Review of Neutrino Mass Measurements

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- Indirect and direct determinations of the neutrino mass scale
- Laboratory bounds: double and single $\beta$ decay
- Status and prospects for single $\beta$ decay
- Status and prospects for double $\beta$ decay
- Conclusions
Neutrino flavor oscillations and mass scale

what we presently know from neutrino flavor oscillations

1. oscillations do occur  ➡  neutrinos are massive

2. given the three $\nu$ mass eigenvalues $M_1, M_2, M_3$ we have approximate measurements of two $\Delta M_{ij}^2$ ($\Delta M_{ij}^2 \equiv M_i^2 - M_j^2$)

   $\Delta M_{12}^2 \sim (9 \text{ meV})^2$  \textbf{Solar}

   $|\Delta M_{23}^2| \sim (50 \text{ meV})^2$  \textbf{Atmospheric}

3. approximate measurements and/or constraints on $U_{ij}$

   $U_{ij} \equiv \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu1} & U_{\mu2} & U_{\mu3} \\ U_{\tau1} & U_{\tau2} & U_{\tau3} \end{bmatrix}$

   elements of the $\nu$ mixing matrix

   parametrized with three angles and three phases

   $c_{ij} \equiv \cos \Theta_{ij}$

   $s_{ij} \equiv \sin \Theta_{ij}$

\[
\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} \end{pmatrix} \begin{pmatrix} s_{12}c_{13} \\ c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} \\ -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} \end{pmatrix} \begin{pmatrix} e^{i\alpha_1/2} & \nu_1 \\ e^{i\alpha_2/2} & \nu_2 \\ \nu_3 \end{pmatrix}
\]
Neutrino flavor oscillations and mass scale

The present knowledge can be summarized in this plot (Strumia-Vissani hep-ph/0503246)

what we do not know from neutrino flavor oscillations:

1. neutrino mass hierarchy

2. absolute neutrino mass scale

3. DIRAC or MAJORANA nature of neutrinos
Tools for the investigation of the $\nu$ mass scale

<table>
<thead>
<tr>
<th>Tools</th>
<th>Present sensitivity</th>
<th>Future sensitivity (a few year scale)</th>
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<tbody>
<tr>
<td>Cosmology (CMB + LSS)</td>
<td>0.7 - 1 eV</td>
<td>0.1 eV</td>
</tr>
<tr>
<td>Neutrinoless Double Beta Decay</td>
<td>0.5 eV</td>
<td>0.05 eV</td>
</tr>
<tr>
<td>Single Beta Decay</td>
<td>2.2 eV</td>
<td>0.2 eV</td>
</tr>
</tbody>
</table>

**Model dependent**

**Direct determination**

**Laboratory measurements**
Model dependent tools

**Neutrinoless Double Beta Decay**

- It works only if neutrino is a Majorana particle \( \nu = \nu^c \)
- Uncertainties from nuclear physics
- Other mechanisms (not only massive neutrinos) can mediate the process

**Cosmology (Cosmic Microwave Background + Large Scale Structure)**

Very sensitive, but considerable spread in recently published results

- Parameter degeneracy
- Dependence on priors on cosmological parameters
- Sensitivity to even small changes of input data

<table>
<thead>
<tr>
<th>author</th>
<th>WMAP</th>
<th>CMB_{h_{1/2}}</th>
<th>SDSS</th>
<th>2dF</th>
<th>other data</th>
<th>(\Sigma m_\nu) [eV]</th>
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</thead>
<tbody>
<tr>
<td>Bar'03</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>h (HST)</td>
<td>&lt; 0.75</td>
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<td>SNIa</td>
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<tr>
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<td>x</td>
<td></td>
<td></td>
<td></td>
<td>&lt; 1.2</td>
</tr>
</tbody>
</table>

