A Search for Double Beta Decay and Cold Dark Matter with the Gotthard Germanium Detector

Recherche de la désintégration bêta double et de la matière noire froide avec le détecteur au germanium au laboratoire du Gothard

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BRIEF REPORTS

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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

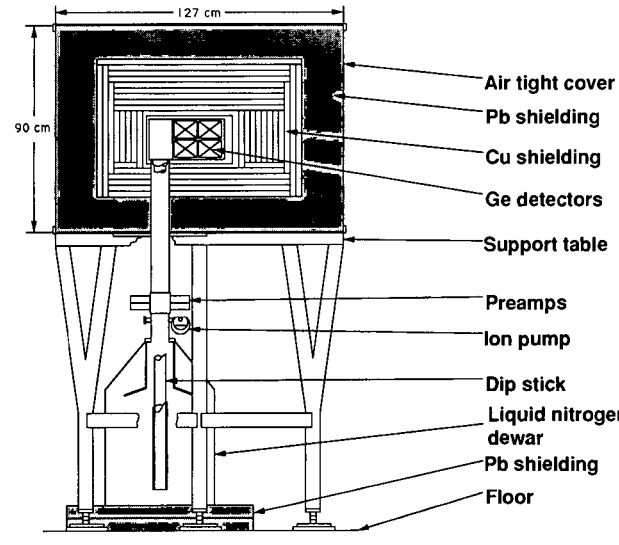

FIG. 1. Schematic view of the experimental setup showing the eight-crystal detector and its shielding.

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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

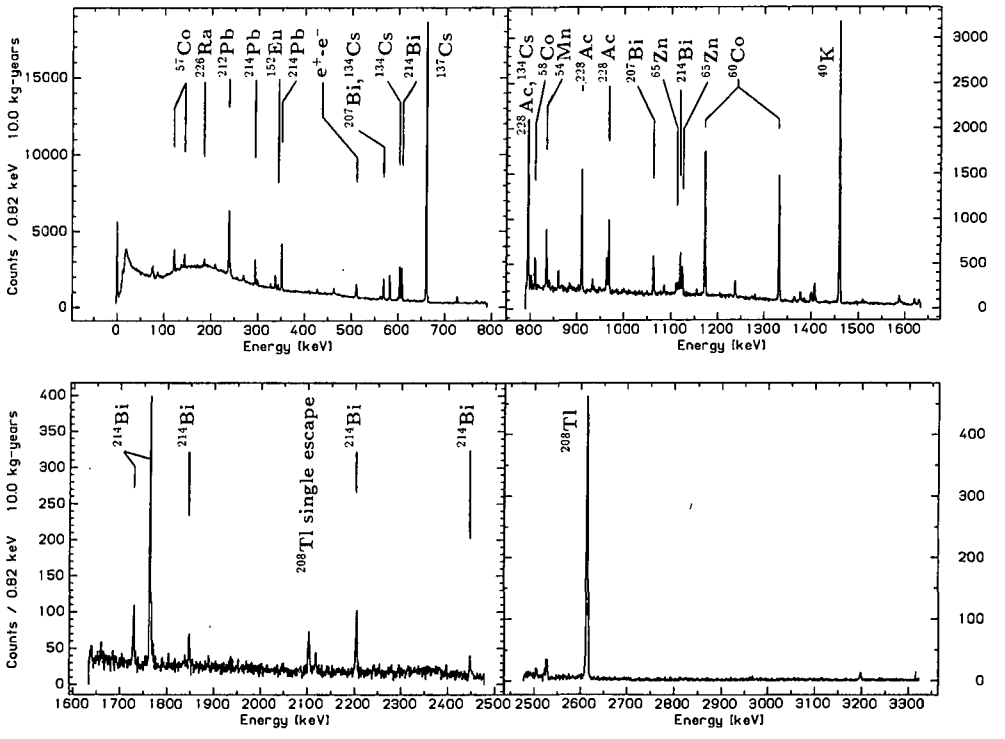

FIG. 2. Raw energy spectra from the Gotthard eight-crystal germanium detector corresponding to 15 058 h of operation (equivalent to 10.0 kg yr).

