Search of Neutrinoless Double Beta Decay of ^{76}Ge with the GERmanium Detector Array, GERDA

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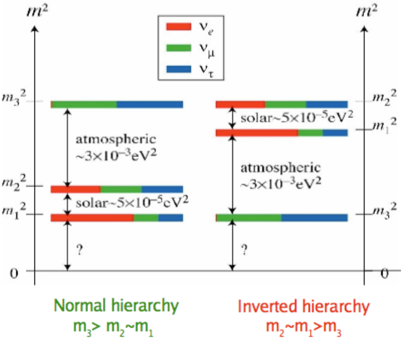
Neutrinos

What we know

1. Mass Scale:
   - Δm^2_{12} and $|\Delta^2_{13}|$ are known;
2. Mixing matrix: U_{ij} characterized by
   - three mixing angles: $\theta_{12}, \theta_{23}, \theta_{13}$
   - one Dirac CP phase: δ
   - two Majorana phases: Φ_2, Φ_3

θ_{12}, θ_{23} measured, upper limits set on θ_{13}



What we do NOT know (yet)

1. Absolute Mass Scale (offset);
2. Mass Hierarchy ($1 \Rightarrow 2 \Rightarrow 3$ or $3 \Rightarrow 1 \Rightarrow 2$)
3. Neutrino Nature (Majorana or Dirac particle);
4. Value of the third mixing angle (θ_{13});
5. CP phases (δ, Φ_2, Φ_3).

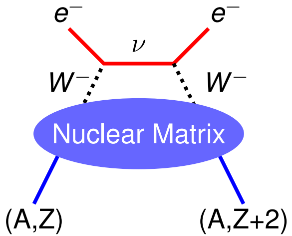
Double Beta Decay experiments can address (3)
If ν is Majorana's $\rightarrow$ shed light on a combination of (1),(2), (5).

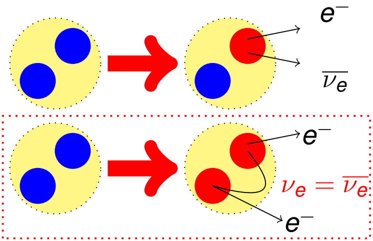
Neutrinos: Majorana versus Dirac particles

- How to test the neutrino mass nature ?
- Experimental problem:

$$P\left(\nu_L \to \nu_R\right) \sim \left(\frac{m_\nu}{E_\nu}\right)^2$$

- is vanishing small, $m_\nu \sim O(\mathrm{eV})$ or smaller ... $E_\nu \sim O(\mathrm{MeV})$ or bigger.





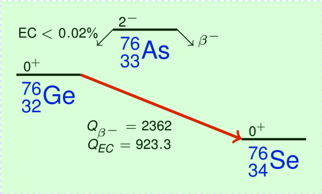
The only know technique is neutrinoless double beta decay.

Double Beta Decays (2ν and 0ν)

$2\nu\beta\beta : (A, Z) \rightarrow (A, Z+2) + 2e^- + 2\overline{\nu_e}$

- 2^{nd} order process, observed in many isotopes
- $T_{1/2} \sim 10^{19} - 10^{21} y$
- $\Delta L = 0$

for ^{76}Ge : $T_{1/2} \sim 1.5 \pm 0.1 \cdot 10^{21} y$



$0\nu\beta\beta : (A, Z) \rightarrow (A, Z+2) + 2e^-$

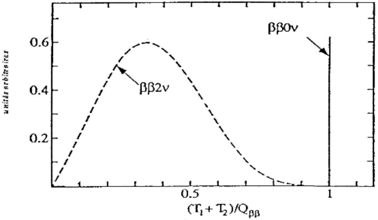
- new physics
- $T_{1/2} > 10^{25} y$
- $\Delta L = 2$

Experimental signature

- peak at $Q_{\beta\beta} = E_{e1} + E_{e2} - 2m_e$
- two electrons from vertex
- grand-daughter isotope produced

$$\frac{1}{\tau} = G(Q_{\beta\beta}, Z)\, |M_{nucl}|^2 < m_{ee} >^2$$

phase space $\propto Q^5_{\beta\beta}$ — nuclear matrix element — effective Majorana Mass



Best limits / values on ^{76}Ge

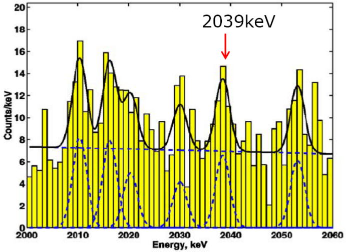
- Use Ge as source of $0\nu\beta\beta$ and detector (high signal efficiency).