Necessity of **direct measurement** and **cross checks** at this scale
**Model independent tool: the kinematics of β decay**

basic idea: use only kinematics

\[ E^2 = M^2 c^4 + p^2 c^2 \]

processes involving neutrinos in the final state

**Single Beta Decay**

\[ (A,Z) \rightarrow (A,Z+1) + e^- + \bar{\nu}_e \]

\[ Q = M_{at}(A,Z) - M_{at}(A,Z+1) \approx E_e + E_\nu \]

\[ \frac{dN}{dE} \propto G_F^2 |M_{ii}|^2 (E_e + m_e c^2) (Q - E_e)^2 F(Z,E_e) S(E_e) \left[ 1 + \delta_R(Z,E_e) \right] \]

finite neutrino mass

electron kinetic energy distribution

\[ (Q - E_e)^2 \Rightarrow (Q - E_e) \sqrt{(Q - E_e)^2 - M_\nu^2 c^4} \]

only a small spectral region very close to \( Q \) is affected
Complementarity of cosmology, single and double $\beta$ decay

Cosmology, single and double $\beta$ decay measure different combinations of the neutrino mass eigenvalues, constraining the neutrino mass scale.

In a standard three active neutrino scenario:

$$\sum \equiv \sum_{i=1}^{3} M_i$$

This expresses a simple sum, which is a pure kinematical effect.

$$\langle M_\beta \rangle \equiv \left( \sum_{i=1}^{3} M_i^2 |U_{ei}|^2 \right)^{1/2}$$

This represents the incoherent sum, which is the real neutrino contribution.

$$\langle M_{\beta\beta} \rangle \equiv \left| \sum_{i=1}^{3} M_i |U_{ei}|^2 e^{i\alpha_i} \right|$$

This expresses the coherent sum, which includes the virtual neutrino and Majorana phases.
**Present bounds**

The three constrained parameters can be plot as a function of the lightest neutrino mass.

Two bands appear in each plot, corresponding to **inverted** and **direct** hierarchy.

The two bands merge in the **degenerate** case (the only one presently probed).
SINGLE BETA DECAY
Effects of a finite neutrino mass on the beta decay

The modified part of the beta spectrum is in a range of the order of \([Q - M_\nu c^2, Q]\).
Effects of a finite neutrino mass on the Kurie plot

The Kurie plot $K(E_e)$ is a convenient linearization of the beta spectrum.

\[\int_{Q-\delta E}^{Q} (dN/dE) \, dE \approx 2(\delta E/Q)^3\]
In case of mass hierarchy:
- the Kurie plot = superposition of three different sub-Kurie plots
- each sub-Kurie plot corresponds to one of the three different mass eigenvalues

The weight of each sub-Kurie plot will be given by $|U_{ej}|^2$, where

$$|\nu_e\rangle = \sum_{i=1}^{3} U_{ei} |\nu_{Mi}\rangle$$

This detailed structure will not be resolved with present and planned experimental sensitivities ($\sim 0.2$ eV)
Mass degeneracy

If the 3 mass components cannot be resolved or degeneracy holds: the Kurie-plot can be described in terms of a single mass parameter, a mean value of the three mass eigenstates

\[
\langle M_\beta \rangle = \left( \sum M_i^2 |U_{ei}|^2 \right)^{1/2}
\]
Two complementary experimental approaches

1. source separate from detector (the source is T - Q=18.6 keV)
   - determine electron energy by means of a selection on the beta electrons operated by proper electric and magnetic fields
   - measurement of the electron energy out of the source
   - magnetic and electrostatic spectrometers
   - present achieved sensitivity: ∼ 2 eV
   - future planned sensitivity: ∼ 0.2 eV

2. source = detector (calorimetric approach) (the source is $^{187}\text{Re}$ - Q=2.5 keV)
   - determine all the “visible” energy of the decay with a high resolution low energy “nuclear” detector
   - measurement of the neutrino energy
   - cryogenic microcalorimeters
   - present achieved sensitivity: ∼ 10 eV
   - future planned sensitivity: under study

completely different systematic uncertainties
These instruments enabled a **major step forward in sensitivity** after 1993. They are the **basic devices for next generation experiments** aiming at the sub-eV range.

