New generation of experiments
aimed to search for neutrinoless $\beta\beta$ decay

and very large efforts during R&D and installation are required

Development and perspectives

A. Smolnikov, LAUNCH ‘09, Heidelberg, Germany, November 9 – 12, 2009
New generation of experiments
aimed to search for neutrinoless $\beta\beta$ decay

Development and perspectives

NEMO
CUORICINO
HD & IGEX
GERDA
MAJORANA

Many thanks
Guido Drexlin
• Majorana vs. Dirac, effective mass, hierarchy, CP phases
$\frac{1}{\tau} = G(Q, Z) \cdot |M_{nucl}|^2 \cdot \langle m_{\beta\beta} \rangle^2$

- Phase space factor ($\sim Q_{\beta\beta}^5$)
- Nuclear matrix element
- Effective Majorana neutrino mass

$$\langle m_{\beta\beta} \rangle = |\sum_j m_j U_{ej}^2|$$

coherent sum
Neutrinoless double beta decay

\[(A, Z) \rightarrow (A, Z+2) + 2 \, e^-\]

Discovery implies $\Delta L = 2$ and Majorana neutrino

Process:

- Light neutrino exchange
- (V+A) current
- Majoron emission

SUSY

parameters

- $\langle m_\nu \rangle$
- $\langle m_\nu \rangle, \langle \lambda \rangle, \langle \eta \rangle$
- $\langle g_M \rangle$
- $\lambda'_{111}, \lambda'_{113}, \lambda'_{131}, \ldots$

Effective mass:

- $\langle m_\nu \rangle = \frac{1}{2} |U_{e1}|^2 + \frac{1}{2} |U_{e2}|^2 + |U_{e3}|^2\text{e}^{i\alpha_1} + \frac{1}{2} |U_{e1}|^2 + \frac{1}{2} |U_{e2}|^2\text{e}^{i\alpha_2}$

Coupling between Majoron and neutrinos

$T_{1/2} = F(Q_{\beta\beta}^{(0\nu)}, Z) |M|^2 <m_\nu>^2$

Electron energy sum $Q_{\beta\beta}$

Arbitrary unit

R-parity violation

$T_{1/2}$ depends on $\lambda'_{111}, \lambda'_{113}, \lambda'_{131}, \ldots$ and squarks and squark mass
Double Beta Spectrometers

Calorimetric
Source = detector
High efficiency
Energy resolution

Semiconductor multi-detector

Tracking
Source ≠ detector
Multi-source
Angular info
Precise signature

76 Ge

100 Mo
Development and installation of the **GERDA** experiment

**GERDA**: the GERmanium Detector Array to search for Neutrinoless Double Beta Decay
The **GERDA** project is based on using very low background High-Purity-Germanium (HPGe) detectors.

HPGe detector fabricated from germanium enriched in $^{76}$Ge isotope (up to 86 %) is simultaneously the $\beta\beta$ decay source and the $4\pi$ detector.

**The advantages** of such type experiments (in comparison with the other types) are due to:
1) the excellent energy resolution (3 keV at 2 MeV),
2) the high purity of Ge crystals (very low intrinsic background),
3) and the high signal detection efficiency (close to 100%).

**Disadvantages:**
1) not the highest $\beta\beta$–transiton energy for $^{76}$Ge: $Q_{\beta\beta}=2039$ keV
   (in comparison with the more promising isotopes, such as Mo-100,Nd-150,Ca-48)

2) only one characteristic of $\beta\beta$ decay - sum energy of two electrons – is possible to detect.