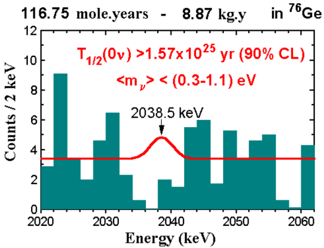
KKDC - part of HD-Moscow Collab.

- H.V. Klapdor-Kleingrothaus et al., Phys. Lett. B 586 (2004) 198.
- 5 enriched ^{76}Ge diodes (71.7 kg·y)
- bck index, $B \sim 0.11$ cts/(keV · kg · y)
- $T^{0\nu}_{1/2} = (0.69 - 4.18) \cdot 10^{25}$ y

IGEX Collab.

- D. Gonzalez et al., NPB (Proc. Suppl.) 87 (2000) 278.
- ^{76}Ge enriched diodes (8.87 kg·y)
- bck index, $B \sim 0.2$ cts/(keV · kg · y)
- $T^{0\nu}_{1/2} > 1.57 \cdot 10^{25}$ y (90% CL)





Confirmation needed with same isotope. Key: reduce background by O(100) for better sensitivity.

Effective Neutrino Mass

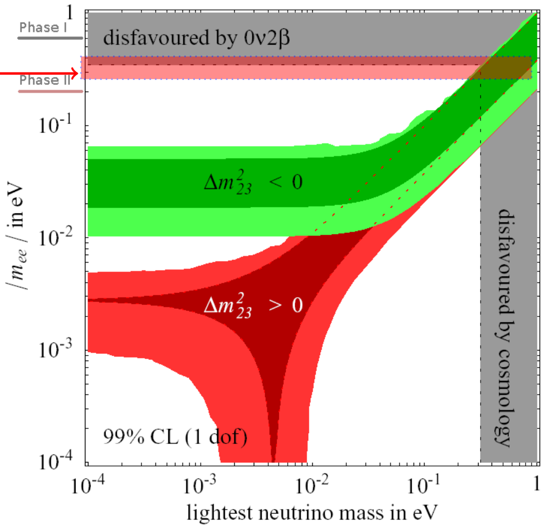
KDKC Claim: [0.17-0.45] eV (PRD79)

F. Feruglio
A. Strumia
F. Vissani
Nucl. Phys. B 659

$< m_{ee} >= \left| \sum_i U_{ei}^2 m_i \right|$

U_{ei} : neutrino mixing matrix (complex)

Negligible errors from oscillations; width of the curves due to CP phases.



The GERDA Concept

- Use naked Ge diode submerged in liquid argon

✓ LAr as cooling and shielding [G. Heusser, Ann. Rev. Nucl. Part. Sci 45 (1995) 543].

✓ minimize surrounding materials.

GERDA

Phase I

- Use ^{76}Ge enr. diodes (HdMo & IGEX)
- Scrutinize KDKC.
  If claim true, expect 13 signal / 3 bck.
  [10 keV window at 2 MeV, 4 keV FWHM]
- Active M: 17.9 kg
- Exposure: $\sim$ 30 kg·y
- bck: 0.01 cts/(keV·kg·y)
- $T_{1/2}: 2 \cdot 10^{25}$ y

