Fifty years of searching for neutrinoless double beta decay with Ge detectors

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It is well known the importance of neutrinoless double beta decay in revealing the properties of neutrinos and new physics beyond the Standard Model. A wide experimental effort is placed worldwide in the search for $0\nu\beta\beta$-decay using a variety of methods and isotopes. Among the programs that aim to detect this decay the experiments operating semiconductor detectors made of germanium continue to play the key role. The use of a germanium diode acting both as source and detector was for the first time implemented by Ettore Fiorini and collaborators more than fifty years ago and their first results were published in 1967. A brief historical overview of the researches performed in this direction are presented. The achieved results, present status of the ongoing experiments as well as expected sensitivities of the next step proposals are reviewed.

Among the programs that aim to detect a neutrinoless double beta decay ($0\nu\beta\beta$) the experiments operating semiconductor detectors made of germanium play the key role due to the excellent energy resolution (~ 3 keV at 2 MeV), the high purity of Ge crystals (very low intrinsic background) and the high signal detection efficiency (close to 100 %). The improvement of the half-life limit in the following five decades by 6 orders of magnitude is due to a reduction of the background and an increase of exposure as well as the introduction of detectors made from material enriched in ^{76}Ge isotope. HPGe detectors fabricated from germanium enriched in ^{76}Ge (up to 87 %) are simultaneously the $\beta\beta$ decay sources and the 4π detectors.

Despite some disadvantages - not the highest $0\nu\beta\beta$–transition energy for ^{76}Ge ($Q_{\beta\beta} = 2039$ keV) amongst the other promising isotopes, such as Mo-100, Se-82, Nd-150, Ca-48 and only one characteristic of $0\nu\beta\beta$ decay (sum energy of two electrons) is possible to detect, one of such type currently running experiments (GERDA) is the first experiment that surpasses a sensitivity for the $0\nu\beta\beta$ half-life of $T_{1/2} \sim 10^{26}$ yr and the first one that operates quasi-background-free thus resulting in a strong discovery potential.

The use of Ge diodes as source and detectors of double beta decay has been suggested more than fifty years by the Milan group, which has also carried out the first experiments [1]. They used Ge(Li) detector of 17 cm^3 active volume in anticoincidence with the scintillation counter. At the background counting rate in region of interest (ROI) about 1.1×10^{-2} $h^{-1}\,keV^{-1}$ for 712 hours of running time they obtained half-life limit $T_{1/2}$ $(0\nu\beta\beta) > 3.1$ x 10^{20} yr (68 % C.L.) [1] - 1967.

Reducing radioactive contaminants in the materials of the detector and its surroundings has been one of the main activities of the experimentalists during all further years. One of the considerable contribution to the remaining backgrounds are activities induced by cosmic rays during the time the materials were above ground, that is why all next experiments being under overburdens from 600 to 5000 m.w.e. (meters of water equivalent).

Below very brief review of the most part of the experiments performed with Ge detectors in the underground facilities is given in a chronological order (the indicated years correspond to dates of publication of the final or current results).

1973 - The underground set up of the Milan group was placed in the Mont-Blanc tunnel (4200 m.w.e.) with Ge(Li) detector of 68.5 cm^3 active volume. At the background rate about 2 $\times\ 10^{-3}$ $h^{-1}\,keV^{-1}$ for 4500 hours of the total running time they achieve the limit $T_{1/2}(0\nu\beta\beta) > 5.0 \times 10^{21}$ yr (68 % C.L.) [2].

1985 – The Zaragoza-Bordeaux-Strasbourg set up was placed in Fréjus tunnel (4800 m.w.e.). Four Ge detectors of about 417 cm^3 total active volume inside 19 hexagonal NaI detectors that gave the possibility to search for $0\nu\beta\beta$–decay 0^+-2^+ to the first exited level of ^{76}Se. The background rate in ROI was 2.3 counts/(kg·keV·yr) and for the exposure 1.6 kg·yr they obtained $T_{1/2}(0\nu\beta\beta,\ 0^+\text{-}2^+) > 6 \times 10^{22}$ yr (68 % C.L.) [3].

1986 – At the same underground level in the Mont-Blanc tunnel the Milan group used two Ge(Li) detectors of 125 cm^3 and 148 cm^3 active volume. The background rate in ROI was achieved as 3.7×10^{-4} h^{-1} keV^{-1} and for (20698 + 15429) hours of running time the limit $T_{1/2}(0\nu\beta\beta) > 3.3 \times 10^{23}$ yr (68 % C.L.) was obtained [4].

