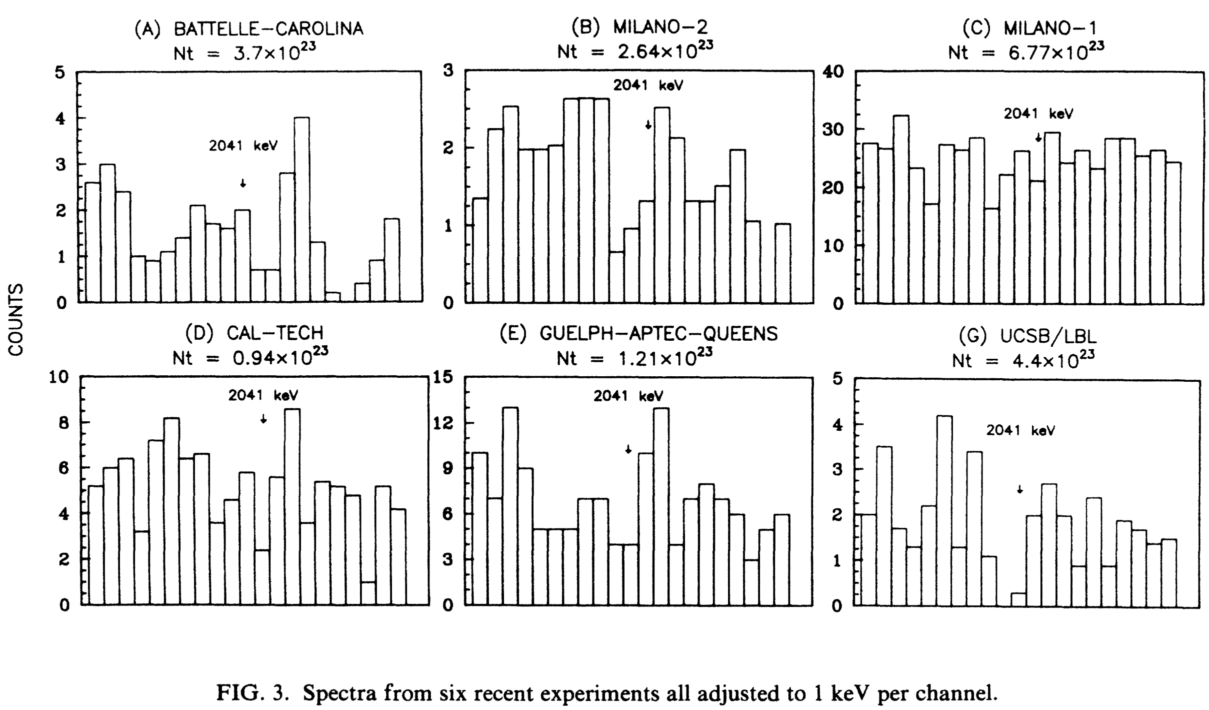

FIG. 3. Spectra from six recent experiments all adjusted to 1 keV per channel.

too high to draw any conclusions concerning a possibility of 0ν $\beta\beta$ decay at an energy 4 keV above the measured value of the decay energy given by Ellis *et al.*[29]

A world limit was obtained by summing the three spectra of lowest background. These were the present spectrum and those from the new Milano detector,[23] and the UCSB-LBL experiment underground.[27] This combined spectrum was subjected to a maximum likelihood analysis with the result $T_{1/2}^{0\nu}(^{76}\text{Ge}) > 3.4 \times 10^{23}$ yr. Considering the limits obtained from the individual spectra, one might have expected a number between 2×10^{23} and 3×10^{23} yr. Maximum likelihood analyses, however, are statistical estimators, and this one assumes that the background is flat as a function of energy. The sum spectrum has a dip at 2041 keV, resulting in a negative value for the most likely number of counts in the $\beta\beta$-decay peak. This results in a slightly longer half-life limit. Ignoring the depression, and off-setting the center of the likelihood function to zero, we find $T_{1/2}^{0\nu} \gtrsim 2\times10^{23}$ yr. This is probably too conservative, but in the interest of not overstating the result, we shall adopt the limit $T_{1/2}^{0\nu} \gtrsim 3\times10^{23}$ yr.

