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Final report on the search for neutrinoless double-β decay of ^{76}Ge from the Gotthard underground experiment

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We report here on the final results of a search for ^{76}Ge double-β decay conducted in the Gotthard underground laboratory. The detector consists of an array of eight high-purity natural germanium crystals totaling 1095 cm^3 fiducial volume. The accumulated data set represents a sensitivity of 10.0 kg yr. No indication of neutrinoless double-β decay was found. The measured half-life limits are $T_{1/2}(0^+\rightarrow 0^+) > 6.0(3.3)\times 10^{23}$ yr for the transition to the ground state and $T_{1/2}(0^+\rightarrow 2^+) > 1.4(0.65)\times 10^{23}$ yr for the transition to the first excited state at 68% (90%) C.L. From these results we derive an upper limit for the Majorana mass of the neutrino in the range of 1.8 to 6.7 eV depending on matrix-element calculations. The same results allow limits to be set for the right-handed-current parameters: $\langle\lambda\rangle < 3.6\times 10^{-6}$ and $\langle\eta\rangle < 2.2\times 10^{-8}$.

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The study of neutrinoless double-β decay ($0\nu\beta\beta$) provides a test of the fundamental properties of the neutrino, its mass, and its behavior under charge conjugation. This decay, requiring a nonvanishing Majorana mass for the neutrino and lepton-number violation, has been studied for many years in various candidate nuclei [1]. We report here the final results of our search for $0\nu\beta\beta$ in ^{76}Ge conducted in the Gotthard underground laboratory.

The laboratory is located at a depth of 3000 meters of water equivalent (m.w.e.). The experimental setup and some earlier results have been described in Refs. [2,3]. The detector, shown schematically in Fig. 1, is an array of eight high-purity natural germanium crystals (with 7.76% ^{76}Ge abundance). The p-type crystals[1] are of coaxial geometry, 56–58 mm in diameter and 60–64 mm in length. The electrical contact to the ground consists of a thin gold layer (p^+-type contact) evaporated at the surface of a center cavity. This cavity is a cylinder coaxial to the detector, about 9 mm in diameter by 38 mm in depth. Collected there, the signal is brought to the first cold preamplifier stage, located immediately outside the copper cup containing the crystal. A lithium-diffused zone is created at the outer surface of the crystal to serve as the positive electrical contact (n^+-type semiconductor). A bias voltage of between 2 and 3 kV is applied to the detectors. The eight detectors, totaling 1095 cm^3

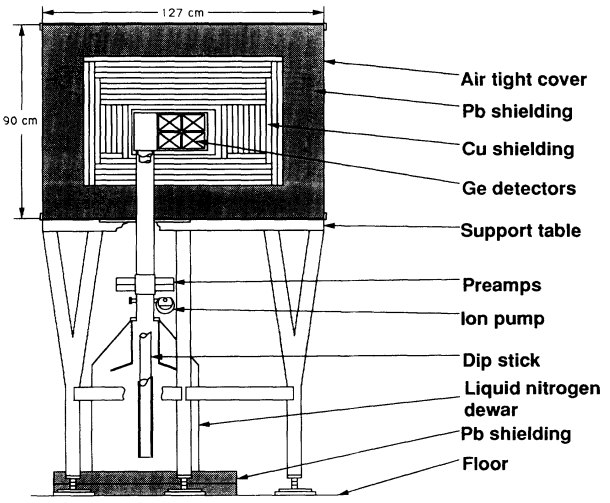

FIG. 1. Schematic view of the experimental setup showing the eight-crystal detector and its shielding.

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[1]The crystals were processed and mounted into the cryostat by Detector Systems GmbH (DSG), Mainz-Hechtsheim, Germany.

fiducial volume (5.83 kg ^{nat}Ge), are housed in a single cryostat made from high purity copper. All the components located inside the cryostat [field-effect transistor (FET), solder, wires, resistors, capacitors] or used for the cryostat itself were tested for radioactive contamination with an actively and passively shielded, low background, 90 cm^3 germanium detector. The sensitivity achieved was roughly 10^{-8}g of ^{232}Th or ^{238}U content per gram of sample. The detector is surrounded by 15 cm of copper and 18 cm of lead to protect against radioactive backgrounds in the tunnel. The shielding itself is contained in an airtight aluminum box constantly flushed with nitrogen to prevent infiltration by radioactive ^{220}Rn and ^{222}Rn.