High magnetic field $B_{\text{max}}$ at source and detector. Low field $B_{\text{min}}$ at center.

All electrons emitted in the forward hemisphere spiral from source to detector.

In the adiabatic limit

$$E_{k \perp} / B = \text{constant}$$

$$E_{k \perp}(\text{center}) = E_{k \perp}(\text{source}) \left( B_{\text{min}} / B_{\text{max}} \right)$$

Since $E_e = E_{k \perp} + E_{k \parallel} = \text{constant}$

**Efficient collimation effect in the center.**

The retarding electric field at the center has maximum potential $U_0$ and admits electrons with

$$E_{k \parallel} > eU_0$$

Integral spectrometer

**Resolving power:**

$$\frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}} \approx 2 \times 10^{-4}$$

$\Delta E \approx 4 \text{ eV at } E \approx 18 \text{ keV}$
Experiments with MAC electrostatic spectrometers

In the 90’s two experiments based on the same principle improved limit on neutrino mass down to about 2 eV at 95% c.l. Both experiments have reached their final sensitivity.

Troitsk (Russia)
- gaseous $^3$He source
- unexplained anomaly close to the end point

Mainz (Germany)
- frozen $^3$He source
- complicated systematic in the source solved

collaborations has joined + other institutions (large international collaboration)

KATRIN
KArlsruhe TRItium Neutrino experiment
new generation experiment aiming at a further factor 10 improvement in sensitivity
Mainz experiment: the results

Mainz experiment: the results

Final experimental sensitivity reached

Clear improvement in signal-to-background ratio from 1994 set-up to 1998-2001 set-up

To reduce systematic uncertainties, only the final 70 eV are used

Similar results from Troitzk, but anomaly at the end-point (unknown peak of variable position and intensity)

results obtained after a difficult struggle against subtle systematic effects

\[ \langle M_\beta \rangle^2 = -0.6 \pm 2.2 \pm 2.1 \text{ eV}^2 \quad \langle M_\beta \rangle < 2.3 \text{ eV} \text{ (95\% c.l.)} \]
Next generation of MAC spectrometer: the KATRIN proposal

Goal: to reach sub-eV sensitivity on $\langle M_\beta \rangle$

Strategy
- better energy resolution $\Rightarrow \Delta E_{FW} \sim 1$ eV
- higher statistic $\Rightarrow$ stronger $T_2$ source – longer measuring times
- better systematic control $\Rightarrow$ in particular, improve background rejection

Better detectors:
- higher energy resolution
- time resolution (TOF)
- source imaging

Double source control of systematic
Pre-spectrometer selects electrons with E>Q-100 eV ($10^{-7}$ of the total)

Main spectrometer
- high resolution
- ultra-high vacuum ($p<10^{-11}$ mbar)
- high luminosity

KATRIN design report
Jan 2005
KATRIN sensitivity

sensitivity
\( \langle M_\beta \rangle < 0.2 \text{ eV (90\% c.l.)} \)

discovery potential
\( \langle M_\beta \rangle = 0.35 \text{ eV @ 5\sigma} \)

first tritium runs: mid 2009
The calorimetric approach to the measurement of the neutrino mass

Calorimeters measure the entire spectrum at once
- use low Q beta decaying isotopes to achieve enough statistic close to Q
- best choice: $^{187}\text{Re} - Q = 2.47 \text{ keV}$ - 1 mg of natural Re ⇒ ~ 1 Bq

event frac. in the last 10 eV: $1.3 \times 10^{-7}$ vs. $3 \times 10^{-10}$ for T beta spectrum

Advantages of calorimetry
- no backscattering
- no energy loss in the source
- no excited final state problem
- no solid state excitation