The background in our experiment has been reduced sufficiently to allow a meaningful analysis of the data in the region 1482 keV corresponding to 0ν $\beta\beta$ decay from the $0+$ ground state of ^{76}Ge to the first excited $2+$ state of ^{76}Se. This mode can only be driven by right handed couplings. The 21 channel partial spectrum is shown in Fig. 4 below. The mean count in the 1482 keV region is 1.91 keV^{-1}. An analysis similar to that above results in the limit $T_{1/2}^{0\nu}(0+\rightarrow2+) \geq 8\times10^{22}$ yr. This is significantly better than that reported in Ref. 26 and again demonstrates the importance of background reduction. A Monte Carlo code was used to determine the efficiency of complete escape of the 559.1 keV γ ray from the detector. The result is $\epsilon=0.49$. This value of ϵ demonstrates the importance of properly considering the large probability of some energy deposition by the escaping γ ray.

A complete interpretation of the data requires consideration of all possible combinations of the terms in Eq. (8). In our earlier paper,[7] the limit on each parameter was evaluated by substituting the best overall half-life limit from Table IV and by assuming that the other parameters are zero. This allowed us to include the work of Grotz and Klapdor[15] in the comparison of limits on the Majorana mass of the neutrino. These results are presented in Table V for $T_{1/2}^{0\nu}=10^{23}$ yr. A more complete analysis has been made, so that the effects of the three interferences between neutrino mass and the two right handed neutrino couplings were accounted for. It should be noted that the ratios of the limits on $\langle m_\nu \rangle$, extracted with and without these interferences, will not depend on the decay rates; hence, the results of the numerical calculations presented here are generally useful.

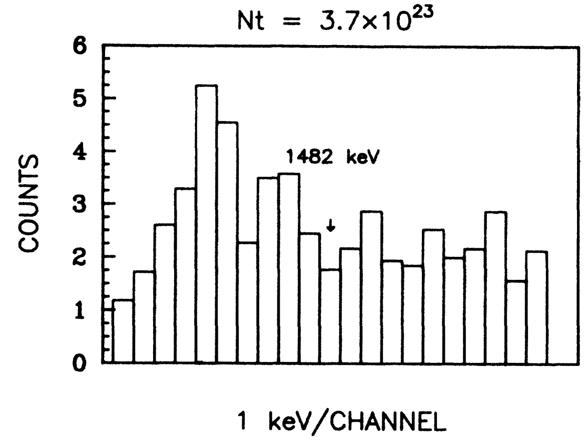

FIG. 4. Partial background spectrum in the energy region sensitive to 0ν $\beta\beta$ decay to the 559 keV level in ^{76}Se.

Accepting the nuclear structure calculations at face value, the limits on the parameters $\langle m_\nu \rangle$, x, y, and z were extracted and are displayed in Table VI also for $T_{1/2}^{0\nu}=10^{23}$ yr. The significant difference between the

TABLE IV. Summary of the results of maximum likelihood analysis of spectra in the region of 2041 keV from various ^{76}Ge $\beta\beta$-decay experiments. Combinations of experiments are given on the last line.

Experiment	$(BG/Nt)\times10^{23}$	Nt (10^{23} yr)	$T_{1/2}^{0\nu}$ limit (10^{23} yr)
(A) PNL-USC	0.40[a]	4.07	1.40
(B) Milano-2	0.68	2.64	0.74
(C) Milano-1	3.63	6.77	0.90
(D) Cal Tech	5.53	0.94	0.18[b]
(E) Guelph-Aptec-Queens	5.79	1.21	0.19[c]
(F) UCSB-LBL	1.68	1.94	0.40
(G) UCSB-LBL	0.42	4.40	1.20[d]
(H) Milano Total	2.80	9.41	1.25[e]
(A) + (B) + (G)	0.48	10.74	3.40

[a]Given in units of counts keV^{-1} per 10^{23} ^{76}Ge atoms per yr.
[b]The value 0.19×10^{23} yr was quoted in Ref. 24 based on more data.
[c]The value 0.32×10^{23} yr is reported in Ref. 25 based on more data.
[d]The value 1.2×10^{23} yr results from new data taken underground (Ref. 27).
[e]The value 1.2×10^{23} yr is reported in Ref. 23.