To extract limits on the half-lives from the raw data, it is necessary to know the actual energy resolution in the sum spectrum at the transition energies. The energy resolution is mainly due to three components: (i) electronic noise [independent of energy and accounting for about 1.0 keV full width at half maximum (FWHM)], (ii) statistical fluctuations of the free charges in the detectors (proportional to the square root of energy, about 1.7 keV FWHM at 1.3 MeV) and (iii) small gain instabilities of the amplification chain, responsible for a further peak broadening in long duration measurements. Over short periods the individual energy resolutions vary from 1.9 to 2.2 keV (FWHM) at 1332.5 keV for all crystals. We kept the gains of all crystals closely matched.

Avoiding a degradation of the energy resolution due to gain shifts represented a major concern. This was done by monitoring the 661.7 and 1460.5 keV background lines of ^{137}Cs and ^{40}K. When necessary, we shifted the individual spectra, based on the position of these lines prior to adding them, once a week, to the current sum spectrum. As a further check on gain stability, a precision pulser was used to deliver, every six hours, ten counts to the input capacitor of each preamplifier. For the determination of the absolute energy calibration, a ^{60}Co source was also introduced into the shielding but at much longer time intervals (the shielding had to be opened, allowing radon to enter the detector).

The $0\nu\beta\beta$ decay energies are 2038.6±0.3 keV [4] for the $0^+ \rightarrow 0^+$ transition, and 1479.5±0.3 keV for the $0^+ \rightarrow 2^+$ transition. To determine the energy resolution at these energies, we have fitted 11 γ lines lying in the sum spectrum between 238.6 and 2614.5 keV with Gaussians superimposed on a linear background. We then fitted a parabola to the energy resolution squared as a function of energy. Interpolation based on this fit gave the energy resolution (FWHM) to be 3.10 keV around 2038 keV and 2.38 keV around 1479 keV.

The data set analyzed here corresponds to a live time of 15 058 h, equivalent to 10.0 kg yr. The final sum spectrum is shown in Fig. 2. We have identified four main background sources. (i) Natural γ activities: from ^{238}U and ^{232}Th decay chains and ^{40}K decay. The typical isotopes are ^{214}Bi, ^{226}Ra, ^{214}Pb descending from ^{238}U and ^{228}Ac, ^{208}Tl, ^{212}Pb from ^{232}Th decay. (ii) Artificial γ activities: several long-lived fission products are contaminating our detector in particular as a result of the Chernobyl nuclear reactor accident. The most relevant ones are ^{134}Cs and ^{137}Cs with respective half-lives of 2.06 and 30.2 yr. (iii) Cosmogenic activation by fast neutrons: this activation occurred when the detector was above ground and not protected against cosmic neutrons. This leads to nuclear reactions in copper (present in the shielding and in the cryostat) yielding a series of γ emitting isotopes comprising ^{56}Co, ^{57}Co, ^{58}Co, ^{60}Co, and ^{54}Mn [2]. Similar reactions in the germanium of the detector itself give rise to ^{65}Zn and especially ^{68}Ge, produced by ^{70}Ge $(n,3n)$ ^{68}Ge ($T_{1/2}$=288 d). This latter isotope is the most disturbing in an ultralow-background experiment as it, in turn, decays by electron capture into ^{68}Ga, a β^+ emitter