Drawbacks of calorimetry
- systematic induced by pile-up effects
- energy dependent background

\[(dN/dE)_{\text{exp}} = [(dN/dE)_{\text{theo}} + A \tau (dN/dE)_{\text{theo}} \otimes (dN/dE)_{\text{theo}}] \otimes R(E)\]

generates “background” at the end-point
Bolometric detectors of particles: basic concepts

- Temperature signal: $\Delta T = E/C \approx 1 \text{ mK}$ for $E = 2.5 \text{ keV}$
- Bias: $I \approx 0.5 \text{ nA} \Rightarrow$ Joule power $\approx 0.4 \text{ pW} \Rightarrow$ Temperature rise $\approx 20 \text{ mK}$
- Voltage signal: $\Delta V = I \times dR/dT \times \Delta T \Rightarrow \Delta V \approx 30 \mu\text{V}$ for $E = 2.5 \text{ keV}$
- Signal recovery time: $\tau = C/G \approx 20 \text{ ms}$
- Noise over signal bandwidth ($\approx 1 \text{ kHz}$): $V_{\text{rms}} = 0.2 \mu\text{V}$

Energy resolution $\approx 10 \text{ eV}$
MIBETA (Milano/Como) experiment: the detectors

Energy absorbers
- AgReO$_4$ single crystals
- $^{187}$Re activity $\approx 0.54$ Hz/mg
- $M \approx 0.25$ mg $\Rightarrow A \approx 0.13$ mHz

Thermistors
- Si-implanted thermistors
- high sensitivity
- many parameters to play with
- high reproducibility $\Rightarrow$ array
- possibility of $\mu$-machining

typically, array of 10 detectors
lower pile up & higher statistics
MIBETA experiment: the Kurie - plot

total Kurie – plot

$5 \times 10^6$ $^{187}$Re decays above 700 eV
MIBETA experiment: the neutrino mass

\[ \langle M_\beta \rangle^2 = -141 \pm 211^{\text{stat}} \pm 90^{\text{sys}} \text{ eV}^2 \] (preliminary)

\[ \langle M_\beta \rangle < 15.6 \text{ eV} \] (90\% c.l.)

Fit parameters

- single gaussian: \( \Delta E_{\text{FWHM}} = 27.8 \text{ eV} \)
- fitting interval: 0.8 – 3.5 keV
- free constant background: 6 \times 10^{-3} \text{ c/keV/h}
- free pile-up fraction: 1.7 \times 10^{-4}

similar results obtained by the MANU experiment (Genoa)
The future of bolometric experiments

MARE
Microcalorimeter Arrays for a Rhenium Experiment

A next-generation calorimetric determination of the neutrino mass through the study of the $^{187}$Re beta spectrum

INFN, Milano, Italy
University of Milano-Bicocca, Department of Physics, Milano, Italy
University of Insubria, Department of Physics and Mathematics, Como, Italy
University of Genoa, Department of Physics, and INFN, Genoa, Italy
ITC-irst, Trento, Italy
University of Heidelberg, Germany
Goddard Space Flight Center, NASA, Maryland, USA
University of Wisconsin, Madison, WI, USA

proposal in preparation for an expansion of the Re experiment
The future of bolometric experiments: MARE

General strategy: push up bolometric technology in order to:
- multiplicate number of channels
- improve energy resolution
- decrease rise-time

goal: reach 2 eV sensitivity

Montecarlo input parameters | 90% CL sensitivity | Possible experimental configurations
---|---|---
$N_{ev}$ [$\times10^9$] | $f_{pile-up}$ [$\times10^{-5}$] | $\Delta E$ [eV] | $m_\nu$ [eV] | $N_{det}$ | $t_M$ [y] | $\langle A_\beta \rangle$ [dec/s] | $\langle \Delta t \rangle$ [$\mu$s]
1.4 | 2.0 | 10 | 3.5 | 100 | 2 | 0.20 | 100
3.2 | 2.5 | 10 | 3.0 | 200 | 2 | 0.25 | 100
4.7 | 2.5 | 10 | 2.5 | 200 | 3 | 0.25 | 100

simulations I phase
The future in bolometric experiments: MARE

Simulations II phase

Goal: reach 0.2 eV sensitivity

Graph

- Sensitivity at 90% c.l. [eV]
- Measurement live time [y]