TABLE V. Limits on $\langle m_\nu \rangle$, y, and z with the simplifying assumption that only one mechanism at a time is operative. Values for $T_{1/2}^{0\nu}=10^{23}$ yr. Scale with square root of the ratio of half lives.

	Ref. 3	Ref. 18	Ref. 19	Ref. 20	Ref. 15
$\langle m_\nu \rangle$ (eV)	4.1	2.9	2.9	4.0	1.6
$\lvert y \rvert$	6.7×10^{-6}	4.6×10^{-6}	5.5×10^{-6}	8.2×10^{-6}	
$\lvert z \rvert$	9.9×10^{-6}	9.6×10^{-6}	6.7×10^{-8}	7.4×10^{-7}	

limiting value of $\langle m_\nu \rangle$ using the parameters given in Ref. 18 and those using the results of Refs. 3 and 20 were of great concern; however, the most recent calculations of Tomoda *et al.*[19] again yield values of $\langle m_\nu \rangle$ in excellent agreement with the other calculations.

In the consideration of the interference terms, several surprises were encountered. First, the values of the parameters extracted from Refs. 3 and 18 look very similar, except for the values of α_3, which differ by about a factor of 2. The conclusions concerning the Majorana ν mass are, however, very different, as can be seen by referring to Table VI. On the other hand, the values of α_3 and α_5 of Refs. 3 and 20 differ by factors of 175 and 18, respectively. While the limits on y and z differ as expected, the limits on x, and hence $\langle m_\nu \rangle$, do not. The reason for these curious facts was that $\alpha_3=0.344$ happens to be extremely near a critical value where the ellipsoidal surface $\omega=\omega(x,y,z)$ becomes an infinitely long elliptic cylinder consisting of a single sheet, and no limit on x can be extracted. This was accidentally discovered by rounding off α_3 to 0.34. For all of the other parameters and for all of the parameters extracted from Refs. 3 and 20, significant variations can be imposed and lead to no qualitative changes.

The major difference between the earlier Tübingen-Jülich[18] and Osaka[20] results was due to an accidental and almost complete cancellation of the p-wave effect by weak magnetism terms which reduces α_3 by more than 2 orders of magnitude. Further reduction by about 1% leads to a catastrophic critical phenomenon. This makes it difficult to pay serious attention to the significant differences in conclusions drawn using Refs. 18 and 20. It was crucially important to resolve this difficulty, and it is interesting to note that the interference between p-wave and weak magnetism corrections can be large without affecting the conclusions concerning limits on $\langle m_\nu \rangle$ significantly, until α_3 approaches this critical value. For values of α_3 which are orders of magnitude larger,[19] the conclusions concerning $\langle m_\nu \rangle$ are not significantly changed. It is, in fact, comforting to note that the latest results from three completely different nuclear structure calculations[3,19,20] yield limits on $\langle m_\nu \rangle$ which are in good agreement, even when all interference terms are included.

POSSIBLE FURTHER BACKGROUND REDUCTION

The dramatic reduction in primordial radioactivity in our present detector[7] compared to that of our earlier detector[22] is given in Table VII below. Two steps are being pursued in an attempt to achieve further reduction. The copper liner was recently replaced by 448 yr old lead which had been carefully surface cleaned and cast into bricks. The preliminary data indicate that the background has been substantially reduced in the energy region of maximum probability for 2ν $\beta\beta$ decay. In addition, all of the γ ray lines below 1461 keV appear to have been eliminated or greatly reduced, although a quantitative statement must await more counting time.