($T_{1/2}=68.3$ 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±3000 ^{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

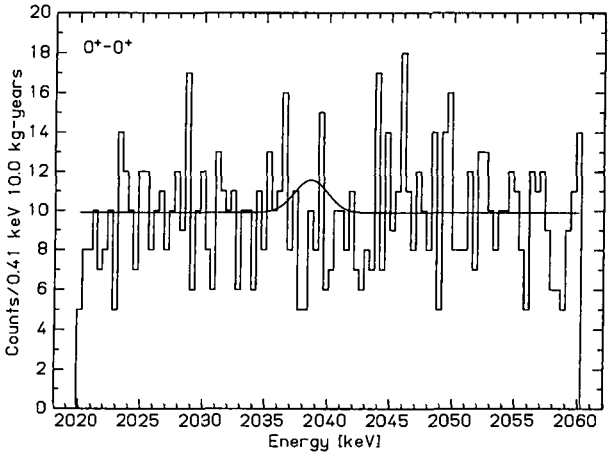

FIG. 3. Raw energy spectrum in the $0^+\rightarrow0^+$ transition energy region. The curve shows the 90% C.L. upper limit of $T_{1/2}(0^+\rightarrow0^+)=3.3\times10^{23}$ yr.

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

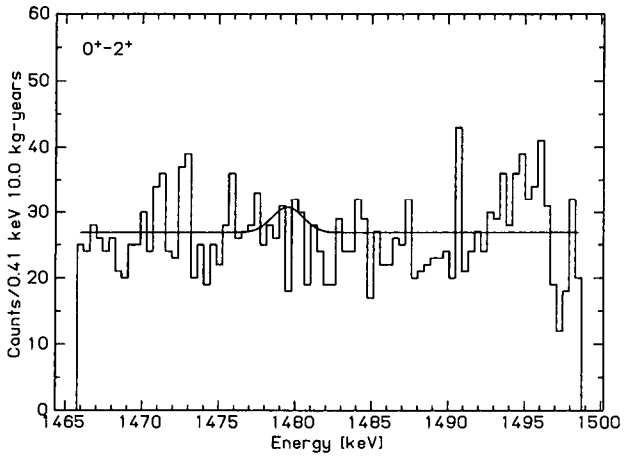

FIG. 4. Raw energy spectrum in the $0^+ \rightarrow 2^+$ transition energy region. The curve shows the 90% C.L. upper limit of $T_{1/2}(0^+ \rightarrow 2^+) = 0.65 \times 10^{23}$ yr.

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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Limits on cold dark matter from the Gotthard Ge experiment

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Data from a high purity Ge detector operated in the Gotthard underground laboratory, corresponding to 51.6 kg day, were used to set limits on cold dark matter. In particular, Dirac neutrinos with masses between 10 and 2400 GeV are ruled out. A new lower limit on the half-life for the decay of the electron into weakly interacting particles of 1.9×10^{23} yr at 68% CL was also derived.

There are several indications, for instance from the dynamics of stars and gas in galaxies, that the universe contains a large amount of dark matter, about 3–10 times more than luminous matter [1]. The theory of galaxy formation favors cold dark matter (CDM), made from heavy, say more than a few GeV, non-relativistic weakly interacting particles. Such particles would be gravitationally bound in galaxies and would form a non-co-rotating halo in which stars would orbit. CDM particles can, with a small probability, hit a nucleus of normal matter and transfer recoil energy to it. As the energies are low, the differential cross-section is generally expected to be isotropic. Although small, say a few keV, the recoil can be measured if the nucleus belongs to the active part of a detector, making direct detection of dark matter possible. Ge detectors, with their relatively large masses and low energy threshold, are ideally suited for CDM searches. The background levels achieved in several experiments give a sensitivity to some viable dark matter candidates, in particular Dirac neutrinos with standard weak coupling, in a given mass range [2,3]. Dirac neutrinos have vector coupling, in which case the nucleus reacts coherently, giving rise to large cross-sections.

We have been operating a 1140 cm^3 high purity Ge detector for three and a half years in the Gotthard underground laboratory to search for double beta decay [4]. More recently we modified the experimental set-up to simultaneously perform a CDM search. The detector consists of an array comprising eight ^{nat}Ge crystals, of which four have a volume of 140 cm^3 and four a volume of 145 cm^3. The eight crystals are housed in a single cryostat made from copper to reduce the natural radioactivity. The cryostat is surrounded by 15–25 cm of copper and 18–20 cm of low activity lead to shield against local radiations. In addition, both detector and shielding are contained in a cover which is continuously flushed with nitrogen to expel radon gas. No veto counter against cosmic rays is necessary as the muon flux is suppressed by a factor of roughly 10^6 due to the 3000 m.w.e. rock overburden. A separate electronic circuit is used in three of the crystals for the low energy events relevant here. The preamplifiers of the crystals are connected to spectroscopy amplifiers, the unipolar outputs of which are going into individual ADC channels, whereas the bipolar outputs are fed into low threshold discriminators to strobe the ADC. Data are read out whenever one of the crystals fires and written, along with the absolute time, event by event on disk.