   *In spite of these disadvantages, up to now such type of experiments are the most sensitive tools in searching for $(0\nu\beta\beta)$-decay.*
So far the **best limits** on $(0\nu\beta\beta)$-decay **half-life**

$1.9 \times 10^{25} \text{ y} \text{ and } 1.6 \times 10^{25} \text{ y}$, which correspond to $|m_{ee}| < 0.3 - 1.1 \text{ eV}$, have been obtained with HPGe detectors

in the predecessor experiments **Heidelberg-Moscow & IGEX**

with using **Enriched Germanium (86\% in }^{76}\text{Ge, } Q_{\beta\beta} = 2038.5 \text{ keV)**

Moreover, the **part** of H-M Collaboration, after additional data treatment, claimed the presence of an excess of events in ROI, which they interpreted as the evidence for $0\nu\beta\beta$ observation

with the best fit $T_{1/2} = 1.2 \times 10^{25} \text{ y, } |m_{ee}| = 0.44 \text{ eV}$

_H.V. Klapdor-Kleingrothaus, A. Dietz, I.V. Krivosheina, O. Chkvorets, NIM A 522 (2004)_
Expected sensitivity of the GERDA experiment

GERDA will probe Majorana nature of neutrino with sensitivity at

**GERDA phase I:**
with background $0.01 \text{ cts} / (\text{kg} \cdot \text{keV} \cdot \text{y})$
► to scrutinize KKDC result within 1 year

**GERDA phase II:**
with background $1 \text{ cts} / (\text{ton} \cdot \text{keV} \cdot \text{y})$
► to cover the degenerate neutrino mass hierarchy ($<m_{ee}> < 0.08 - 0.29 \text{ eV}$)

**Phase III:**
world wide GERDA–MAJORANA collaboration
background $0.1 \text{ cts} / (\text{ton} \cdot \text{keV} \cdot \text{y})$
► to cover the inverted neutrino mass hierarchy

$m_{ee} \sim 10 \text{ meV}$
The main conceptual design of the GERDA experiment is to operate with “naked” HPGe detectors (enriched in Ge-76) submerged in high purity liquid argon supplemented by a water shield. “Naked” detector means the bare Ge crystal without traditional vacuum cryostat.

In the framework of the extensive R&D program the main GERDA experimental concepts were proven and the methods of further background reduction were developed and tested.
Using of ultra pure LAr (instead of LN) both as a cooling media and shielding material is the other perspective idea of the GERDA project. In this case there are several advantages:

1) the higher reduction factor of the external background due to higher LAr density (1.4 g/cm³);
2) anti-coincidence with LAr scintillation should reduce both the inner and external background;

As it was shown in the IGEX and H-M experiments, the main part of the detector background is due to radioactive contamination in the surrounding materials, including the copper cryostats. Thus, minimizing of the support material mass in the case of using “naked” Ge detectors should provide considerable (up to 100) reduction of the inner background.
In the Phase I all **8 existing and reprocessed enriched detectors** (in total **18 kg of \(^{76}\text{Ge}\)) from the previous Heidelberg-Moscow and IGEX experiments, and **6 reprocessed natural HPGe detectors** (in total **15 kg of \(^{\text{Nat}}\text{Ge}\)) from the Genius Test-Facility will be deployed in strings.

In the Phase II the new segmented or BeGe detectors (>20kg of \(^{76}\text{Ge}\)) made from recently produced **enriched in \(^{76}\text{Ge}\) material** will be added. In total: **40 kg of \(^{76}\text{Ge}\) + 15 kg of \(^{\text{Nat}}\text{Ge}\).

In addition several detectors from **depleted in \(^{76}\text{Ge}\) material (DepGe)** will be incorporated too.

A stainless steel cryostat (**25 t**, U/Th \(\leq 5 \text{ mBq/kg}\)) with **internal Cu shield (20 t,** U/Th \(\leq 16 \mu\text{Bq/kg}\)) will contain **100 tones of LAr, \(^{222}\text{Rn} \leq 1 \mu\text{Bq/m}^3\).**

The cryostat is immersed in a water tank (**590 t of water**). The **Ge detector array** is made up of individual detector strings and is situated in the central part of the cryostat.
The **ultra-pure water buffer** serves as a **gamma and neutron shield** and, instrumented with 66 photomultipliers, as Cherenkov detector **for efficiently vetoing** cosmic muons. Recent simulations show, that an **efficiency of more than 99 % can** be achieved, reducing the muon induced background to a level of $10^{-5}$ events/(keV $\cdot$ kg $\cdot$ y).

