NEUTRINOLESS DOUBLE BETA DECAY OF ^{76}GE WITH GERDA

L. Niedermeier[1] for the GERDA collaboration

[1] *Universität Tübingen, Auf der Morgenstelle 14, D–72076 Tübingen*

Abstract: A new, ultra-low background germanium detector with innovative cryogenic liquid shielding design to investigate neutrinoless double beta decay is presented. With 37.5 kg of enriched germanium oxide, we aim for 100 kg·y of quasi background-free data taking leading to a sensitivity to half-lifetimes up to $T_{1/2}^{0\nu}=2\cdot10^{26}$ y corresponding to effective neutrino masses larger than m_{ee}=0.1–0.3 eV in case of massive Majorana neutrino exchange.

1. Neutrinoless Double Beta Decay

Double beta decay is a phenomenon appearing in even-even nuclei within isobars caused by the energy difference of levels in nuclei with even or odd proton or neutron numbers. In some cases, as for ^{76}Ge, this energetically prohibits single beta decay, thus leaving double beta decay $({}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}Y+2e^{-}+2\bar{\nu}_e)$ the only decay mode. 2β half lives are usually beyond 10^{18} y.

Under the conditions $\nu=\bar{\nu}$ (Majorana neutrino), and $m_\nu>0$ enabling helicity flip with a probability proportional to $1-(v_\nu/c)^2$, a neutrinoless double beta decay channel $({}^{A}_{Z}X \rightarrow {}^{A}_{Z+2}Y+2e^{-})$ exists.

The experimentally observable energy of the escaping electrons corresponds to a beta continuum in case of the 2β2ν channel, but to a Gaussian peak at the energy $E_0 = Q_{2\beta} - E_{nucl.recoil}$ for the neutrinoless channel 2β0ν. The 2β0ν channel can experimentally be proven by observation of this peak. Main difficulties arise from continuous external and internal

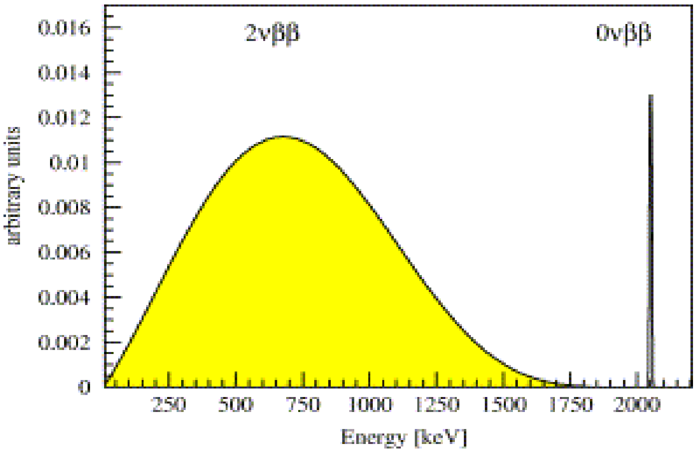

Fig. 1: Energy spectra of escaping electrons for 2β2ν and 2β0ν decay channels in ^{76}Ge.

backgrounds and from possible γ lines around E_0 in combination with the low rate due to ultra-long 2β0ν half lives expected in the range beyond 10^{21} y.

In case of an observable number S of 2β0ν events during the time t with a detector of N atoms of type ${}^{A}X$ and an efficiency ε, the half life $T_{1/2}{}^{0\nu}$ can be determined from

$$T_{1/2}^{0\nu} = \frac{Nt\varepsilon \ \ln 2}{S_{2\beta 0\nu}} \qquad (1)\,.$$

If no 2β0ν peak is observed, a limit corresponding to the square root of the number of background events B around the region of interest can be derived:

$$T_{1/2}^{0\nu} > \frac{Nt\varepsilon \ln 2}{\sqrt{B}} = \frac{amt\varepsilon\, N_A \ \ln 2}{M\sqrt{bmt\delta E}} = \frac{N_A \ \ln 2 \ a\varepsilon}{M}\sqrt{\frac{mt}{b\delta E}} \qquad (2)$$

with	b	Bgr. rate in $(\text{kg y keV})^{-1}$	a	${}^{A}X$ atomic abundance
	m	${}^{A}X$ mass	N_A	Avogadro constant
	M	${}^{A}X$ molecular mass	δE	Energy binning