We have discovered a broad peak at 5.2 MeV with its leading edge at 5.3 MeV followed by a significant continuum. A similar peak has been observed in the UCSB-LBL detector[31] at 5.1 MeV and has been attributed to a Doppler broadened line produced by the reaction ^{28}Si(n,nγ)^{28}Si. We have been successful in reproducing our line at 5.2 MeV in a simple laboratory experiment. When soft solder is melted, the ^{210}Po, from the sequential decays of ^{210}Pb and ^{210}Bi, concentrates on the surface of the bead. After melting and solidifying several beads of solder, α spectra from their surfaces observed with a surface barrier detector were also found to contain this peak. The same phenomenon was observed in the UCI (University of California, Irvine) time projection chamber, and the solder beads on the wires had to be covered with epoxy. Another prototype Ge detector, with a fiducial volume of 140 cm^3, is being prepared with no solder beads in direct line with the detector. It will be run in the

TABLE VI. Experimental limits on $\langle m_\nu \rangle$, x, y, and z with all interference terms included in Eq. (8). Values for $T_{1/2}^{0\nu}=10^{23}$ yr. For other values of $T_{1/2}^{0\nu}$, the ratios to those in Table V remain the same.

	Ref. 3	Ref. 18	Ref. 19	Ref. 20
$\langle m_\nu \rangle_{max}$ (eV)	4.9	18.9	3.4	4.2
x(max)	9.5×10^{-6}	3.7×10^{-5}	6.6×10^{-6}	8.3×10^{-6}
y(min)	-9.3×10^{-6}	-9.7×10^{-6}	-5.6×10^{-6}	-8.2×10^{-6}
y(max)	1.1×10^{-5}	3.1×10^{-5}	5.6×10^{-6}	8.4×10^{-6}
z(min)	-1.4×10^{-5}	-2.0×10^{-5}	-6.8×10^{-8}	-7.4×10^{-7}
z(max)	1.6×10^{-5}	8.8×10^{-5}	7.7×10^{-8}	8.1×10^{-7}

TABLE VII. Comparison of primordial radioactivity levels in the background of the Ge spectrometer before and after rebuilding with radiopurity selected materials.

Primordial radionuclide	Gamma ray energy (keV)	Count rate before rebuilding (counts/h)	Count rate after rebuilding (counts/h)	Improvement factor
^{235}U	185.72	73.0	<0.0029	$>25\,000$
$^{228}Ac(^{232}Th)$	911.07	9.0	<0.0012	>7500
$^{234}Pa^{m}(^{238}U)$	1001.03	3.4	$<0.000\,80$	>4300
^{40}K	1460.75	22.0	0.014	1600
$^{208}Tl(^{228}Th)$	2614.47	1.0	$<0.000\,68$	>1500

Homestake gold mine alongside the present detector. The completion and installation of our first 770 cm^3 detector will be delayed until our background reduction reaches the point that no significant further reduction is feasible. Our program of continued background reduction is motivated mainly by the theoretical nuclear structure uncertainties and the fact that a measurement of 2ν $\beta\beta$ decay of ^{76}Ge is necessary to support the search for 0ν $\beta\beta$ decay.

Important insight into the impact of various sources of background on 0ν $\beta\beta$-decay experiments can be gained by comparing the backgrounds in the present experiment with those of the UCSB-LBL experiment. We particularly refer to their data acquired underground and given in a recent report.[27] This experiment had the same background, in counts keV^{-1} per 10^{23} ^{76}Ge atoms, as our data, as can be seen by referring to Table IV. The UCSB-LBL spectrum, as well as other published spectra, show definite γ ray lines at 185.72, 911.07, 1001.03, 1460.75, and 2614.47 keV and other lines associated with the decays of ^{235}U, ^{228}Ac, $^{234}Pa^{m}$, ^{40}K, and ^{208}Tl. The only one of these lines in our spectrum is that of the 1460.75 keV γ ray from the decay of ^{40}K, as shown in Table VII and Fig. 5. The count rates under the peaks of the UCSB-LBL spectrum[27] have been estimated and compared to the rates in our experiment, renormalized to an equivalent Ge volume. These results are presented in Table VIII. The rate of the 2614 keV γ ray peak is more than 39 times higher in the UCSB-LBL spectrum than the renormalized limit on the corresponding rate in our experiment. The continuum background rates at 2041 keV are the same for both experiments; hence, one must conclude that the dominant source of background in this energy region is not from ^{208}Tl. In our spectrum there are no peaks between 1460 keV and the degraded, broad α peak at ~ 5.2 MeV. This peak, and its associated continuum, must be the dominant source of counts in the 2041 keV region of interest, and its elimination has priority in our program at present. A similar peak also appears high in the UCSB-LBL spectrum as discussed above.