**Plastic scintillator panels** (20 m$^2$, 20 x 2 = 40 modules) on top of the detector will tag muons which enter the cryostat through the neck with the **vetoing efficiency of about 98 %**.
A **cleanroom** and **radon tight lock** on top of the vessel assembly allow to insert and remove individual detector strings without contaminating the cryogenic volume.
Testing of naked HPGe detectors in LN$_2$/LAr

Long-term stability tests (3 HPGe detectors in LN2/LAr during 2 years)

Detectors were tested in liquid Argon with FWHM $\sim$2.5keV (at 1332keV), and a stable leakage current.

Problems reported from GENIUS-TF about “limited long-term stability of naked detectors in liquid nitrogen”

[H.V.Klapdor-Kleingrothaus and I.Krivosheina, NIM A556 (2006) 472]

have been overcome by GERDA.

Long term stability for > 1 year. Detector performances are stable in LAr!
The main results achieved during modification of naked HPGe detectors and tests in LAr

1. It was shown that *naked Ge crystals can work directly in liquid argon* with the leakage current and energy resolution corresponding to their standard values in the traditional cryostats.

2. Their parameters *are stable during several months* after a few dozen cycles of removing and submerging from/in the LAr even after irradiation with intensive gamma sources (*modification without passivation layer*).

It shows the feasibility of the overall GERDA project.
Construction of the GERDA set up started in 2007 in the INFN Gran Sasso National Laboratory (LNGS), Italy. The “nested type” assembly has already installed in the deep underground facility (Hall A) at 3500 m w.e.

Installation of the GERDA set up

Detector string
Glove box & lock
Clean room
Cryostat & μ-veto
Heat exchanger & pipes
The commissioning of Gerda has started with the cooling of the cryostat on November 2.

The liquid argon filling will be completed by the end of November.

The single-string commissioning lock is scheduled for installation in February 2010 and non-enriched detectors will be deployed in the cryostat as the final step of the commissioning phase.
To reach the background level required for the Phase II \(10^{-3}\) \(\text{cts/(keV\cdot kg\cdot y)}\), additional new methods are required mostly to suppress the intrinsic background of the detectors.

1. Research and development are carried out to produce new segmented and BeGe types of germanium detectors which can resolve multi-site energy deposits.

2. Another effective approach is to discriminate multi-site deposits from the pulse shape analysis of the signal as well as to use anticoincidence between nearby detectors assembled in several strings.

3. The novel concept to use the LAr scintillation light as anti-coincidence signal for further background suppression is developed.
Novel Ge-detectors with advanced $0\nu\beta\beta$-signal recognition & background suppression

- $0\nu\beta\beta$: point-like events
- $\text{Bgd}$: multi-site or partial energy deposition outside crystal

n-type detectors with 18-fold segmented electrodes

p-type with small readout electrode; Similar performance with thick-window BEGe detectors

SSE/MSE discrimination with BEGe is comparable with 18-fold segmented detector

Budjas et al. IEEE 2008
$\pm 0.9\%$
$\pm 0.7\%$
$\pm 10.1\%$
$\pm 0.7\%$

Budjas et al. IEEE 2008
It was shown that the **LAr scintillator** is a powerful tool to be used in the **GERDA Phase II and III** as:

1. **Gamma spectrometer** with large active volume  
   
   (for direct measurement of gamma background inside the GERDA facility)

2. **Large volume Neutron detector**  
   
   (for direct measurement of neutron background and neutron – gamma delayed (anti-) coincidence inside the GERDA facility)

3. **Radon detector / alpha-spectrometer**  
   
   (for direct monitoring of Radon inside the GERDA facility)

The pilot setup **Mini-LArGe on the base of LAr scintillator** was successfully operated and demonstrates the power of the LAr scintillation concept.