1986 – The PNL-USC group placed their set up with Ge detector of 135 cm^3 volume in the Homestake gold mine (1438 m of rock). The background rate in ROI was 1.7 counts/(kg·keV·yr) and for 8089 hours the obtained the limit $T_{1/2}(0\nu\beta\beta) > 1.4 \times 10^{23}$ yr (68 % C.L.) [5].

1987 – ELEGANTS set up was situated at the Kamioka underground laboratory (2700 m.w. e.). HPGe detector of 171 cm^3 volume was surrounded by 4π NaI (Tl). The background rate in ROI was 5.5 counts/(kg·keV·yr) and for 8621 hours of running time $T_{1/2}(0\nu\beta\beta) > 7.3 \times 10^{22}$ yr (68 % C.L.) was obtained [6].

1990 – One of the most sensitive experiments using detectors from natural germanium material was performed by UCSB - LBL group. The setup consisted from 8 Ge detectors with fiducial volumes of about 160 cm^3 each operating inside NaI(Tl) shield and was located 600 m.w.e. deep in the Oroville dam, USA. The background rate in ROI was 1.2 counts/(kg·keV·yr) and for the exposure 21 kg·yr they achieved the limit $T_{1/2}(0\nu\beta\beta) > 1.2 \times 10^{24}$ yr (68 % C.L.) [7].

1990 – The first Ge experiment with enriched in ^{76}Ge detectors. The ITEP-Yerevan group used two 0.5 kg enriched Ge detectors (enriched in ^{76}Ge to 85 %) in a salt mine in Yerevan at a depth of 645 m.w.e. They observed for the first time two-neutrino decay of ^{76}Ge [8], confirmed by after by IGEX collaboration [9] and later by the Heidelberg-Moscow collaboration [10]. The array consisted of three Ge-detectors inside a NaI(Tl) active shield. The detector set with 2 enriched in ^{76}Ge crystals, 106 cm^3 and 109 cm^3, and one of natural germanium, 115 cm^3 was also used to obtain the limit $T_{1/2}(0\nu\beta\beta) > 1.3 \times 10^{24}$ yr (68 % C.L.) at the background rate in ROI of 2.6 counts/(kg·keV·yr) for the exposure 0.87 kg·yr (^{76}Ge) [8].

1992 – Set up of the Caltech-SIN-Neuchatel group in the Gotthard tunnel (3000 m.w.e.) 8 HPGe detectors (NatGe) totaling 1095 cm^3 fiducial volume. At the background rate of 2.4 counts/(kg·keV·yr) for 15058 hours (10 kg·yr) they obtained the limit $T_{1/2}(0\nu\beta\beta) > 6.0 \times 10^{23}$ yr (68 % C.L.) [11].

2001 – The Heidelberg-Moscow (HdM) experiment, which operates five enriched ^{76}Ge detectors (11 kg total mass) in a low-level facility at LNGS, Italy (3500 m.w.e.) achieved the lower limit on the half-life of the $0\nu\beta\beta$ decay obtained with pulse shape analysis (PSA) of $T_{1/2} > \times$ 1.9 10^{25} yr (90 % C.L.) for 35.5 kg yr[10].

2004-2006 - While the HdM collaboration used their data to set a limit on $T_{1/2}$, some members of the collaboration reinterpreted the data: with a total exposure of 72 kg·yr at background 0.06 counts/(kg·keV·yr) (after reinterpreted pulse shape analysis), an evidence of $0\nu\beta\beta$ decay has been claimed with an half-life of $T_{1/2}$=$(1.19^{+0.37}_{-0.23})\times10^{25}$ yr (68 % C.L.) at 4.2σ[12]. Two years later even more strong evidence within 6.2σ was claimed by two members of HdM as $T_{1/2}$=2.23×10^{25} yr[13].

2002 – No positive indication for such the evidence came from the IGEX experiment performed at the Canfranc tunnel, Spain (2500 m.w.e.) and Baksan Neutrino Observatory, Russia (660 m.w.e.). For the exposure of 8.9 kg·yr and background 0.2 counts/(kg·keV·yr) before PSA and 0.1 counts/(kg·keV·yr) after PSA, the obtained lower limit on the half-life was of $T_{1/2}$ $(0\nu\beta\beta)$ $> 1.6 \times 10^{25}$ yr (90 % C.L.)[9].

To scrutinize the existing claim or improve the limit on half-life the new generation Ge experiments (GERDA and Majorana) were proposed.