We have tried various ways of lowering the thresh-

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old of our detector array and of reducing the background in the keV region, where one may expect recoil events. It turns out that although the response of our eight crystals is identical above 10 keV, they behave quite differently below that energy. We thus chose the best crystal for CDM search. Its background is to a large extent due to microphonics resulting from the release of thermal stresses in the cryostat superstructure as the liquid nitrogen in the dewar boils off. Fortunately, these microphonics are not distributed evenly in time, but come in bursts which are particularly frequent after the dewar has been refilled. Between bursts the average count rate above 1.4 keV is 3.5 per minute in all three crystals. We thus first perform a time plot of the count rate, and cut all two-minute periods in which it is above a threshold of 6 counts per minute. Doing so reduces extensively the microphonics at a cost of 25% live time. Since the Poisson distribution allows the random occurrence of counts per bin above our threshold with 5% probability we lower the live time by that amount. Then we reconstruct the spectrum of each crystal using the two other ones in anticoincidence, with a threshold around 2 keV. This further contributes to the reduction of microphonics, without increasing the dead time. The spectrum left after these cuts for our best crystal, the only one we use in the following, is shown in fig. 1. It corresponds to 1662 h of live time (51.6 kg day).

The energy calibration is somewhat delicate since the background lines are too weak to be used. Therefore we had to perform the calibration in two steps. First we determined the offset with a precision pulser connected to the crystal through an attenuator. The offset position is given by extrapolation to infinite attenuation. Second we determined the slope using the lines from a radioactive ^{60}Co source and the ^{137}Cs background line. In order to obtain an accurate calibration we developed an automatic procedure based on peak fitting. The stability was checked systematically by a weekly calibration with the pulser. In all, the energy for a given channel can be determined to within 0.05 keV below 15 keV.

Looking at the spectrum in fig. 1 one can notice that above 1.8 keV the electronic noise is negligible and that the background looks reasonably low and smooth. Our raw spectrum constitutes a significant improvement over those of ref. [2] and even of ref.

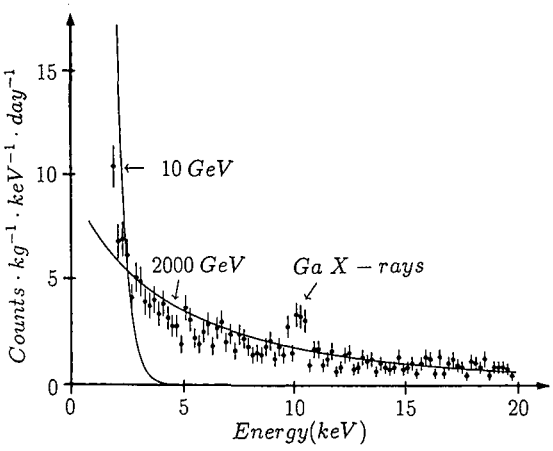

Fig. 1. The low energy spectrum of our best crystal, from 1662 h of data (live time, 51.6 kg day). The peak at 10.37 keV is due to Ga X-ray emission after electron capture in ^{68}Ge. Also shown are the expected recoil spectra for Dirac neutrinos of mass 10 and 2000 GeV.

[3], where the corresponding noise level is at 3 keV. The peak at 10.37 keV is due to the Ga X-rays emitted after electron capture in ^{68}Ge [^{68}Ge, which has a half-life of 288 days, was cosmogenically produced in the crystals in the ^{70}Ge(n, 3n)^{68}Ge reaction before the detector was taken underground]. The X-ray line provides a cross-check of our energy calibration. Its intensity in our spectrum is roughly a factor 2 respectively 5 less than in those of ref. [2] and ref. [3].