A long-term stability (**about 2 year**) with light yield of **1800 pe/MeV** was achieved. The **Pulse Shape Discrimination** methods were developed, which allow to perform gamma / alpha / neutron selection with a strong discrimination factor for background suppression.
LAr scintillation veto by tagging extra energy in LAr


Factor 300 reduction in ROI
The LArGe Setup
with 1.3 tons of LAr

**Lock:** Can house up to 3 strings (9 detectors)

**9 PMTs:** 8” ETL9357

**VM2000 & wavelength shifter**

**Cryostat:** Inner diameter: 90 cm, Volume: **1000 liter**

**Shield:**
- Cu 15 cm
- Pb 10 cm
- Steel 23 cm
- PE 20 cm
The main parts of LArGe are installed in the LNGS underground facility GDL
The liquid argon filling was carried out on November 1. LAr is sub-cooled to -188 C (boiling temperature is -186 C) with a liquid nitrogen flow corresponding to 2.2 m3/hour. The filling level is stable and no argon is lost in this operational mode. The next steps are the start-up of the PMTs, their calibration, monitoring of the scintillation light yield and first background measurements of $^{39}$Ar and of radon.
The planned MAJORANA experiment will consist of a few hundred detectors enriched in \(^{76}\text{Ge}\) grouped into a collection of modules constructed from electroformed copper. All detectors will be segmented or point contact types and instrumented for pulse-shape analysis. The plan is to house about 55 kg of crystals per cryostat, arranging cryostats in pairs such that 500 crystals of about 1.05 kg each would comprise the 525 kg of \(^{76}\text{Ge}\) in the total experiment.

Now the **MAJORANA** project is in the R & D stage. Initial phase: **R&D demonstrator module**: Total 60 kg (30 kg of \(^{76}\text{Ge}\).
The NEMO-3 is a combined (track gas detectors + scintillation calorimeters + magnetic field) facility capable to measure not only the total energy of ββ-decay electrons but also all other parameters of this process for ββ-interesting isotopes of total mass up to 10 kg.

**Source:** 10 kg of ββ isotopes cylindrical, $S = 20 \text{ m}^2$, 60 mg/cm²

**Tracking detector:**
- drift wire chamber operating in Geiger mode (6180 cells)

**Calorimeter:**
- 1940 plastic scintillators coupled to low radioactivity PMTs

**Magnetic field:** 25 Gauss
**Gamma shield:** Pure Iron (18 cm)
**Neutron shield:** borated water + Wood
Calorimetry + Tracking

- Reconstruction of final state topology and kinematics for double beta decays, and nuclear decays from natural radioactivity:
  - $e^\pm$ individual energy (100 keV-10MeV),
  - charged particle trajectory ($e^\pm$, $\alpha$, $\mu$)
  - angular distribution, vertex, magnetic field curvature
  - time of flight,

- Background rejection through particle identification: $e^-$, $e^+$, $\gamma$, $\alpha$

- Source is separated from the detector: can measure several $\beta\beta$ isotopes
### $\beta\beta$ decay isotopes

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Mass (g)</th>
<th>$Q_{\beta\beta}$ (keV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{100}$Mo</td>
<td>6914</td>
<td>3034</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>932</td>
<td>2995</td>
</tr>
<tr>
<td><strong>0$\nu\beta\beta$ search + 2$\nu\beta\beta$ meas.</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>405</td>
<td>2805</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>9.4</td>
<td>3350</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>37.0</td>
<td>3367</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>7.0</td>
<td>4272</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>454</td>
<td>2529</td>
</tr>
<tr>
<td><strong>2$\nu\beta\beta$ measurement</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{nat}$Te</td>
<td>491</td>
<td>see $^{130}$Te</td>
</tr>
<tr>
<td>Cu</td>
<td>621</td>
<td>-</td>
</tr>
<tr>
<td><strong>External background measurement</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$^{nat}$Te</td>
<td>491</td>
<td>-</td>
</tr>
</tbody>
</table>

*Enriched isotopes produced by centrifugation in Russia*
$2\nu\beta\beta$ results for $^{100}\text{Mo}$

