Neutrinoless Double Beta Decay
Experimental techniques

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The CUORE background model

The sources of the background

1. Radioactive contamination in the detector materials (bulk and surface)
2. Radioactive contamination in the set-up, shielding included
3. Neutrons from rock radioactivity
4. Muon-induced neutrons

Monte Carlo simulation of the CUORE background based on:

1. CUORE baseline structure and geometry
2. Gamma and alpha counting with HPGe and Si-barrier detectors
3. Cuoricino experience ⇒ Cuoricino background model
4. Specific measurements with dedicated detectors in test refrigerator in LNGS

Results.....
## The CUORE background components

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The only limiting factor
The Cuoricino background and the surface radioactivity model

Gamma region

Alpha region, dominated by α peaks (internal or surface contaminations)

~ 0.2 c / keV kg y
Reconstruction of the Cuoricino spectrum in the region 2.5 – 6.5 MeV
Reconstruction of the Cuoricino spectrum in the region 2.5 – 6.5 MeV

Additional component required here
The additional component: inert material surface contamination

In order to explain the 2.0 - 4 MeV region BKG, one has to introduce $^{238}\text{U}$ or $^{210}\text{Pb}$ surface contamination of the copper structure facing the detectors.

**Surface contamination level:** $\sim 100 \text{ pg/g}$ vs bulk c.l. : $< 1 \ (0.1) \text{ pg/g}$ for Cu (TeO$_2$)

**Contamination depth:** $\sim 10 \mu\text{m}$ in agreement with direct measurement on Cu
Strategies for the control of the surface background from inert materials

(A) Passive methods $\Rightarrow$ surface cleaning

- Mechanical action
- Chemical etching / electrolitical processes
- Passivation

1. "Legnaro" method
2. "Gran Sasso" method

(B) Active methods ("reserve weapons") $\Rightarrow$ events ID

1. surface sensitive bolometers (Como)
2. scintillating bolometers able to separate $\alpha$ from elettrons / $\gamma$ (LNGS / Roma)
The diagnostic problem

It is **difficult and quite demanding** in terms of time and money to verify the effectiveness of a method to reduce the surface radioactivity.

Two methods:

(A) Direct counting

\[ A_{3-4\text{ MeV}}^{\text{sup}} \approx 1.7 \text{ counts/cm}^2\text{ y} \]

runs in hall C

(B) Concentration measurements

contamination in U – Th of the order of ng/g

Not applicable at all for \(^{210}\text{Pb}\) or \(^{226}\text{Ra}\)

ICPMS analysis

Assuming CUORICINO background
Laser ablation in conjunction to HR-ICPMS was proved to be a powerful method for surface activity diagnostic.

Plasma cleaning is under tests.

Receipt for cleaning: several ingredients

- **T** ⇒ Mechanical barrel polishing by Tumbling
- **E** ⇒ Removal of ~100 micron by Electropolishing
- **C** ⇒ Removal of ~ tenths of microns by Chemical Etching
- **M** ⇒ Removal of few microns by Magnetron Sputtering in UHV
- **I** ⇒ Removal on nanometric scale by Ion Beam Cleaning in UHV

**CUORICINO:** T + C

**CUORE:** T + E + C + M + (I on the site - LNGS)
From HM / IGEX to GERDA
(The GERmanium Detector Array)

- Next generation $^{76}$Ge double beta decay experiment at Gran Sasso
- Significant reduction of background around $Q_{\beta\beta}$ to $\leq 10^{-3}$ cts/(kg·keV·y)
- Contamination in previous experiments mainly in cryostat / diode holder
  → Bare diodes in cryogenic liquid (LAr)
- Cryogenic liquids have very high radiopurity
GERDA phases and sensitivity

- Phase I: operate refurbished HM & IGEX enriched detectors (~20 kg)
  - Under commissioning
  - Background: 0.01 counts/ keV kg y
  - Scrutinize $^{76}$Ge claim with the same nuclide (exclude 99% c.l. or confirm $5\sigma$)
  - Half life sensitivity: $3 \times 10^{25}$ y
  - Start data taking: 2009

- Phase II: additional ~20 kg $^{76}$Ge diodes (segmented detectors)
  - Background: 0.001 counts / keV kg y
  - Sensitivity after 100 kg y (~3 years): $2 \times 10^{26}$ y

- Phase III (depending on physics results of Phase I/II)
  - $\langle M \rangle < 90 - 290$ meV
  - $\langle M \rangle < 20 - 50$ meV
  - $\Rightarrow$ ~ 1 ton experiment in world wide collaboration with MAJORANA
phase II

$\Delta E_{\text{FWHM}} = 4 \text{ keV}$

90% prob. lower limit $T^{1/2}$ [10^{25} y]

Phase I

Phase II

KKDC claim

\[ \langle M^0_{\nu}\rangle = 3.92 \]


The GERDA detectors

- In 2006 3 IGEX diodes and 5 HM diodes were removed from their cryostats
- Dimensions were measured
- Construction of dedicated low-mass holder for each diode
Phase I prototype testing