Phase II

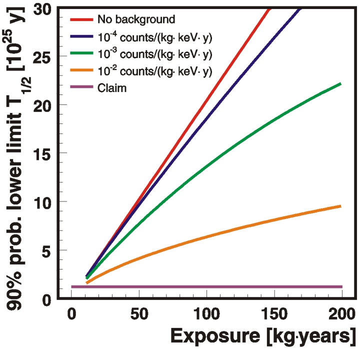
- Add new enriched ^{76}Ge detectors
- 37.5 kg enriched ^{76}Ge available.
- Active M: $\geq$ 40 kg (yield unknown.
  R&D on detector technology ongoing)
- Exposure: $\sim$ 100 kg·y
- bck: 0.001 cts/(keV·kg·y)
- $T_{1/2}: 15 \cdot 10^{25}$ y

Phase III

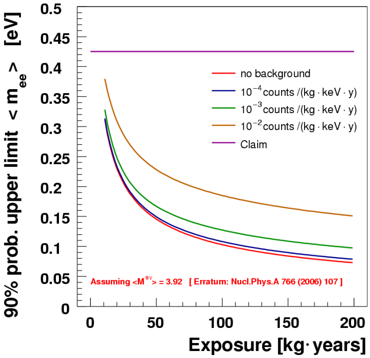
- a worldwide collaboration for a real big experiment (Exposure $\sim 10^3$ kg $\cdot$ y).
- Close contacts & MOU with the MAJORANA collaboration established

GERDA sensitivity

measured



deduced

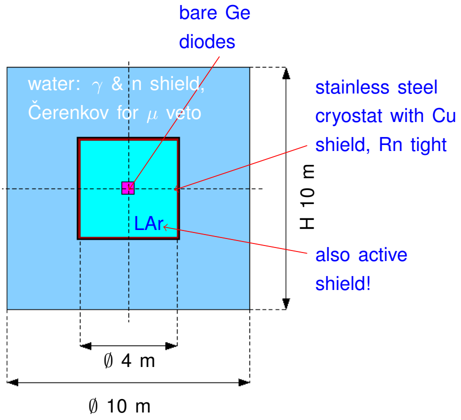


$$T_{1/2} \propto \sqrt{M \cdot T/(b \cdot \Delta E)}$$

M = Detector mass, T = exposure, b = background index,
ΔE = energy resolution.

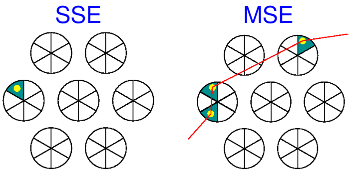
Background reduction in GERDA

- External bck: γ (Th, U), n, μ
- Shielding is possible



- Intrinsic bck:
  - cosmogenic ^{60}Co (5.3 y), ^{68}Ge (270 d),
  - radioactive surface contaminations
- Discriminate Single & MultiSite Events:

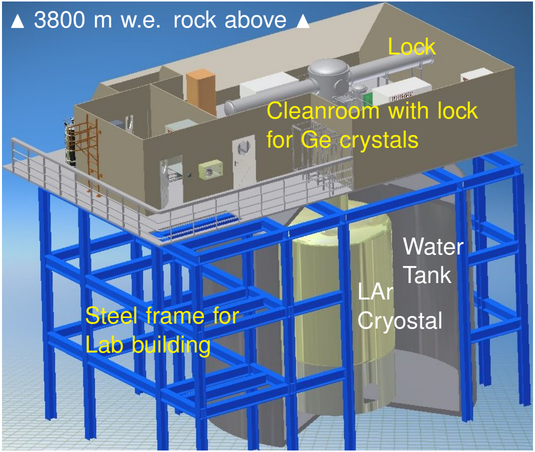
SSE : $\beta\beta$, DEP;
MSE : Compton



array of (segmented) Ge detectors

- anti-coincidence of detectors (and of detector segments)
- pulse shape analysis (PSA)

GERDA : designer's view



- designed for external γ, n, μ background $\sim$ 0.0001 cts/(keV·kg·y);
- water vessel : $\emptyset = 10$ m;
- LAr cryostat : $\emptyset = 4.2$ m;
- 70 m^3 of LAr;
- 650 m^3 of water;
- up to five Ge diodes arranged in strings, 16 strings in total;

Water:

- moderator for neutrons;
- Čerenkov medium for μ veto;
- cheaper, safer and more effective than LN2 (LAr).

