Ultralow-Background Study of Neutrinoless Double β Decay of ^{76}Ge: New Limit on the Majorana Mass of ν_e

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(Received 4 March 1985)

A lower limit of 1.16×10^{23} yr (1σ) is reported for the half-life of no-neutrino $\beta^-\beta^-$ decay of ^{76}Ge which results from 3763 h of counting with an ultralow-background, 135-cm^3 prototype detector located 1438 m underground. A limit of 1.7×10^{23} yr (1σ) results from the best combination of our data with that from other experiments. Straightforward application of shell-model matrix elements to this limit implies that $\langle m_\nu\rangle < 3.2$ eV (1σ).

PACS numbers: 23.40.Bw, 14.60.Gh, 27.50.+e

Neutrinoless $\beta^-\beta^-$ decay is interesting because the process can be driven by Majorana neutrino mass as well as by explicit chiral-symmetry-breaking terms in the neutrino current. A number of grand unified theories (GUTs) predict neutrinos with nonzero Majorana mass while others, left-right–symmetric theories, for example, predict finite contributions to the right-handed neutrino current. Comprehensive reviews were written by Primakoff and Rosen[1] and by Haxton and Stephenson.[2] Recent papers by Bellotti *et al.*,[3] Forster *et al.*,[4] Simon *et al.*,[5] Ejiri *et al.*,[6] and Caldwell *et al.*[7] report the results of other searches for this exotic process. A new limit of $T_{1/2} > 4.1\times10^{19}$ yr has been placed on the total $\beta^-\beta^-$ decay of ^{82}Se by Moe and his co-workers[8] which might influence future interpretation of ^{76}Ge data with shell-model matrix elements.[9] This paper reports the lowest-background data to date and the combination of it with data from other experiments to obtain an optimum "world limit" on $\langle m_\nu\rangle$.

The first phase of our program was to obtain "bench mark" data with a standard low-background facility.[10] The second was to identify the sources of radioactivity, to evaluate and select radio-pure construction materials, and to fabricate and test an ultralow-background prototype Ge spectrometer.[11] The data presented here are results of this second phase. One of two 720-cm^3 mosaic Ge detectors has been constructed to specifications determined in previous phases of the program and is presently being tested. The final phase will consist of counting for several years with the 1440-cm^3 mosaic assembly in the Homestake gold mine. If other groups eventually achieve comparably low levels of background, the data can be combined to provide greater sensitivity. The details of our background reduction are given elsewhere[11]; however, typical results are presented in Table I. The impact of this reduction on the (2040.71 ± 0.52)-keV region of interest[12] is given in the second column of Table II along with the background rates (B) from other experiments. The assumption that the background is approximately proportional to the detector volume is reasonable when the volumes are within a factor of 2. The gross background spectrum is shown in Fig. 1. The low-energy continuum has been positively identified as the bremsstrahlung spectrum from the decay of ^{210}Bi and will be eliminated by use of 400-yr-old lead shielding near the detector, perhaps enabling us to observe ordinary, two-neutrino $\beta^-\beta^-$ decay.

The data were analyzed with a maximum-likelihood technique rather than the Monte Carlo method[13] used in our earlier work.[10] The likelihood function was cal-

TABLE I. 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 (c/h)	Count rate after rebuilding (c/h)	Improvement factor
^{235}U	185.72	73.0	<0.0048	>15 000
^{228}Ac(^{232}Th)	911.07	9.0	<0.0013	>7100
^{234m}Pa(^{238}U)	1001.03	3.4	<0.000 97	>3500
^{40}K	1460.75	22.0	0.014	1600
^{208}Tl(^{228}Th)	2614.47	1.0	<0.000 68	>1500

TABLE II. 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 four lines.