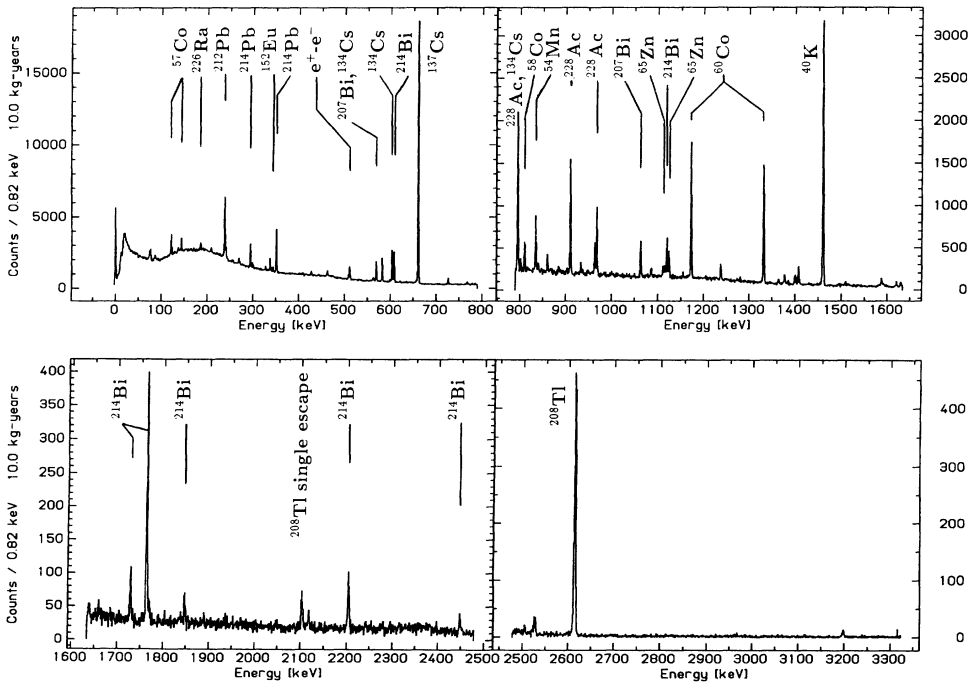

FIG. 2. Raw energy spectra from the Gotthard eight-crystal germanium detector corresponding to 15 058 h of operation (equivalent to 10.0 kg yr).

($T_{1/2}=68.3$ min) with an end point at 1.9 MeV. Furthermore, the background due to ^{68}Ga actually extends up to 2.92 MeV as one or both of the two 0.511-MeV annihilation γ's can interact in the detector. From the peak at 10.4 keV due to the x rays following electron capture in ^{68}Ge, we can estimate the total number of ^{68}Ge decays that occurred during the experiment active life. For this purpose we made use of data collected for dark-matter search, which had an energy threshold much below the x rays [5]. We have fitted the 10.4-keV peak using the same procedure as the one used for determining the $0\nu\beta\beta$ rate [2]. We took into account the time dependence and then integrated over the data-taking time, ending up with a value of $32\,000\pm3000$ ^{68}Ge decays for 10.0 kg yr. (iv) Miscellaneous: finally, there are two more unstable isotopes, most likely from the solder used for electric connections: ^{125}Sb and ^{110m}Ag. The photopeak activities for relevant isotopes are listed in Table I. The background level at 2 MeV has dropped, as ^{68}Ge was decaying, from 3.7 to 1.6 counts keV^{-1} kg^{-1} yr^{-1} between the beginning and the end of the data taking; the overall mean background being 2.37 counts keV^{-1} kg^{-1} yr^{-1}. Considering the entire run, 40% of the background is due to ^{68}Ge and 60% is caused by the Compton scattering of the 2614.5-keV γ's from ^{208}Tl decay.

The spectra around 2038.6 and 1479.5 keV, presented in Figs. 3 and 4, are flat. We fitted these regions with a constant, using an expression for χ^2 valid for low statistics [2,6], and obtained χ^2 of 83.6 for 97 degrees of freedom (DF) and 94.5 for 79 DF, respectively. The reduced χ^2 do not improve significantly when peaks are fitted at the transition energies. The raw peak contents given by the best fit are -11.9 ± 11.7 counts for the $0^+\rightarrow0^+$ transition and -2.4 ± 15.5 counts for the $0^+\rightarrow2^+$ transition. Thus we can conclude we found no evidence of $0\nu\beta\beta$ decay. Restricting then the χ^2 distribution to positive

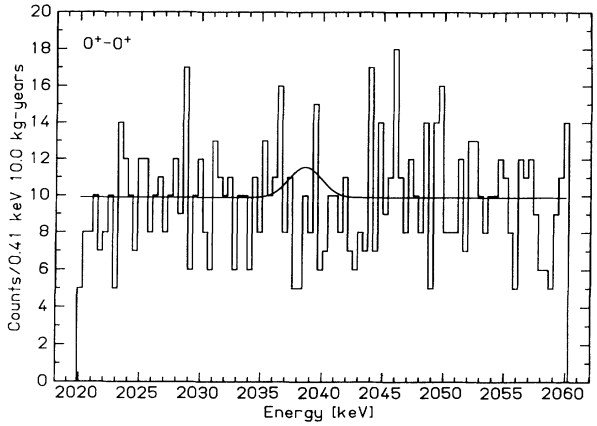

FIG. 3. Raw energy spectrum in the $0^+\rightarrow0^+$ transition energy region. The curve shows the 90% C.L. upper limit of $T_{1/2}(0^+\rightarrow0^+)=3.3\times10^{23}$ yr.

TABLE I. Photopeak activities in the background spectrum for the main contaminant isotopes. The asterisk indicates that a γ (or two) and an x ray are seen simultaneously, the contaminant being inside the crystal.