For 2β0ν decay due to exchange of a massive Majorana neutrino, calculations [1] yield

$$T_{1/2}^{0\nu} = (G^{ov}(E_0,Z)\cdot\left|M^{0n}\right|^2\cdot m_{ee}{}^2)^{-1} \qquad (3)$$

with the effective neutrino mass $$m_{ee} = \left|\sum_{n=1}^{3} U_{en}{}^2 m_n\right| \qquad (4)$$

and	$G^{0\nu}$	Nucleus matrix element	U_{en}	Neutrino mixing matrix elements
	$M^{0\nu}$	Transition matrix element	m_n	Neutrino masses

2. Motivation of GERDA

The GERDA experiment aims for determining the half life of neutrinoless double beta decay of ^{76}Ge. A non-zero 2β0ν rate by massive Majorana neutrino exchange would further allow an estimate of m_{ee} via (1) and (3).

Based on current values of the neutrino mass square differences Δm^2_{12} and Δm^2_{23}, knowledge of m_{ee} would help to constrain absolute neutrino masses and to possibly solve the neutrino mass hierarchy problem. According to Fig. 2 [2], $m_{ee} \leq 0.01$eV would exclude the inverse hierarchy $m_1 > m_2 > m_3$, provided neutrinos are Majorana particles.

The Heidelberg-Moscow experiment already investigated the 2β0ν decay of ^{76}Ge from 1990 to 2003. A part of the collaboration has published a positive 2β0ν signal corresponding to $T_{1/2}^{0\nu}=[0.69–4.18]\cdot 10^{25}$ y and a deduced $m_{ee}=[0.24–0.58]$ eV on a 4.2σ level; the best fit value is at $T_{1/2}^{0\nu}=1.2\cdot 10^{25}$ y [3]. Other members of the collaboration have claimed only a limit $T_{1/2}^{0\nu}>1.55\cdot 10^{25}$ y [4]. GERDA aims to test the above results and to further improve the $T_{1/2}^{0\nu}$ sensitivity by an order of magnitude, profiting from ultra-low background due to a different shielding design.

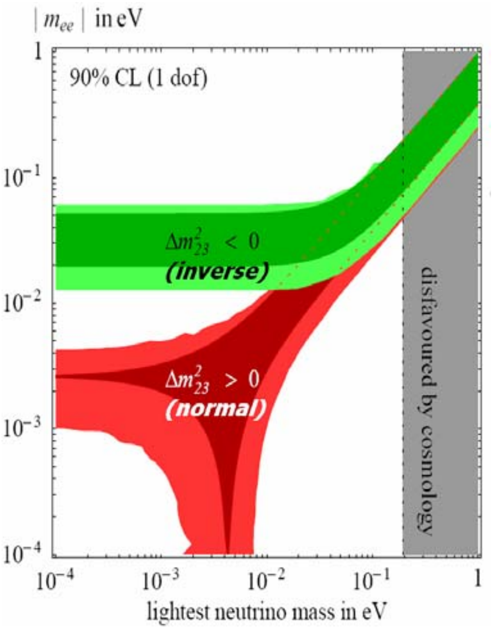

Fig. 2: Relation between m_{ee} and mass of the lightest neutrino for inverse and normal mass hierarchy [2].