Experiment	$10^{23}\frac{B}{Nt}$	Nt (10^{23} yr)	$T_{1/2}^{0\nu}$ limit (10^{23} yr)
Ref. 10 (A)	0.30[a]	1.88	1.16
Detector 2 of Ref. 3 (B)	0.68	2.64	0.74
Detector 1 of Ref. 3 (C)	3.63	6.77	0.90
Ref. 4 (D)	5.53	0.94	0.18[b]
Ref. 5 (E)	5.79	1.21	0.19[c]
Both spectra of Ref. 3 (F)	2.80	9.41	1.25[d]
Ref. 7 (G)	6.32	1.94	0.40[e]
A+B+D+E	2.27	6.67	0.96
A+B+D	1.45	5.46	1.10
A+B+C+D+E	2.96	13.44	1.64
A+F	2.23	11.29	1.73

[a]Given in units of counts keV^{-1} per 10^{23} ^{76}Ge atoms per year.
[b]The value 0.19×10^{23} yr was quoted in Ref. 4, based on more data.
[c]The value 0.32×10^{23} yr is reported in Ref. 5, based on more data.
[d]The value 1.2×10^{23} yr is reported in Ref. 3.
[e]The value 0.5×10^{23} yr is reported in Ref. 7. These small differences can result from differing methods of obtaining the means and of selecting the limits of the variance integral.

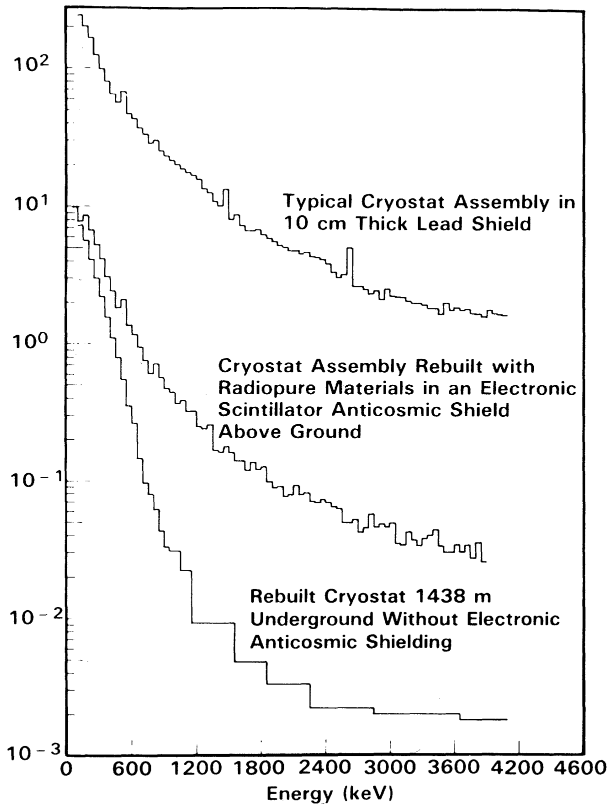

FIG. 1. Background spectra for the 135-cm^3 prototype Ge spectrometer in three different cryostat and shielding configurations.

culated on the assumption of 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 datum point was calculated by use of Poisson statistics. The likelihood function $L(\lambda)$ is the product of these probabilities and was maximized by variation of λ. The confidence level was calculated by numerical integration of $L(\lambda)$.

The published spectra[3-5] 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 the adding of 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 were computed by weighting each Gaussian by its corresponding Nt. The results of these analyses appear in the last column of Table II. Our analyses of the data of Refs. 3 and 4 yield essentially the same results given in those references, which implies that the data-compression procedure does not change the result significantly. The experiment of Ejiri *et al.*[6] is a search for the decay to the first excited 2^+ state in ^{76}Se and is a coincidence experiment of significantly higher background than the other recent experiments. That of Caldwell *et al.*[7] was also analyzed; however, because of its high background level it did not contribute to an improvement in the world limit.

The number given, in counts/keV·yr·(10^{23} ^{76}Ge atoms), in the second column of Table II provides a figure of merit of the radiopurity of each experiment. Note that the experiment of Avignone *et al.* described in Ref. 10 yields a limit of 1.16×10^{23} yr (1σ) while the detector-2 experiment of Bellotti *et al.* described in Ref. 3 yields 0.74×10^{23} yr (1σ) even though the product Nt is larger in the experiment of Bellotti *et al.* The best overall limit is obtained by adding the spectra of Ref. 10 and that of both detectors 1 and 2 of Ref. 3. All other combinations lead to less sensitive results, clearly demonstrating that low background is the key to ultimate sensitivity.