10,000 detectors deployed per year

50,000 channels in 5 y

ΔE(eV), τ_R(μs), A(Hz)

- (2.5, 2, 5)
- (5.0, 5, 20)
- (5.0, 1, 10)
- (2.5, 1, 10)
DOUBLE BETA DECAY
Decay modes for Double Beta Decay

Two decay modes are usually discussed:

1. \((A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e\)

   - 2ν Double Beta Decay (allowed by the Standard Model)
   - already observed \(- \tau \geq 10^{19} \text{ y}\)

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

   - neutrinoless Double Beta Decay (0ν-DBD)
   - never observed (except a discussed claim) \(\tau > 10^{25} \text{ y}\)

Process 2 would imply new physics beyond the Standard Model.

It is a very sensitive test to new physics since the phase space term is much larger for the neutrinoless process than for the standard one.

Interest for 0ν-DBD lasts for 65 years!

Goeppert-Meyer proposed the standard process in 1935
Racah proposed the neutrinoless process in 1937
**Neutrino properties and 0ν-DBD**

- **IF neutrinos are massive **DIRAC** particles:**
  - Helicities can be accommodated thanks to the **finite mass**, **BUT** Lepton number is rigorously conserved

- **IF neutrinos are massive **MAJORANA** particles:**
  - Helicities can be accommodated thanks to the **finite mass**, **AND** Lepton number is not relevant

---

- A LH neutrino \((L=-1)\) is absorbed at this vertex
- A RH antineutrino \((L=1)\) is emitted at this vertex

---

**Observation of 0ν-DBD**

\(m_\nu \neq 0\)

\(\bar{\nu} \equiv \nu\)
0\nu-DBD and neutrino flavor oscillations

how 0\nu-DBD is connected to neutrino mixing matrix and masses

\[ \frac{1}{\tau} = G(Q,Z) |M_{\text{nucl}}|^2 \langle M_{\beta\beta} \rangle^2 \]

\[ \langle M_{\beta\beta} \rangle = \left| U_{e1} \right|^2 M_1 + e^{i\alpha_1} \left| U_{e2} \right|^2 M_2 + e^{i\alpha_2} \left| U_{e3} \right|^2 M_3 \]

can be of the order of \( \sim 50 \) meV in case of inverted hierarchy
The problem of nuclear matrix elements

Large systematics introduced by nuclear physics in the calculation of $|M_{\text{nucl}}|^2$

**lifetimes** foreseen by different nuclear models for $\langle M_{\beta\beta} \rangle = 50$ meV

Unit: $10^{26}$ year $\Rightarrow$ in the best cases, 1 decay / year / 100 moles!

<table>
<thead>
<tr>
<th>nuclide</th>
<th>nuclear models</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>6.8 70.8 56.0 9.3 12.8 14.4</td>
</tr>
<tr>
<td>$^{130}\text{Te}$</td>
<td>0.6 23.2 2.8 2.0 3.6 3.4</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>4.0 5.1 1.2 15.6</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$</td>
<td>0.1 0.2</td>
</tr>
</tbody>
</table>
The shape of the two electron sum energy spectrum enables to distinguish among the three different discussed decay modes.
Experimental approaches to direct searches

Two approaches for the detection of the two electrons:

1. Source = Detector
   (calorimetric technique)
   - scintillation
   - cryogenic macrocalorimeters (bolometers)
   - solid-state devices
   - gaseous detectors
   high energy resolution

2. Source ≠ Detector
   - scintillation
   - gaseous TPC
   - gaseous drift chamber
   - magnetic field and TOF
   event reconstruction
Experimental sensitivity to 0ν-DBD

**sensitivity F**: lifetime corresponding to the minimum detectable number of events over background at a given (1σ) confidence level.