The primordial background in the other detectors might well be due to the presence of aluminum in some cases or of aluminized Mylar, which commonly is used as a multilayer infrared reflector. Although the elimination of this material introduces complications in maintaining low liquid nitrogen consumptions, it is a source of background, as indicated in Table II. The installation of our large multidetector unit will be delayed until elimination of the broad peak at 5.2 MeV has been verified with our new prototype mentioned above. This should reduce the background in the 2041 keV region by about 2 orders of magnitude. The lack of the 2614 keV γ ray in our detector should leave nothing in the 2041 keV region except the discovery of new sources of background, at much lower levels, heretofore unobservable. Therefore 2 orders of magnitude reduction, over that quoted in Table IV, should be a realistic expectation for our next experimental phase soon to begin. This approach does not appear to be an option for background reduction with the other detectors, which still show evidence of the 2614 keV peak.

OTHER LABORATORY $\beta\beta$-DECAY EXPERIMENTS

While this paper is dominated by the discussion of important theoretical as well as experimental aspects of ^{76}Ge

TABLE VIII. Comparison of primordial radioactivity levels in the backgrounds of the PNL-USC and UCSB-LBL detectors. The PNL-USC rates are scaled by the fiducial volume ratio 5.26.

Primordial radionuclide	Gamma ray energy (keV)	Count rate UCSB-LBL (counts/min)	Count rate PNL-USC (counts/min) ($\times 5.26$)	Ratio
^{235}U	185.72	0.36	<0.015	>23
$^{228}Ac(^{232}Th)$	911.07	0.14	<0.0063	>23
$^{234}Pa^{m}(^{238}U)$	1001.03	0.07	<0.0042	>16
^{40}K	1460.75	3.36	0.074	45
$^{208}Tl(^{228}Th)$	2614.47	0.14	<0.0036	>39