- Low mass detector holder developed and tested
- Definition of detector handling protocol
- Optimization of thermal cyclings
  >40 warming and cooling cycles carried out

Same performance in LN$_2$/LAr
Issue of the radiation-induced leakage current
Four irradiations without applying HV: the leakage current is recovered
Problem much more serious if irradiation of the bottom part

Origin of the problem: the passivation layer

- $p^+ (B)$
- $\sim 0.3 \, \mu m$
- $n^+ (Li)$
- $\sim 0.7 \, mm$ (not on scale)

Diagram:"
Collection of +/- charges changes conductivity of passivation layer

- +(-) charges collected on the inner (outer) part of the passivation layer

- γ radiation-induced decrease of LC: UV light from LAr scintillation
Solution

Calibration 1 week → negligible increase of LC during live-time of GERDA (<10 pA)
(Note: $\Delta LC \sim 1$ nA $\rightarrow$ 1.6 keV deterioration)
GERDA design

- Additional inner copper shield
- Germanium-detector array
- Liquid argon
- Vacuum-insulated double wall stainless steel cryostat
R&D on phase II detectors

- test three 18-fold segmented detectors immersed directly in LN (full GERDA string)
- test 18-segment p-type detector
- detector response to IR & UV light
**EXO 200 sensitivity**

Assumptions on detector performance and background:
- 200 kg of Xe enriched to 80% in 136
- $\sigma(E)/E = 1.4\%$ obtained in EXO R&D
- Low but finite radioactive background: 20 events/year in the $\pm 2\sigma$ interval centered around the 2.481 MeV endpoint
- Negligible background from 2$\nu$ DBD ($T_{1/2} > 1 \cdot 10^{22}$ yr R. Bernabei et al. measurement)

Background: 40 counts in 2 y
Sensitivity (2 years, 90% c.l.): $6.4 \times 10^{25}$ y

If $^{76}\text{Ge}$ claim is correct:
- Worst case (QRPA, upper limit) 15 events (40 events bkg) $\Rightarrow 2\sigma$
- Best case (NSM, lower limit) 162 events (40 events bkg) $\Rightarrow 11\sigma$

\[ \langle M \rangle < 270 - 380 \text{ meV} \]
DBD option in SNO+ is sometimes referred to as **SNO++**

- it is possible to **add ββ isotopes** to liquid scintillator, for example
  - dissolve Xe gas
  - organometallic chemistry (Nd, Se, Te)
  - dispersion of nanoparticles (Nd\(_2\)O\(_3\), TeO\(_2\))

**SNO+ collaboration researched these options and decided that the best isotope and technique is to make a Nd-loaded liquid scintillator**
SNO++: concepts

- A liquid scintillator detector has poor energy resolution; but enormous quantities of isotope (high statistics) and low backgrounds help compensate.

- Large, homogeneous liquid detector leads to well-defined background model.

- Possibly source in–source out capability.

- Using the technique that was developed originally for LENS and now also used for Gd-loaded scintillator.

- SNO+ collaboration managed to load Nd into pseudocumene and in linear alkylbenzene (>1% concentration).

- With 1% Nd loading (natural Nd) a very good neutrinoless double beta decay sensitivity is predicted, but…
a liquid scintillator detector has poor energy resolution; but enormous quantities of isotope (high statistics) and low backgrounds help

- large, homogeneous liquid detector leads to well-defined background model
- possibly source in–source out capability
- using the technique that was developed originally for LENS and now also used for Gd-loaded scintillator
- SNO+ collaboration managed to load Nd into pseudocumene and in linear alkylbenzene (>1% concentration)

- at 1% loading (natural Nd), there is too much light absorption by Nd
  \[ 47 \pm 6 \text{ pe/MeV (from Monte Carlo)} \]

- at 0.1% loading (isotopically enriched to 56%)
  \[ 400 \pm 21 \text{ pe/MeV (from Monte Carlo)} \]

  good enough to do the experiment

  beta decay sensitivity is predicted, but...
1 yr, 500 kg isotope, $m_\nu = 150$ meV
Open questions

- Large scale enrichment: laser isotope separation possible in France using a dismissed facility for U \( \Rightarrow \) the facility must be re-operated and tuned to \(^{150}\text{Nd}\)
- \(^{150}\text{Nd}\) nuclear matrix elements
Scintillating bolometers

CUORICINO Background

γ-region
α-region

Environmental “underground” Background:

- $^{238}$U and $^{232}$Th trace contaminations

- $^{76}$Ge
- $^{130}$Te
- $^{116}$Cd
- $^{100}$Mo
- $^{82}$Se

CUORICINO Background
Scintillating bolometers

Scintillating Bolometer

Bolometer

2615 keV γ-ray

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<th>Amplitude [a.u.]</th>
<th>Time [ms]</th>
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<td>600</td>
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Heat Signal in CdWO4
Light Signal
Scintillating bolometers
Scintillating bolometers