The shell-model results of Haxton, Stephenson, and Strottman,[9] in their latest version,[2] lead to the following simple relation between the composite Majorana mass $\langle m_\nu\rangle$ and half life:

$$\lambda=(3.42\times10^{-21}\ \mathrm{sec}^{-1})\{\xi^2-0.38\eta\xi+0.65\eta^2\} \quad (1)$$

where $\xi\equiv\langle m_\nu\rangle/m_e$ and η is the weighting of the right-handed term in the neutrino current. The result of Avignone *et al.*, quoted in Table II, implies $\langle m_\nu\rangle<3.6$ eV (1σ) while the best limit, obtained by combining the spectra from Ref. 10 and Ref. 3, is $\langle m_\nu \rangle < 3.2$ eV (1σ). The combined spectra imply a value of $\eta < 7\times 10^{-6}$ for the relative amplitude of the right-handed neutrino current.

When the recent experimental result of Caldwell *et al.*,[7] $T_{1/2}(^{82}\mathrm{Se}) > 4.1\times 10^{19}$ yr, is compared to the shell-model prediction,[2] 2.62×10^{19} yr, one might be tempted to scale the theoretical matrix elements accordingly. There is no compelling justification for assuming that this disagreement is the same in ^{76}Ge. The intermediate nucleus ^{76}As has 33 protons and 43 neutrons, and its detailed structure might differ significantly from the intermediate nucleus ^{82}Br in the ^{82}Se decay which has 35 protons and 47 neutrons. A firm determination of values for or limits on $\langle m_\nu \rangle$ and η must await measurements of the two-neutrino $\beta^-\beta^-$ decay of ^{76}Ge.

Figure 2 shows that all of the spectra appear to have several channels with high numbers just above the arrows corresponding to 2041 keV. Most are not statistically significant; however, the low background of the data of Ref. 10 allows a more precise analysis. There are eight counts in the four-channel bin 2043–2046 keV. A straightforward binomial analysis yields a probability of <0.01 for having the eighteen events which appear in the 20-keV interval beginning at 2031 keV distributed as they are if the events are in fact due to a random, flat, background. This analysis was extended to 100 channels and yielded an even smaller probability (0.006) that this is a statistical peak. In addition, we have checked our calibration and find it to be accurate to within 0.5 keV. We conclude, then, that a peak exists at 2044.72 keV with a level of confidence $>99\%$. The most probable number of counts in this four-channel interval due to a random flat background is 2. The mean number of counts per kiloelectronvolt over the 100-keV interval centered at 2041 keV attributable to random background is 0.570 ± 0.076. Accordingly, then, 5.7 ± 2.8 of these counts are in a peak which occurs 4.01 keV above the energy of the ^{76}Ge-^{76}Se mass difference measured by Ellis *et al.*[12] with the Manitoba-II spectrometer. If we assume for the moment that the 5.7 ± 2.8 counts at 2044.72 keV are in fact due to neutrinoless $\beta^-\beta^-$ decay, the half life would be 1.5×10^{22} yr $< T_{1/2}^{0\nu} < 4.5\times 10^{22}$ yr (1σ). The corresponding limits on the neutrino mass are 6 eV $< \langle m_\nu \rangle <$ 11 eV (68% C.L.). There is no reason to conclude that systematic errors exist in the Manitoba-II experiment; however, considering the importance of the consequences, the possibility should not be disregarded.

Recent calculations of Tomoda, Faessler, Schmid, and Grümmer, sent to us prior to publication, account for relativistic corrections to the nuclear current including weak magnetism. The present "world limit" of 1.7×10^{23} yr, analyzed with the calculations of Tomoda *et al.*, implies $\langle m_\nu \rangle < 2.1$ eV and a limit on the right-handed neutrino current almost three orders of