3. Detector Overview

The GERDA detector [5] will be located in Hall A of the Laboratori Nazionali del Gran Sasso, Italy, at a depth of 3600 m.w.e. About 20 germanium crystals produced from a total of 37.5 kg of enriched germanium oxide will be placed in a copper suspension system with Teflon insulation and positioned close to the centre of a 70 m³ stainless steel cryostat filled with liquid argon for passive shielding and cooling. A 10–15 cm inner copper lining will shield against the radioactivity from the steel. The germanium crystals will be inserted into the cryostat through a stainless steel neck connected to the lock system located inside a clean-room on top of the experiment. The outer water tank with 630 m³ of deionised water is designed as water-Cherenkov muon veto and will provide further passive and active shielding. About 70 water-

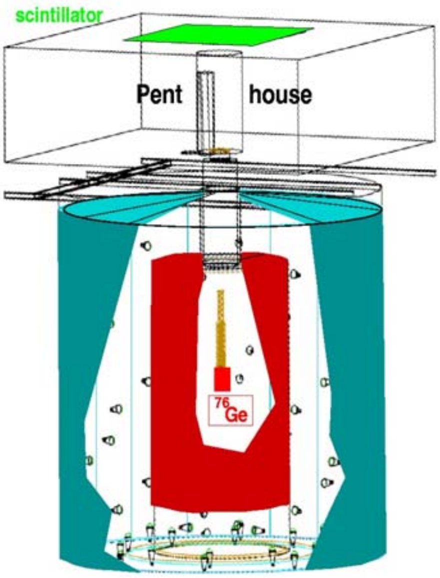

Fig. 3: GERDA detector overview.

tight, encapsulated photomultipliers will be placed inside the tank, and reflector foil fixed to surfaces will surround the active water volume. Plastic scintillator panels on the roof of the clean-room compensate for missing active water volume around the cryostat neck. Additional copper or lead shielding will be placed at the bottom of the water tank and within the lock to compensate for the restricted height of the water tank.

4. Background

Table 1. Estimation of background sources for the GERDA detector, referring to the main phase II, described in chapter 5. Numbers are from [5] unless otherwise indicated.

source	*b* $[10^{-3}\ (\mathrm{keV \cdot kg \cdot y})^{-1}]$	*b* after bkg. rejection $[10^{-3}\ (\mathrm{keV \cdot kg \cdot y})^{-1}]$	*b* after add. det. segm. $[10^{-3}\ (\mathrm{keV \cdot kg \cdot y})^{-1}]$
ext. γ from ^{208}Tl, ^{228}U	≈1	≈0.4	≈0.2
ext. neutrons	≤0.05	≤0.03	≤0.02
ext. muon-induced events [6]	≈0.3	≈0.2	≈0.2
ext. muons, incl. 90% veto [7]	≈0.2	≈0.02	≤0.02
internal ^{68}Ge (phase II)	12	1.1	0.3
internal ^{60}Co (phase II), 30d of cosmic ray exposure assumed	2.5	0.8	0.2
^{222}Rn in LAr/LN	0.2	≤0.1	≤0.1
^{208}Tl, ^{228}U in holder material	≤1	≤0.1	≤0.1
surface contamination	≤0.6	≤0.1	≤0.1

Table 1 gives an overview of several important GERDA background sources; their rates around the region of interest at 2040 keV are given in the left column. The middle column refers to rejection methods consisting in anti-coincidence of different crystals, decay coincidence for ^{68}Ge, and pulse shape analysis. The latter is based on different signal shape for non-localised energy deposition, which is characteristic for background events. The last column includes improved anti-coincidence obtained after additional crystal segmentation, which discriminates critical internal background by at least a further order of magnitude.

The studies conducted so far indicate that the background level of 10^{-3} (kg y keV)$^{-1}$ is achievable in the main phase of the experiment (phase II); 100 kg·y of data lead to only 0.36 background events (quasi background-free) in a 3.6 keV region of interest [5]. In this case, and according to (1), the sensitivity to the half life of a $2\beta0\nu$ signal improves linearly with ^{76}Ge mass and time.