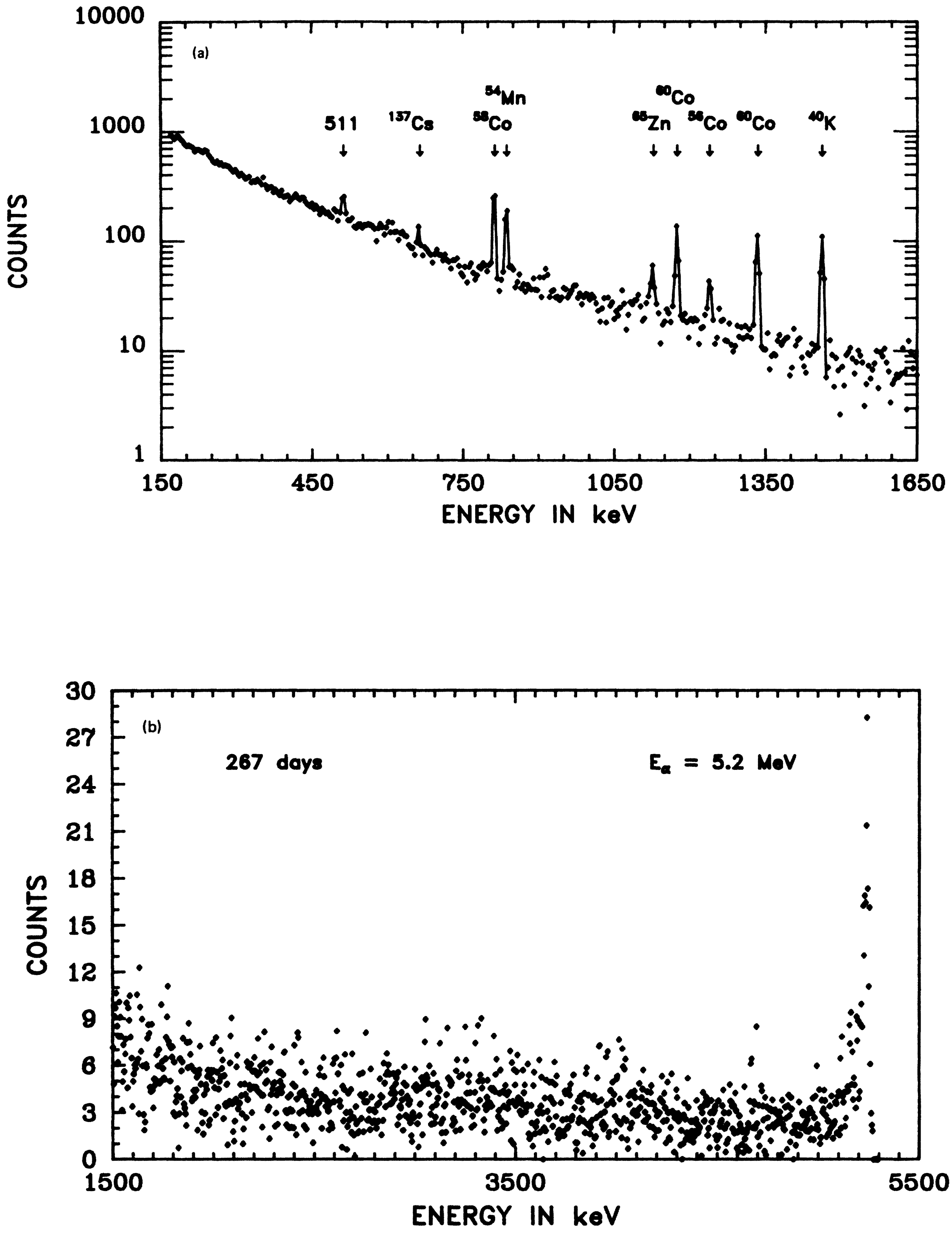

FIG. 5. Background in the 135 cm^3 prototype Ge detector after 267 d of counting. Clearly visible are the α peak, its continuum, and γ ray peaks from ^{40}K and from cosmogenically produced isotopes.

$\beta\beta$ decay, there are important competitive experiments investigating other $\beta\beta$ decays. The one which is most likely to first convincingly observe $\beta\beta$ decay in the laboratory is the UCI time projection chamber of Moe and co-workers.[2] The experiment is designed to observe the 2ν and 0ν $\beta\beta$ decay of ^{82}Se in an 80 cm diam chamber with 14 g of 97% enriched ^{82}Se sandwiched between thin sheets of aluminized Mylar. Their current half-life limit, $T_{1/2}(\text{total}) \geq 10^{20}$ yr, is based on 32 ± 7 candidate events. This experiment is close to a direct observation of $\beta\beta$ decay of ^{82}Se if the geochronological results are correct.

Another promising experiment, although in an earlier stage of development, involves the high resolution search for $\beta\beta$ decay of ^{130}Te and ^{100}Mo. The effort is underway at LBL with collaboration from Mt. Holyoke College and the University of New Mexico. Earlier attempts and other plans were mentioned by Fiorini at FWOGU.[32] The Berkeley effort involves stacks of 7.62 cm diam Si(Li) detectors with 7 μm thick foils of ^{100}Mo between them. A stack of five Si(Li) detectors has been tested in a radiopure cryostat shielded with 5.1 cm of Hg and 10 cm of Pb inside of a five sided scintillator for cosmic ray veto. Initial results are encouraging, and this experiment has an excellent chance of providing another direct measurement of $\beta\beta$ decay.