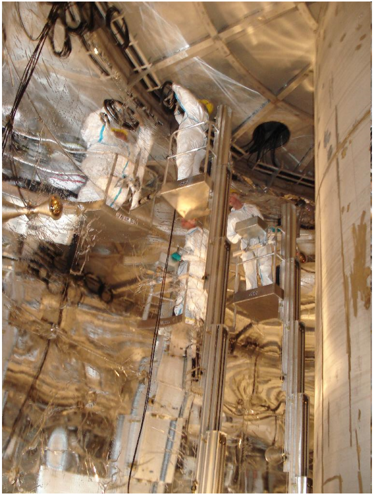
Cryotank and Water Tank constructed

Cryotank (Mar. 2008)

Water Tank (Aug. 2008)

Clean Room and Water Tank PMTs installed

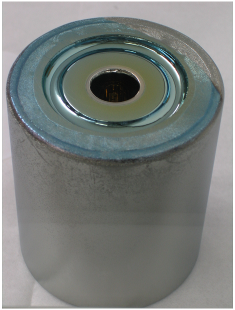
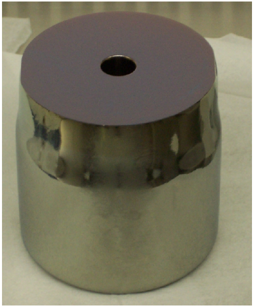
Clean Room (May 2009)



PMT installation
inside Water Tank (May 2009)

Phase I detector status

- Running for $\sim$ 1 year with 3 IGEX and 5 HdMo diodes. Mass : 17.9 kg.

Heidelbeg-Moscow & IGEX (before reprocessing)

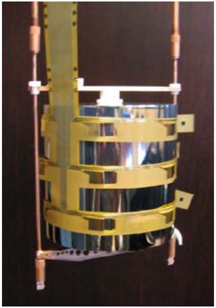
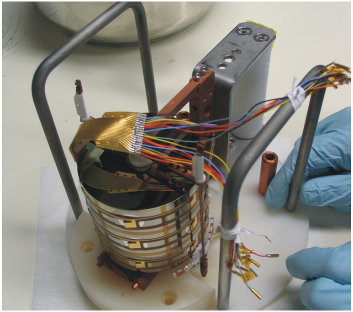
- All detectors reprocessed and tested in liquid Argon;
- FWHM $\sim$ 2.5 keV at 1332 keV, leakage current stable.

Phase II detector R&D

- 37.5 kg of ^{enr}Ge (86% ^{76}Ge) have been procured by MPI-München and are stored underground;
- natural GeO_2 had been reduced to metal and purified to 6N material for Czochralski pulling
- two detector technologies are currently under investigation:
  - segmented Ge detectors;
  - point contact Ge detectors (BEGe);

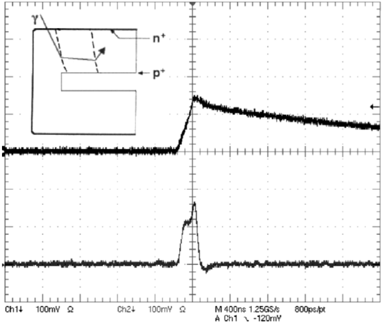
Phase II : segmented Ge detectors

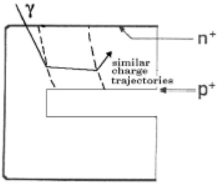
- First ^{nat}Ge crystals pulled with dedicated puller at Institut für KristallZüchtung in Berlin (no commercial company found)
- 3 × 6-fold segmented prototype detector works fine:
  - ▷ 3 keV resolution at 1.3 MeV obtained for both core and segments
  - ▷ novel low mass contacting scheme verified (I. Abt at al, NIM A577 (2007) 574).
  - ▷ contacts work in LN2, good energy resolution w/o any optimization.