5. Status and Programme

The experiment is foreseen to proceed in two phases. In the first phase, enriched detectors with a total of 14.8 kg of ^{76}Ge, which were previously operated by the Heidelberg-Moscow and IGEX collaborations, will be redeployed. The background rate, predominantly due to internal ^{60}Co and ^{68}Ge, has been estimated to about 10^{-2} (kg y keV)$^{-1}$ [5]. Up to one year of data taking is intended. This would allow to reach a limit of $T_{1/2}^{0\nu}>3\cdot10^{25}$ y (90% C.L.), corresponding to an effective neutrino mass m_{ee} < 0.3 – 0.9 eV depending on the nuclear matrix element used. The Heidelberg-Moscow publication [3] could already be checked in this way.

In the main phase II, custom-made detectors of low internal background, which are fully coaxial and segmented, will be additionally installed. The goal is to accumulate 100 kg·y of data in about three years with a background level of 10^{-3} (kg y keV)$^{-1}$. A limit of $T_{1/2}^{0\nu}>2\cdot10^{26}$ y (90% C.L.) can be reached, corresponding to m_{ee} < 0.09 – 0.29 eV [5].

Currently, the previous Heidelberg-Moscow and IGEX detectors are dismounted and tested at the so-called LArGe test bench at the LNGS. Old crystal holders are substituted by purer holders. The resolution of the Ge detectors has been measured to 2–3 keV at 1330 keV, and can probably be improved if needed by refurbishing the Ge diodes. Concerning phase-II detectors, 37.5 kg of enriched germanium oxide (a>0.86) has already been produced. Segmentation in 18 segments per crystal has been achieved with a prototype and successfully been tested in a set-up at MPI Munich.

The construction of GERDA will start in autumn of 2006. The water tank will be constructed on-site around the off-site fabricated cryostat. The muon veto will be installed after the completion of the water tank. The germanium detectors will be inserted at the very end after the completion of the GERDA facility. This can be done in a modular way to service the two phases of the experiment.

6. Conclusion

With a new shielding design based on cryogenic liquids, GERDA will provide a background level as low as 10^{-3} (kg y keV)$^{-1}$. This will be the best achieved in a germanium detector experiment. The depth of 3600 m.w.e. at LNGS and an additional water-Cherenkov muon veto reduce muon-induced background to a negligible level. Thus, on the scale of some years, GERDA will be able to measure practically background-free in the region of interest around 2040 keV, aiming to a sensitivity for the neutrinoless double beta decay half life of ^{76}Ge at $2{\cdot}10^{26}$ y. The Heidelberg-Moscow publications [3] and [4] will be tested either specifying $T_{1/2}$ more precisely or establishing a new lower limit in case of no $2\beta0\nu$ signal.

REFERENCES

Journals

1. *S.R. Elliott, P. Vogel*, Double Beta Decay // Ann. Rev. Nucl. Part. Sci. – 2002 – Vol. 52 – P. 115 – 151.
2. *F. Feruglio, A. Strumia, F. Vissani*, Addendum to: Neutrino oscillations and signals in β and 0ν2β experiments // Nucl. Phys. – 2003 – Vol. B659 – P. 359 – 362.
3. *H.V. Klapdor-Kleingrothaus et al.*, Search for Neutrinoless Double Beta Decay with Enriched ^{76}Ge in Gran Sasso 1990-2003 // Phys.Lett. – 2004 – Vol. B586 – P. 198 – 212.
4. *A.M. Bakalyarov et al.*, Results of the Experiment on Investigation of ^{76}Ge Double Beta Decay // Phys. Part. Nucl. Lett. – 2005 – Vol. 2 – P. 77 – 81.

Other contributions

5. *GERDA collaboration*, The GERmanium Detector Array for the search of neutrinoless ββ decays of ^{76}Ge at LNGS // Proposal to the LNGS P38/04 – 2004 – 112 pages.
6. *L. Pandola et al.*, Monte Carlo evaluation of the muon-induced background in the GERDA double beta decay experiment // To be published in NIM A.
7. *M. Knapp et al.*, Monte Carlo evaluation of the external muon background in the GERDA double beta decay experiment // To be published in NIM A.