\[ F \propto \left( \frac{MT}{b \Delta E} \right)^{1/2} \]

- Source mass
- Live time
- Energy resolution
- Background level

**b**: specific background coefficient [counts/(keV kg y)]

- \( b \neq 0 \)
- \( b = 0 \)

Importance of the nuclide choice (but large uncertainty due to nuclear physics)

\[ F \propto MT \]

\[ \left\langle M_{\beta\beta} \right\rangle \propto \left( \frac{F/Q}{|M_{\text{nucl}}|^2} \right)^{1/2} \]

\[ \propto \frac{1}{Q^{1/2}} \left( \frac{b \Delta E}{MT} \right)^{1/4} \left( \frac{M_{\text{nucl}}}{MT} \right) \]
Present experimental situation in the search for 0ν-DBD

I will give some details about three presently most sensitive experiments:

- **Heidelberg – Moscow (HM) (Gran Sasso)**
  the most sensitive DBD experiment since 10 years *(stopped in May 03)*

- **NEMO3 (Modane)**
  it is an intermediate generation experiment capable to study different candidate nuclides and to improve the HM results *(running)*

- **CUORICINO (Gran Sasso)**
  it is an intermediate generation experiment with the potential to improve the HM result *(running)*
  it is also a prelude to a new generation experiment, **CUORE (Cryogenic Underground Observatory for Rare Events)**,
The Heidelberg Moscow experiment

Source = detector
Well established technology of Ge diodes

- Five Ge diodes for an overall mass of 10.9 kg isotopically enriched (86%) in $^{76}$Ge
- Underground operation in the Gran Sasso laboratory (Italy)
- Lead box and nitrogen flushing of the detectors
- Digital Pulse Shape Analysis (PSA) (factor 5 reduction)

$7.6 \times 10^{25} \ ^{76}\text{Ge}$ nuclei

This technique has been dominating the field for decades and is still one of the most promising for the future.

E. Fiorini – 60s

Background in the region of DBD:

$b = 0.17 \text{ counts/(keV kg y)}$

$\langle M_{\beta\beta} \rangle < 0.3 - 2.5 \text{ eV}$

similar results obtained by IGEX experiment
Suddenly, in December 2001, 4 authors (KDHK) of the HM collaboration announce the discovery of neutrinoless DBD

KDHK claim: \( m_{ee} = 0.11 - 0.56 \text{ eV} \) (0.39 eV b.v.)

\( \tau_{1/2}^{0\nu} (y) = (0.8 - 18.3) \times 10^{25} \text{ y} \) (1 \( \times 10^{25} \text{ y b.v.})

(95 \% c.l.)


later, the authors widen the allowed range for \( m_{ee} \) to account for nuclear matrix element uncertainty:

\[ \langle M_{\beta\beta} \rangle = 0.05 - 0.84 \text{ eV (95\% c.l.)} \]

immediate skepticism in DBD community


Klapdor-Kleingrothaus HV hep-ph/0205228
H.L. Harney, hep-ph/0205293

Comments and reanalysis of HD-M data

Independent replies to the Comments
Recent new papers about claim of evidence

With respect to the 2001 results, now data with higher statistics and with better quality show an increase of the statistical significance of the “peak”:

- **2001**: 54.98 kg\(\cdot\)y 2.2 \(\sigma\)
- **2004**: 71.7 kg\(\cdot\)y 4.2 \(\sigma\)
Recent new papers about claim of evidence

Many background features are still to explain

Looking at a larger range, many structures resemble the DBD “peak” and need to be explained

The statistical significance depends on the flat component of the background

Strumia-Vissani hep-ph/0503246
Source ≠ detector

Well established technologies in particle detection:
- tracking volume with Geiger cells
- plastic scintillators
- magnetic field

- Different sources in form of foil can be used simultaneously
- Underground operation in the Frejus laboratory (France)
- Water and iron shields