DISCUSSION AND CONCLUSIONS

Strong justification for extending the technology of 0ν $\beta\beta$-decay searches is made in Refs. 3–5. Why question exact lepton number conservation at all? The absence of a massless gauge field or second photon, with significant coupling to the fermions, suggests that there is no corresponding local gauge invariance and that L is therefore not exactly conserved. It is possible that the boson mass, associated with the broken symmetry, is too heavy to have been experimentally observed. A broken global gauge invariance would result in a massless Goldstone boson[3] (the Majoron) appearing with a continuous energy spectrum. One mechanism for producing $\Delta L = 2$ $\beta\beta$ decay is with a Majorana ν mass. This mass determines the energy of the pole of the ν propagator and characterizes the $\Delta L = 2$ transition amplitude. The question arises whether or not the Majorana masses are likely to be large enough to produce observable 0ν $\beta\beta$ decay. Predictions of conventional gauge theories are parameter dependent; however, there exist reasonable scenarios in grand unification which would result in observable 0ν $\beta\beta$ decay of ^{76}Ge, for example.

In his study of SO(10), Whitten[33] discovered that the right-handed Majorana ν automatically acquires mass by virtue of two-loop diagrams. If this is the only mechanism, then the left-handed ν appears with a mass on the order of 1 eV. Let us accept this estimate within a factor of 10. Whether the experimental results presented here have tested this result on the 1 or 10 eV level depends critically on the nuclear structure questions raised above. Accepting the results of Refs. 3, 19, or 20, the experiments discussed earlier in this article have probed the 1 eV level and can be projected to probe the 0.1 eV regime. In the case of large cancellations between the p-wave effect and weak magnetism,[18] the decay of ^{76}Ge has only probed the 10 eV level and perhaps will only ultimately attain the 1 eV level. The resolution of these disagreements between the theoretical predictions of Refs. 3, 19, and 20 was critically important and hopefully has now been achieved.

Finally, it is interesting to consider the impact of exciting new breakthroughs in superstring theories. In particular, there is real promise that Majorana masses might someday be predicted with no free parameters. Whatever the prediction, it will be crucially important to continue to improve experimental searches for ν mass, ν oscillations, and 0ν $\beta\beta$ decay. In the case of ^{76}Ge $\beta\beta$ decay experiments, background can be reduced further, detector volume can still be increased, while, finally, isotope enrichment of ^{76}Ge may be feasible with new technology.

Recently, the Cal Tech group has presented significantly improved data[34] with a figure of merit $(BG/Nt) \times 10^{23} = 0.50$. This is to be compared to their earlier published value of 5.53 given in Table IV. In addition, the Guelph effort has also achieved this level. This is to be compared to the value of 5.79 given in Table IV.[35] Also the UCSB-LBL group has very recently published new results with a similar specific background and corresponding to $T_{1/2}^{0\nu} \gtrsim 2.5 \times 10^{23}$ yr.[36]

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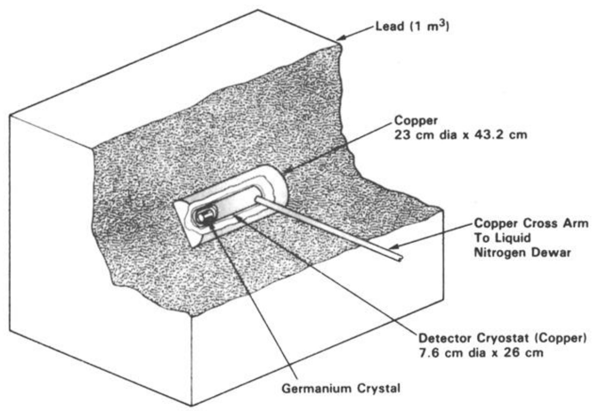

FIG. 1. Ultra-low-background, 135 cm^3 prototype Ge detector with copper inner shield.