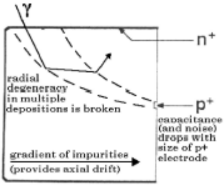
Phase II : Broad Energy Ge detectors

- Modified electrode detectors :
  - ▷ Luke at al., IEEE TNS 36 (1989).
  - ▷ Barbeau et al., JCAP 09, (2007), 09.
- non-segmented but powerful PSA
- very interesting candidate, mass production under investigation at Canberra.

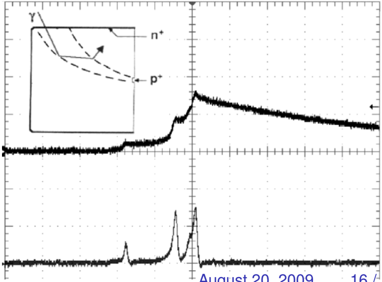




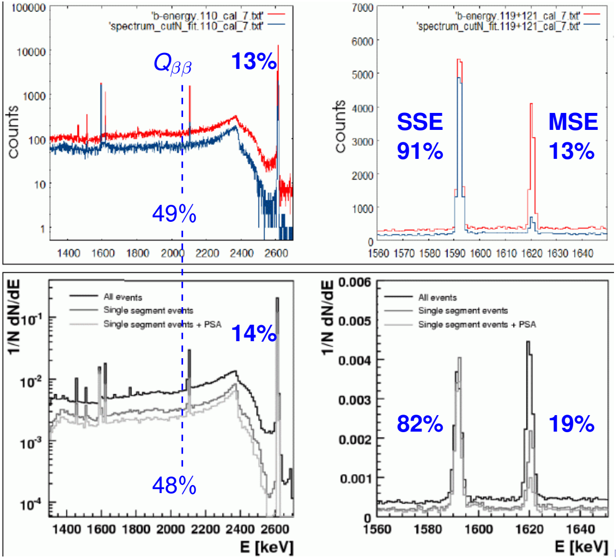
standard coaxial HPGe



P-type modified electrode



Phase II : SSE/MSE Discrimination Examples ^{228}Th



- ▷ BEGe, point-contact detector (Canberra)

⇐ fraction after PSA cut

- ▷ 3 × 6-fold segmented coaxial detector

⇐ fraction after single segment and PSA cut

Summary and Outlook

- ✓ Approved LNGS experiment in 2005;
- ✓ Construction has started in Hall A;
- ✓ Phase I Ge detectors (8 diodes, $\sim$ 18 kg) refurbished and ready;
- ✓ R&D for GERDA Phase II ongoing (parallel activity)

Next steps

- 2009: complete installation and start apparatus commissioning;

Goals

Phase I : background level $\sim$ 0.01 cts/(kg·keV·y)

- scrutinize KKDC result within 1 year after start of background measurement

Phase II : background level $\sim$ 0.001 cts/(kg·keV·y)

- $T_{1/2} > 1.5 \cdot 10^{26}$ y, $< m_{ee} >< 0.12$ eV[a]

[a] with Nuclear Matrix Elements from Rodin et al.

The GERDA Collaboration

- Institute for Reference Materials and Measurements, Geel, Belgium
- Institut für Kernphysik, Universität Köln, Germany
- Max-Planck-Institut für Kernphysik, Heidelberg, Germany
- Max-Planck-Institut für Physik (Werner-Heisenberg-Insititut), München, Germany
- Physikalisches Institut, Universität Tübingen, Germany
- Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Germany
- Dipartimento di Fisica dell'Univeristà di Padova e INFN Padova, Padova, Italy
- INFN Laboratori Nazionali del Gran Sasso, Assergi, Italy
- Università di Milano Bicocca e INFN Milano, Milano, Italy
- Jagiellonian University, Cracow, Poland
- Institute for Nuclear Research of the Russian Academy of Sciences, Moscow, Russia
- Institute for Theoretical and Experimental Physics, Moscow, Russia
- Joint Institute for Nuclear Research, Dubna, Russia
- Russian Research Center Kurchatov Institute, Moscow, Russia
- University Zurich, Switzerland