4.1 \times 10^{25} ^{100}\text{Mo} nuclei

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Study</th>
<th>Mass(g)</th>
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<tr>
<td>^{82}\text{Se}</td>
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<tr>
<td>^{48}\text{Ca}</td>
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</table>

The most sophisticated DBD detector with external source

1 SOURCE
2 TRACKING VOLUME
3 CALORIMETER

detector scheme
NEMO3

Beautiful results on $^{100}$Mo and on other nuclides

$\tau_{1/2}^{2\nu}(y) = 7.8 \pm 0.09_{\text{stat}} \pm 0.8_{\text{syst}} \times 10^{18} \text{ y}$

$\tau_{1/2}^{0\nu}(y) > 3.5 \times 10^{23} \text{ y}$

$\langle M_{\beta\beta} \rangle < 0.7 - 1.2 \text{ eV}$

intrinsic limits:
- source strength
- low energy resolution $\Rightarrow 2\nu$ background

2ν spectrum

final sensitivity: $0.2 - 0.35 \text{ eV}$
Nuclide under study: $^{130}\text{Te}$

CUORICINO source

\[ 5.2 \times 10^{25} \, ^{130}\text{Te} \text{ nuclei} \]

The bolometric technique for the study of DBD was proposed by E. Fiorini and T.O. Niinikoski in 1983

The bolometric technique for the study of DBD was proposed by E. Fiorini and T.O. Niinikoski in 1983.

Source = detector

Bolometric technique:
young (born in ~ 1985) but now firmly established

\[ \Delta T = \frac{E}{C} \]

thanks to a proper thermometer,

\[ \Delta T \Rightarrow \Delta V \]

In order to get low specific heat, the temperature must be very low (5 – 10 mK)

Typical signal sizes: 0.1 mK / MeV, converted to about 1 mV / MeV
CUORICINO = tower of 13 modules,
11 modules x 4 detector (790 g) each
2 modules x 9 detector (340 g) each

M = ~ 41 kg
Underground operation in the Gran Sasso laboratory (Italy)
CUORICINO modules

single TeO$_2$ crystal
- 790 g
- 5 x 5 x 5 cm

thermometer (doped Ge chip)
CUORICINO results and sensitivity

Anticoincidence background spectrum 5.0 kg y
Background level 0.18 ±0.02 c/keV/kg/y

\[ \tau_{1/2}^{0\nu} (y) > 1.8 \times 10^{24} \text{ y} \]
\[ \langle M_{\beta\beta} \rangle < 0.2 - 1.1 \text{ eV (90\% c.l.)} \]

3 y sensitivity (with present performance):
\[ 1 \times 10^{25} \text{ y} \]
\[ \langle M_{\beta\beta} \rangle < 0.13 - 0.31 \text{ eV} \]