Origin	Isotope	$T_{1/2}$	γ-ray energy (keV)	Branching ratio	Photopeak content (counts/kg yr)
^{238}U	^{226}Ra	1600 yr	186.2	0.055	144±25
decay chain	^{214}Pb	26.8 min	352.0	0.37	733±20
	^{214}Bi	19.7 min	2204.2	0.05	42±4
			609.3	0.46	493±14
^{232}Th	^{228}Ac	6.13 h	911.1	0.29	363±11
decay chain	^{212}Pb	10.6 h	238.6	0.44	1079±27
	^{208}Tl	3.05 min	2614.5	1.0	252±6
			583.	0.86	390±14
Cosmogenic	^{65}Zn	244.1 d	1124.5*	0.51	97±7
activation	^{60}Co	5.27 yr	1332.5	1.0	426±10
			1173.2	1.0	449±11
	^{58}Co	70.8 d	810.8	0.99	95±9
	^{57}Co	271.7 d	144.2*	0.11	199±23
			122.1	0.86	343±24
	^{56}Co	78.8 d	846.8	1.0	9.9±6.8
	^{54}Mn	312.2 d	834.8	1.0	196±10
Fission	^{137}Cs	30.2 yr	661.7	0.85	4563±27
products	^{134}Cs	2.06 yr	604.6	0.97	597±15
	^{152}Eu	13.2 yr	344.3	0.245	131±16
			1112.	0.12	51±7
Other	^{40}K	1.28×10^9 yr	1460.75	0.11	926±13
	^{207}Bi	38.3 yr	1063.4	0.74	127±8
	^{110m}Ag	252.2 d	937.5	0.33	11±7
			884.7	0.75	20±7
	^{125}Sb	2.7 yr	635.9	0.115	24±8
	e^+-e^-		511.0		308±16

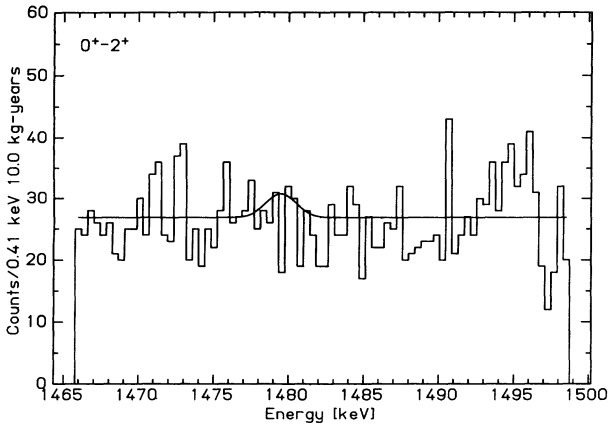

FIG. 4. Raw energy spectrum in the $0^+ \rightarrow 2^+$ transition energy region. The curve shows the 90% C.L. upper limit of $T_{1/2}(0^+ \rightarrow 2^+) = 0.65 \times 10^{23}$ yr.

peaks, and renormalizing it accordingly, we derive the following limits for the peak contents: 7.4 (13.4) counts for $0^+ \rightarrow 0^+$ transition and 10.9 (24.1) for the $0^+ \rightarrow 2^+$ transition at 68% (90)% C.L. These values translate into the following half-life limits: $T_{1/2}(0^+ \rightarrow 0^+) > 6.0(3.3) \times 10^{23}$ yr and, taking into account a γ escape probability of 35%, $T_{1/2}(0^+ \rightarrow 2^+) > 1.4(0.65) \times 10^{23}$ yr at 68% (90%) C.L.

Up until very recently, the accepted transition energies were 2040.7±0.5 $(0^+ \rightarrow 0^+)$ and 1481.6±0.5 keV $(0^+ \rightarrow 2^+)$ [7]. Using these values, our analysis gives $T_{1/2}(0^+ \rightarrow 0^+) > 6.6(3.7) \times 10^{23}$ yr. This limit does not depend strongly on the assumed transition energy. Further, we find $T_{1/2}(0^+ \rightarrow 2^+) > 2.0(1.1) \times 10^{23}$ yr. For comparison, using the old transition energy, the UCSB-LBL Collaboration obtained with 21 kg yr sensitivity $T_{1/2}(0^+ \rightarrow 0^+) > 2.2(1.2) \times 10^{24}$ yr [8], while Vasenko *et al.* obtained, with an enriched ^{76}Ge detector, $T_{1/2}(0^+ \rightarrow 0^+) > 1.3 \times 10^{24}$ yr at 68% C.L. [9]. Our limit for $0^+ \rightarrow 2^+$ transition improves on the previous best limit of $T_{1/2}(0^+ \rightarrow 2^+) > 6 \times 10^{22}$ yr at 68% C.L. by Busto *et al.* [10].