![Graph showing light signal vs energy for 3x3x6 CdWO₄ scintillating bolometers. The graph highlights different energy ranges for beta/gamma and alpha particles, with a heater and ¹⁸⁰⁰ W alpha mentioned.]
Scintillating bolometers

Light Detector

3x3x3 CdWO₄

3x3x6 CdWO₄
Calibration results on CdWO$_4$

$^{\text{232}}$Th + $^{56}$Co Calibration

0.2% FWHM @ 2615 keV

Heat
Calibration results on CdWO$_4$

$^{232}$Th + $^{56}$Co Calibration

Scintillation

2.9% FWHM @ 2615 keV

2.9% FWHM is the best result ever achieved with CdWO$_4$ as scintillator
CdWO₄ - some considerations
CdWO$_4$ - some considerations II
CdWO₄ - some considerations II

\[ E_{\text{rotated}} = \text{Heat} \cos \theta + \text{Light} \sin \theta \]

FWHM @ 2615 improves by ~ 40 % !!!!!
CdWO$_4$ - some considerations II

$$Erotaded = \text{Heat} \cos \theta + \text{Light} \sin \theta$$
Outline of the lectures

- Neutrino mass and Double Beta Decay
- Experimental challenge and strategies
- Present situation
- Overview of the future projects
- Some very promising experimental approaches
- Prospects and conclusions
Prediction of the Moore’s law for the sensitivity

(super) CUORE, GERDA III, maybe SNO++...
## Future scenarios and branching points in terms of discovery

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<th>Experimental Situation</th>
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- degenerate hierarchy
- inverted hierarchy - atmospheric
- direct hierarchy - solar

$\Delta M^2$ region

big leap in sensitivity - new approaches required
100 tons of isotopes is the typical scale

discovery if neutrino is a Majorana particle
unpredictable time scale

if this range holds (or if $^{76}$Ge claim is right):
- SUPERNEMO may investigate the mechanism ($^{82}$Se or $^{150}$Nd)
- GERDA phase I / II will see it in $^{76}$Ge
- EXO-200 will see it in $^{136}$Xe
- SNO++, if done, could see it in $^{150}$Nd
- CUORE will see it in $^{130}$Te and may do
  multi-isotope searches simultaneously
  ($^{130}$Te - $^{116}$Cd - $^{100}$Mo)

large scale enrichment required
reduction of uncertainties in NME

precision measurement era for 0$\nu$-DBD!
Future scenarios and branching points in terms of discovery

100 - 500 meV

- sensitivity to \( \langle M \rangle \)
- degenerate hierarchy
- 100-200 kg isotope - 5 year scale
- CUORE – GERDA I / II - EXO-200 - SUPERNEMO
- inverted hierarchy - atmospheric \( \Delta M^2 \) region
- 1000 kg isotope - 10 year scale
- straightforward in some cases (enriched CUORE)
- GERDA phase III could see it in \( ^{76}\text{Ge} \)
- CUORE could see it in a couple of isotopes in sequence (after \( ^{130}\text{Te}, ^{116}\text{Cd} \) ?)
- discovery in 3 or 4 isotopes necessary (and possible...)
- to confirm the observation and to improve \( \langle M_{\beta\beta} \rangle \) estimate

15 - 50 meV

- if this range holds:
  - SUPERNEMO could marginally see it in \( ^{82}\text{Se} \) or \( ^{150}\text{Nd} \)
  - SNO++, if done, could see it in \( ^{150}\text{Nd} \)
  - GERDA phase III could see it in \( ^{76}\text{Ge} \)

2 - 5 meV

- direct hierarchy - solar \( \Delta M^2 \) region
- big leap in sensitivity - new approaches required
- 100 tons of isotopes is the typical scale
- discovery if neutrino is a Majorana particle
- unpredictable time scale

- unexpected time scale

inverted hierarchy - atmospheric \( \Delta M^2 \) region
1000 kg isotope - 10 year scale
straightforward in some cases (enriched CUORE)
GERDA phase III – EXO final - …. 

direct hierarchy - solar \( \Delta M^2 \) region
big leap in sensitivity - new approaches required
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*if this range holds:*
- new strategies have to be developed
- it is worthwhile to start to elaborate them now
- next generation experiments are precious for the selection of the future approaches
- a large investment in enrichment is mandatory
**What about a ~ 5 meV experiment?**

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<th>$T^{0\nu}$</th>
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<td>50 meV</td>
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<td>5 x $10^{26}$ y</td>
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<tr>
<td>5 meV</td>
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<td>5 x $10^{28}$ y</td>
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If we require **10 counts in 5 years with 0 background**

**Experiment with $10^{29}$ nuclei and 0 background**

For example: **30 ton of TeO$_2$ enriched**

**100 ton of TeO$_2$ natural**

- **Selection** of the most promising technique
- **Design** of the experiment

Only “one bit” information ⇒ direct hierarchy - Majorana nature of neutrino
Exciting times for neutrino masses:

- degeneracy will be deeply probed
- discovery potential in case of inverted hierarchy