Powerful test of KDHK
The future: a great number of proposed experiments

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Isotopes</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>COBRA</td>
<td>$^{130}$Te</td>
<td>10 kg CdTe semiconductors</td>
</tr>
<tr>
<td>DCBA</td>
<td>$^{150}$Nd</td>
<td>20 kg Nd layers between tracking chambers</td>
</tr>
<tr>
<td>CAMEO</td>
<td>$^{114}$Cd</td>
<td>1 t CdWO$_4$ crystals</td>
</tr>
<tr>
<td>CANDLES</td>
<td>$^{48}$Ca</td>
<td>Several tons CaF$_2$ crystals in liquid scint.</td>
</tr>
<tr>
<td>CUORE</td>
<td>$^{130}$Te</td>
<td>750 kg TeO$_2$ bolometers</td>
</tr>
<tr>
<td>EXO</td>
<td>$^{136}$Xe</td>
<td>1 ton Xe TPC (gas or liquid)</td>
</tr>
<tr>
<td>GEM</td>
<td>$^{76}$Ge</td>
<td>1 ton Ge diodes in liquid nitrogen</td>
</tr>
<tr>
<td>GENIUS</td>
<td>$^{76}$Ge</td>
<td>1 ton Ge diodes in liquid nitrogen</td>
</tr>
<tr>
<td>LNGS-Loi 35/04</td>
<td>$^{76}$Ge</td>
<td>1 ton Ge diodes in liquid nitrogen/argon</td>
</tr>
<tr>
<td>GSO</td>
<td>$^{160}$Gd</td>
<td>2 t Gd$_2$SiO$_5$:Ce crystal scint. in liquid scint.</td>
</tr>
<tr>
<td>Majorana</td>
<td>$^{76}$Ge</td>
<td>500 kg Ge diodes</td>
</tr>
<tr>
<td>MOON</td>
<td>$^{100}$Mo</td>
<td>Mo sheets between plastic scint., or liq. scint.</td>
</tr>
<tr>
<td>Xe</td>
<td>$^{136}$Xe</td>
<td>1.56 t of Xe in liq. Scint.</td>
</tr>
<tr>
<td>XMASS</td>
<td>$^{136}$Xe</td>
<td>10 t of liquid Xe</td>
</tr>
</tbody>
</table>
Potential large-mass (~1 ton) future experiments

More promising projects (attack the 50 meV mass scale):

GERDA
SUPERNEMO
CUORE
EXO
MAJORANA

Europe
Europe + US
US

In Europe, joint effort on common problems

IDEA project – Integrated Double-beta-decay European Activities
funded by the European Commission inside a large astroparticle physics program
New $^{76}$Ge experiment. Basic points:

- Collect all the existing $^{76}$Ge material (HM+IGEX) $\Rightarrow$ ~20 kg (+ 30 kg new) (collaboration with Kurchatov)
- Operate it in liquid nitrogen, which acts as a coolant and as a passive shielding (+ traditional shielding)
- Replace possibly liquid nitrogen with scintillating liquid argon (active shield)
- Acquire the 20 kg enriched material in a 0 background set-up

  ▪ powerful intermediate experiment
  ▪ test KDHK evidence with the same nuclides (lifetime sensitivity: $3 \times 10^{25}$ y)
- Procurement of further enriched material $\Rightarrow$ final ~ 1 ton experiment

$\langle M_{\beta\beta} \rangle < 20 - 50$ meV
GERDA: Baseline design

- Clean room lock
- Water tank / buffer / muon veto
- Vacuum insulated copper vessel
- Liquid N / Ar
- Ge Array
CUORE = closely packed array of 988 detectors
19 towers - 13 modules/tower - 4 detectors/module
M \sim 750 \text{ kg}

Compact structure, ideal for active shielding

Each tower is a CUORICINO-like detector

Special dilution refrigerator
**CUORE background and sensitivity**

Monte Carlo simulations of the background show that

\[ b = 0.001 \text{ counts}/(\text{keV} \; \text{kg} \; \text{y}) \]

is possible with the present bulk contamination of detector materials.

The problem is the **surface background** (alpha, beta energy-degraded)

it must be reduced by a factor 10 – 100

work in progress!

---

5 y sensitivity with **pessimistic** background:

\[ b = 0.01 \text{ counts}/(\text{keV} \; \text{kg} \; \text{y}) \]

\[ F^0_{\nu} = 9.4 \times 10^{25} \times (T \; [\text{y}])^{1/2} \]

\[ \langle M_{\beta\beta} \rangle < 20 - 100 \text{ meV} \]

enriched CUORE

5 y sensitivity with **optimistic** background:

\[ b = 0.001 \text{ counts}/(\text{keV} \; \text{kg} \; \text{y}) \]

\[ F^0_{\nu} = 2.9 \times 10^{26} \times (T \; [\text{y}])^{1/2} \]

\[ \langle M_{\beta\beta} \rangle < 10 - 50 \text{ meV} \]

\[ \langle M_{\beta\beta} \rangle < 7 - 38 \text{ meV} \]
Conclusions

Exciting times for neutrino masses:

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