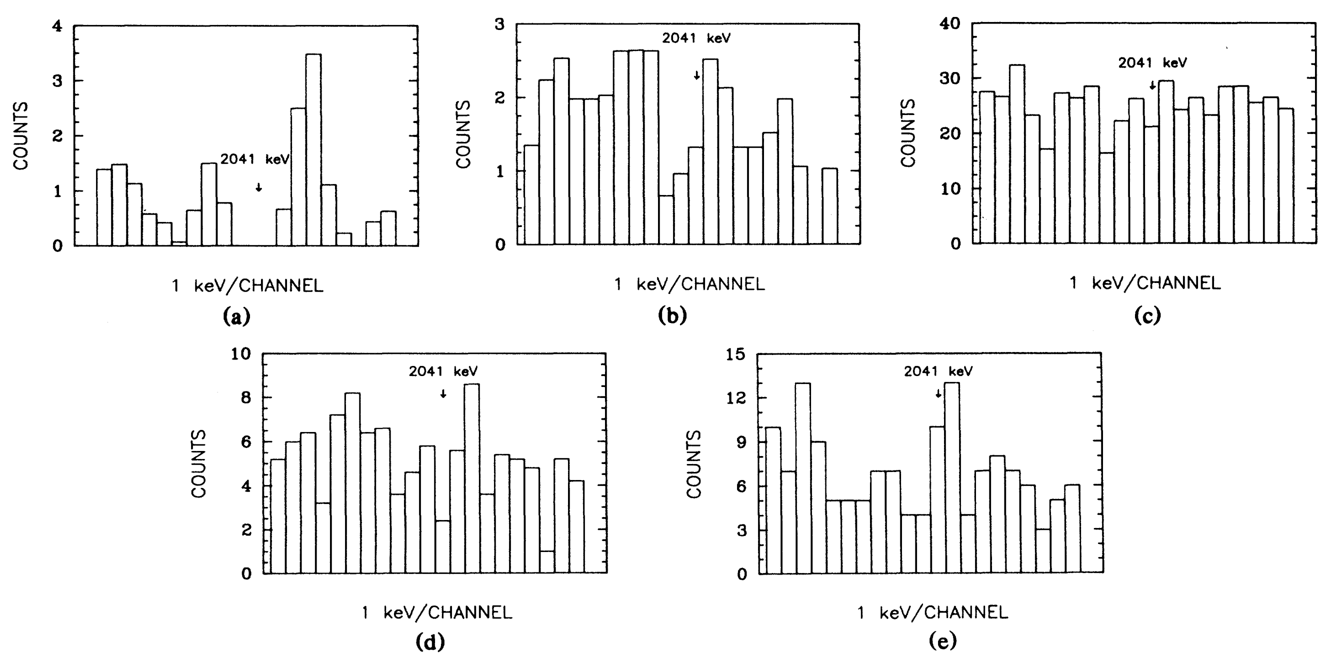

FIG. 2. Spectra from the four recent experimental searches for the neutrinoless $\beta^-\beta^-$-decay of ^{76}Ge. All spectra are gain shifted to 1 keV per channel. (a) Present work, $Nt = 1.88\times 10^{23}$ yr; (b) Ref. 3, detector 2, $Nt = 2.64\times 10^{23}$ yr; (c) Ref. 3, detector 1, $Nt = 6.77\times 10^{23}$ yr; (d) Ref. 4, $Nt = 0.94\times 10^{23}$ yr; (e) Ref. 5, $Nt = 1.21\times 10^{23}$ yr.

magnitude more stringent than that deduced with use of the results of Haxton and Stephenson.[2]

Finally, recent extensive calculations by Doi, Kotani, and Takasugi[14] include the p-wave effect of the relativistic electron wave functions and give results somewhat different from those of Haxton and Stephenson,[2] but the differences are smaller than and in the opposite direction from those of Tomoda *et al.* An analysis of our data using these results will be given in a future article.

The authors are grateful to R. Davis, A. Gilles, C. K. Lee, K. Lande, M. Cherry, and R. Thompson for their valuable assistance in the Homestake experiments. We thank Professor Faessler, Professor Tomoda, and Professor Kotani for sending their results prior to publication and Professor W. C. Haxton and Professor S. P. Rosen for their constant theoretical support and advice. This work was supported by the U. S. Department of Energy under Contract No. DE-AC06-76RLO 1830 and the National Science Foundation under Grant No. PHY-8405654.

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