**Energy sum**

- Number of events/0.05 MeV
- $E_{2\nu}$ (MeV)

**Angular distribution**

- Number of events
- $\cos(\Theta)$

$^{100}\text{Mo}$

- Statistics: 219,000 events
- Exposure: 6914 g $\times$ 389 days
- $S/B = 40$

- data (background subtracted)
- $2\nu\beta\beta$ Monte Carlo
- background
The NEMO 3 $\beta\beta$ factory: a tool for precision tests

<table>
<thead>
<tr>
<th>Isotope</th>
<th>$T_{1/2}^{2\nu\beta\beta}$ (y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{100}$Mo</td>
<td>$[7.11 \pm 0.02(stat) \pm 0.54(syst)] \times 10^{18} ,*$ (SSD favored)</td>
</tr>
<tr>
<td>$^{100}$Mo$(0^+_1)$</td>
<td>$5.7^{+1.3}_{-0.9}(stat) \pm 0.8(syst)] \times 10^{20} ,**$</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>$[9.6 \pm 0.3(stat) \pm 1.0(syst)] \times 10^{19} ,*$</td>
</tr>
<tr>
<td>$^{116}$Cd</td>
<td>$[2.8 \pm 0.1(stat) \pm 0.3(syst)] \times 10^{19} ,**$</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>$[6.9 \pm 0.9(stat) \pm 1.0(syst)] \times 10^{20} ,**$</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>$[9.20^{+0.25}_{-0.22}(stat) \pm 0.73(syst)] \times 10^{18} ,**$</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>$[2.35 \pm 0.14(stat) \pm 0.19(syst)] \times 10^{19} ,**$</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>$[4.4^{+0.5}_{-0.4}(stat) \pm 0.4(syst)] \times 10^{19} ,**$</td>
</tr>
</tbody>
</table>

* Phase 1 (high radon data), Phys. Rev. Lett. 95 (2005) 182302
  (additional statistics are being analysed, to be published soon)

** Phase 1 data

*** Phases 1 and 2, preliminary
Counting [2.8 – 3.2] MeV

- Data: 20 events
- Expected background: 18.6 events
- Excluded 90% C.L.: 9.6 events
- Efficiency = 0.0726

Likelihood [2.0 – 3.2] MeV

- Excluded 90% C.L.: 18 events
- Efficiency = 0.174
- $T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{24}$ y @ 90% C.L.
- $< m_\nu > < 0.45-0.93$ eV
Current limits on neutrinoless DBD (90% C.L.):

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Exposure (kg.y)</th>
<th>$T_{1/2}^{0\nu\beta\beta}$ (y)</th>
<th>$&lt;m_\nu&gt;$ (eV)</th>
<th>[nme ref.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{100}$Mo</td>
<td>26.6</td>
<td>$&gt;1.1 \times 10^{24}$</td>
<td>$&lt;0.45$-0.93</td>
<td>[1-3]</td>
</tr>
<tr>
<td>$^{82}$Se</td>
<td>3.5</td>
<td>$&gt;3.6 \times 10^{23}$</td>
<td>$&lt;0.9$-1.6 &lt;2.3</td>
<td>[1-3] [7]</td>
</tr>
<tr>
<td>$^{150}$Nd</td>
<td>0.095</td>
<td>$&gt;1.8 \times 10^{22}$</td>
<td>$&lt;1.7$-2.4 &lt;4.8-7.6</td>
<td>[4-5] [6]</td>
</tr>
<tr>
<td>$^{130}$Te</td>
<td>1.4</td>
<td>$&gt;9.8 \times 10^{22}$</td>
<td>$&lt;1.6$-3.1</td>
<td>[4,5]</td>
</tr>
<tr>
<td>$^{96}$Zr</td>
<td>0.024</td>
<td>$&gt;8.6 \times 10^{21}$</td>
<td>$&lt;7.4$-20.1</td>
<td>[2,3]</td>
</tr>
<tr>
<td>$^{48}$Ca</td>
<td>0.017</td>
<td>$&gt;1.3 \times 10^{22}$</td>
<td>$&lt;29.6$</td>
<td>[7]</td>
</tr>
</tbody>
</table>

nme: nuclear matrix element:

SuperNEMO project

Physics goals and technique

- Search for $0
\nu\beta\beta$ decay at $T_{1/2} \approx 10^{26}$ y $\sim < m_\nu > \approx 50$ meV
- Extends and improves NEMO-3 technique:
  tracker+calorimeter, modular design, baseline $\approx 100$ kg $^{82}$ Se
- R&D phase: 2005-2009

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<td>Search for $0\nu\beta\beta$ decay at $T_{1/2} \approx 10^{26}$ y $\sim &lt; m_\nu &gt; \approx 50$ meV</td>
</tr>
<tr>
<td>Extends and improves NEMO-3 technique: tracker+calorimeter, modular design, baseline $\approx 100$ kg $^{82}$ Se</td>
</tr>
<tr>
<td>R&amp;D phase: 2005-2009</td>
</tr>
</tbody>
</table>
R&D stages

Source:

- baseline with $^{82}\text{Se}$ (already have 4.5 kg),
- purification techniques are available: chemical & distillation
- 40 mg/cm$^2$ foil production: ala NEMO-3 & new coating method
- 100 kg enrichment is possible by centrifugation in Russia

Thin source foil radiopurity:

- BiPo1 0.8 m$^2$ prototype detector: measure the radiopurity of thin foils in $^{214}\text{Bi}$ and $^{208}\text{Tl}$
  $\sim A^{(212}\text{Bi}) \approx 1\mu\text{Bq/m}^2$ (after 1 year)
- next step: BiPo 3.5 m$^2$ detector: sensitivity $A^{(208}\text{Tl}) < 3\mu\text{Bq/kg}$ (after 6 months)
Tracker:
- 90 cells prototype shows good tracking performances (efficiency and resolution)
- wiring robot is under development (full detector is ≈500000 wires)

Calorimeter:
- main goal is $r=7\%$ FWHM @ 1 MeV (scintillator block + 8" PMT)
- accurate calibration and control quality of mass production
- $r=6.7\%$ and 7.8\% have been reached resp. with Photonis and Hamamatsu high QE PMTs + 10 cm thick plastic scintillator block.
- Calorimeter design to be choosen between:
  - blocks (15000 channels @ $r=7\%)$
  - or bars (7500 ch. @ $r=10\%$)

![Image of calorimeter and spectrum](image-url)
SuperNEMO demonstrator (1\textsuperscript{st} module)

- Demonstrate the feasibility of a large scale detector with required performances: efficiency, energy resolution, radiopurity…
- Measure the radon background
- Finalize the detector design
- Produce competitive physics measurements:
  \[ T^{0\nu\beta\beta}_{1/2} > 6.5 \times 10^{24} \text{ y} \]
  \[ < m_{\nu} > < 210 – 570 \text{ meV} \]
  with 7 kg of \(^{82}\text{Se}\) after 2 y of data taking
- Schedule:
  - construction: 2010-2011 (+BiPo 3.5 m\(^2\))
  - running: 2012-2013
- Location: possibly @ LSM (in place of NEMO 3)
SuperNEMO full detector

- Baseline: $\approx 20$ modules with 5 kg of $^{82}\text{Se}$
- Other candidate isotopes: $^{48}\text{Ca}$ and $^{150}\text{Nd}$
- Expected sensitivity with 500 kg.y of $^{82}\text{Se}$ (preliminary):
  \[ T^{0\nu\beta\beta}_{1/2} > 1 \times 10^{26} \text{ y} \sim < m_\nu > < 53 - 145 \text{ meV} \]
- Schedule:
  - construction: 2012+
  - running: 2013+
- Location: new 60000 m$^3$ extension at LSM (2012)
CONCLUSION

New generation of the $0\nu\beta\beta$ experiments has a good chance to penetrate deeper in understanding of the neutrino properties.