The half-life limits can be expressed in terms of an effective Majorana mass for the neutrino. Using our limit at 68% C.L. and the matrix element of [11], we obtain $\langle m_\nu \rangle < 4-6.7$ eV. Here we have taken the value $\alpha_1' = -375 \pm 15$ MeV fm^3 which allows us to reproduce well the observed $2\nu\beta\beta$ half-lives in ^{82}Se [12], ^{76}Ge [9,13,14], ^{100}Mo, and ^{130}Te [1]. Taking the matrix element of [15] we are led to $\langle m_\nu \rangle < 2.0$ eV, whereas making use of [16] our conclusion is $\langle m_\nu \rangle < 1.9-2.3$ eV. Still with Ref. [16], the limits for the right-handed current parameters are $\langle \lambda \rangle < 3.6 \times 10^{-6}$ and $\langle \eta \rangle < 2.2 \times 10^{-8}$.

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[1] M. Moe, in *Neutrino 90,* Proceedings of the 14th International Conference on Neutrino Physics and Astrophysics, Geneva, Switzerland, 1990, edited by J. Panam and K. Winter [Nucl. Phys. B (Proc. Suppl.) **19**, 158 (1991)]; for an overview of the subject, see F. Boehm and P. Vogel, *Physics of Massive Neutrinos* (Cambridge University Press, Cambridge, England, 1987).
[2] P. Fisher *et al.*, Phys. Lett. B **218**, 257 (1989).
[3] P. Fisher, Ph.D. thesis, Caltech, 1988 (unpublished).
[4] J. G. Hykawy *et al.*, Phys. Rev. Lett. **67**, 1708 (1991).
[5] D. Reusser *et al.*, Phys. Lett. B **255**, 143 (1991).
[6] S. Baker and R. D. Cousins, Nucl. Instrum. Methods **221**, 437 (1984).
[7] R. J. Ellis *et al.*, Phys. Lett. **136B**, 146 (1984).
[8] D. O. Caldwell *et al.*, in *Proceedings of the 14th European Physical Society Conference on Nuclear Physics,* Bratislava, Czechoslovakia, 1990, edited by P. Povinec [J. Phys. G Suppl. **17**, 137 (1991)]; D. O. Caldwell *et al.*, Phys. Rev. Lett. **59**, 419 (1987).
[9] A. A. Vasenko *et al.*, Mod. Phys. Lett. A **5**, 1299 (1990).
[10] J. Busto *et al.*, Nucl. Phys. **A513**, 291 (1990).
[11] J. Engel, P. Vogel, and M. E. Zirnbauer, Phys. Rev. C **37**, 731 (1988).
[12] S. R. Elliot, A. A. Hahn, and M. K. Moe, Phys. Rev. Lett. **59**, 2020 (1987).
[13] H. S. Miley *et al.*, Phys. Rev. Lett. **65**, 3092 (1990).
[14] F. T. Avignone *et al.*, Phys. Lett. B **256**, 559 (1991).
[15] W. C. Haxton and G. J. Stevenson, Jr., Prog. Part. Nucl. Phys. **12**, 409 (1984).
[16] K. Muto, E. Bender, and H. V. Klapdor, Z. Phys. A **334**, 187 (1989).

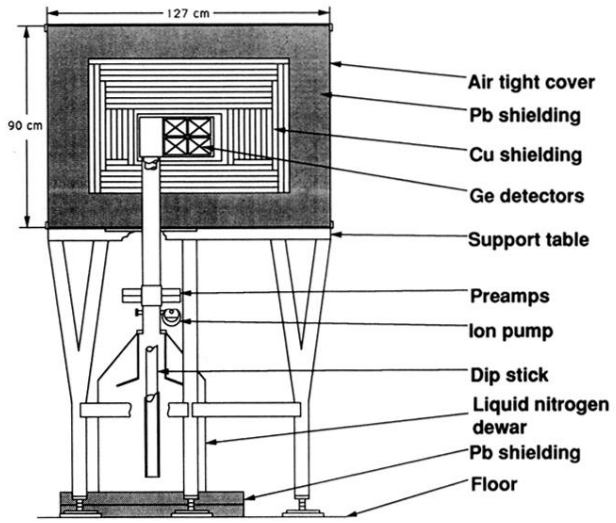

FIG. 1. Schematic view of the experimental setup showing the eight-crystal detector and its shielding.