We then compare our spectrum to expectations. We assume, as described in ref. [1], that the dark matter has a local density of 0.3 GeV cm^{-3}, a Maxwell velocity distribution with $\langle v^2 \rangle^{1/2} = 261$ km s^{-1} truncated at the escape velocity $v_e = 640$ km s^{-1}, and that the relative earth to halo velocity is 230 km s^{-1} (we measured between June and September). Then for a given mass m of a CDM particle we calculate the expected recoil spectrum, assuming an isotropic differential cross-section. Realistically our experiment is only sensitive to dark matter candidates with vector coupling, for which the cross-section is large because the nucleus reacts coherently. Coherence is not total, however, and we correct for this by introducing a form factor in the differential cross-section [2]. We also take into account that a Ge recoil nucleus ionizes only about 30% as much as an electron of equivalent energy (see ref [5] for a review on this subject). The exact ratio in function of recoil energy was taken from

the Lindhard theory [6], with the parameterization of Robinson [7]. The calculated spectrum is then folded with the response function, the energy resolution being 800 eV FWHM at low energy. The comparison with the calculated spectra of ref. [3] is difficult since no information is given there about the applied correction for the loss of coherence.

The calculated spectrum is then confronted with the measured one, shifted up by 0.06 keV to take into account the uncertainty on the energy calibration. This way the true energy is less than the one we assume with 90% probability. Maintaining the mass m constant we vary the total cross-section σ until 3 consecutive data points out of the 66 between 1.8 and 15 keV are more than 1.2 standard deviation below the calculated spectrum. We interpret this cross-section value as 90% upper limit on the cross-section for the given mass. The area in the σ versus m plane that we can rule out this way is shown in fig. 2 Also shown is the predicted cross-section as a function of mass for heavy Dirac neutrinos (ν_D) with standard coupling. One sees that ν_D with masses between 10 and 2400 GeV are ruled out. Majorana fermions with axial coupling are expected to have much smaller cross-sections and our experiment has essentially no sensitivity to them.

Our analysis does not use any background subtraction. The disadvantage is that it can only produce limits, but not show the existence of dark matter. The advantage is simplicity and complete model independence, therefore we consider our limits to be reliable. They are somewhat more restrictive than those of ref. [3], limits on σ for a given m being better by a factor 2–4. They are, however, not quite good enough to rule out Dirac neutrinos of any mass with effective coupling $\sin^2\phi_z$ as explained in ref. [8]. Using the limits of ref. [3] referred to in ref. [8] leads to a much less stringent exclusion curve than that actually shown in fig. 1 of ref. [8]. In the future we hope to gain in sensitivity by taking advantage of the yearly modulation of the earth–halo relative velocity.

The low energy part of the spectrum can also be used to look for the decay of the electron into weakly interacting particles. One channel could be $\bar{e} \rightarrow \bar{\nu}_e \nu_e \nu_e$ [9]. The decay of a K-shell electron would leave a hole, giving rise to an X-ray cascade resulting in a peak at 11.10 keV, the binding energy of a 1s electron in Ge. With our resolution this peak could be distinguished from the Ga peak. For this analysis we use the sum spectrum of all three crystals. From a fit with two gaussian peaks and a parabolic background we derive a lower limit on the half-life of the electron of $1.9(1.2) \times 10^{23}$ yr at the 68(90)% confidence level, almost an order of magnitude better than the previous one [10].

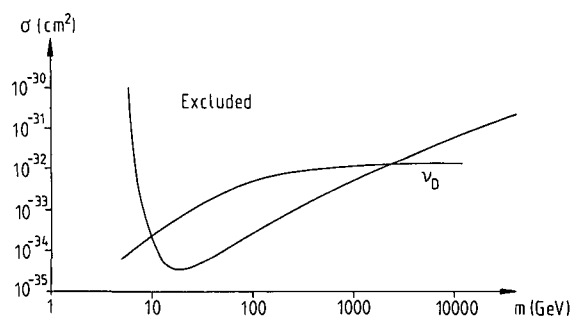

Fig. 2. Exclusion plot for CDM from our experiment. CDM candidates with given mass m and interaction cross section σ above the curve are excluded. In particular Dirac neutrinos ν_D with standard coupling between 10 and 2400 GeV are ruled out.

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Liste des articles publiés pour la thèse:

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

  Auteurs: D. Reusser, M. Treichel, F. Boehm, P. Fisher, K. Gabathuler, H.E. Henrikson, V. Jörgens, L. W. Mitchell, C. Nussbaum, and J.-L. Vuilleumier.

  Paru dans: Physical Review **D45** (1992) p. 2548.

- Titre: "Limits on cold dark matter from the Gotthard Ge experiment"

  Auteurs: D. Reusser, M. Treichel, F. Boehm, C. Broggini, P. Fisher, L. Fluri, K. Gabathuler, H. Henrikson, V. Jörgens, L. W. Mitchell, C. Nussbaum, and J.-L. Vuilleumier.

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