2013 (Phase I), **2018** (Phase II), ... – The GERDA collaboration searches for the $0\nu\beta\beta$ decay of ^{76}Ge by operating bare germanium detectors in an active liquid argon shield at LNGS (Laboratori Nazionali del Gran Sasso), Italy (3500 m.w.e.). With a total exposure of 82.4 kg·yr (841 mol·yr of ^{76}Ge) at background level $\sim 6 \times 10^{-4}$ counts/(kg·keV·yr), they observe no signal and derive a lower half-life limit of $T_{1/2}$ $(0\nu\beta\beta) > 0.9 \times 10^{26}$ yr (90 % C.L.) and the sensitivity assuming no signal is 1.1×10^{26} yr[14,15] leading to the boundaries on the effective mass $<m_{\beta\beta}>$ from 104 to 228 meV depending on uncertainties in nuclear matrix elements calculation. GERDA is the first experiment that surpasses a sensitivity for the $0\nu\beta\beta$ decay half-life of 10^{26} yr and that operates in a background-free regime such that the expected number of background events is less than 1 in the energy region of interest at the final exposure.

2018, ... – The Majorana Demonstrator (MJD)[16] is operating at SURF, USA (4800 m.w.e. depth). The MJD contains 35 PPC detectors (29.7 kg) enriched up to 88 % in ^{76}Ge. The detectors are mounted in two vacuum cryostats whithin a traditional graded passive shield. With the background rate of 4.7×10^{-3} counts/(kg·keV·yr) at exposure 26 kg·yr (enrGe) no $0\nu\beta\beta$ signal candidate is observed which implies a lower limit of $T_{1/2}$ $(0\nu\beta\beta) > 2.7\times10^{25}$ yr (90 % C.L.)[16].

The leading performance of GERDA in terms of background suppression, energy resolution and sensitivity opens the way to LEGEND, a next generation Ge experiment, to explore half-lifes of 10^{27} yr and beyond. A first phase 200 kg ^{76}Ge experiment, LEGEND-200[17], is currently under preparation at LNGS.

Main characteristics of the Ge experiments and the $T_{1/2}$ half-life limits are summarized in Table 1.

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Table 1: Main characteristics of the Ge experiments and the $T_{1/2}$ half-life limits; the background counting rate is given for energies around $Q_{\beta\beta}$ (2039 keV) [1967-2006: years of the final result publications; 2013-2018: years of the current result publications].

Year	Experiment	Depth (m.w.e.)	Enrichment (%)	Background counts/ keV·kg·yr	Exposure (kg ^{76}Ge)	$T_{1/2}$ years 68 % CL	Ref.
1967	Milan group	Day surface	7.8	$\sim 1\times10^{3}$	6×10^{-4}	$>3.1\times10^{20}$	1
1973	Milan group	4200 MB tunnel	7.8	48	3.5×10^{-2}	$>5\times10^{21}$	2
1985	ZBS	4800 Fréjus	7.8	2.3	0.12	$>6\times10^{22}$	3
1986	Milan group	4200 MB tunnel	7.8	22.5	0.85	$>3.3\times10^{23}$	4
1986	PNL-USC	3800 Homestake	7.8	1.7	1.24	$>1.4\times10^{23}$	5
1987	ELEGANTS	2700 Kamioka	7.8	5.5	1.68	$>7.3\times10^{22}$	6
1990	UCSB-LBL	600 Calif. dam	7.8	1.2	1.64	$>2.4\times10^{24}$	7
1990	ITEP Yerevan	645 Avan mine	84.6	2.2	0.87	$>1.3\times10^{24}$	8
1992	CIT-SIN Neuchâtel	3000 Gotthard	7.8	2.4	0.78	$>6.0\times10^{23}$	11
2001	Heidelberg Moscow	3500 LNGS	86	0.11 (0.06)	30.5	$>1.9\times10^{25}$ 90 % CL	10
2004	Part HdM (KKDC)	3500 LNGS	86	Reanalysis with PSD	61.7	1.2×10^{25} $(4.2\,\sigma)$	12
2006	Part HdM (KK)	3500 LNGS	86	Reanalysis with PSD	61.7	2.2×10^{25} $(6.2\,\sigma)$	13
2002	IGEX	2500 Canfranc 660 Baksan	86	0.2 (0.1) PSD	7.7	$>1.6\times10^{25}$ 90 % CL	9
2013	GERDA	3500 LNGS	87	0.01	20.5	$>2.1\times10^{25}$ 90 % CL	14
2018	Majorana demonstrator	4800 SURF	88	0.05	22.9	$>2.7\times10^{25}$ 90 % CL	16
2018	GERDA	3500 LNGS	87	0.006	71.7	$>0.9\times10^{26}$ 90 % CL	15