Direct measurements of neutrino masses

$\beta$ decays: neutrino mass modify the electron spectrum shape close to the endpoint $E_0$.

Da E. Fermi, "Vershuch einer Theorie der beta-Strahlen", Z.Phys.88, 161-77 (1934)

A very tiny effect
Electron spectrum:

\[ \frac{dN}{dE} = G_F^2 \frac{m_e^5 c^4}{2\pi^3 \hbar^7} \cos^2(\theta_C) |M|^2 F(Z, E)pE(E_\circ - E)[(E_\circ - E)^2 - m_\nu^2]^{1/2} \]

- max electron energy: \( E_{e}^{Max} = E_\circ - m_\nu = M_s - M_e - m_\nu \)
- \( M_s, M_e \): atomic mass (start, end of the process)
- \( F(Z, E) \): Coulomb correction
- Neutrino mass effects visible only close to \( E_\circ \).
- Decay rate in a region \( \Delta E \) close to \( E_\circ \) depends from \( Q = E_\circ - m_e \) and \( \propto (\Delta E/Q)^3 \).

Good nuclei candidates must have small Q and a high decay rate (lifetime “short”).

**Best candidate:** Tritium:

\[ ^3H \rightarrow ^3He + e^- + \bar{\nu}_e \]

\( E_\circ \simeq 18.6 \text{ KeV} \)

Fraction of useful decays: \( \sim 10^{-10} \).
Experimental progress of neutrino mass limits

![Graph showing the experimental progress of neutrino mass limits over time.](image-url)
Magnetic Adiabatic Collimation + Electrostatic Filter (MAC-E-Filter)

Electron kinetic energy in the solenoid:

\[ T = \frac{1}{2}mv^2 = \frac{1}{2}mv_{\perp}^2 + \frac{1}{2}v_z^2 = T_{\perp} + T_z = T_0 = \text{cost} \]

\[ v_{\perp} = \omega r, \quad mv_{\perp}r = \text{cost} \Rightarrow \]

\[ T_{\perp} = \frac{1}{2}mv_{\perp}^2 = \frac{1}{2}mv_{\perp}r\omega \propto B \]

\[ B_1 = \frac{B_0}{5000} (\sim 1.7 \times 10^{-3}T) \Rightarrow T_{\perp}(B_1) = \frac{T_{\perp}(B_0)}{5000} \]

\Rightarrow \text{In the smallest } B_T \text{ region the trajectory is almost longitudinal}

\Rightarrow \text{Applying an electrostatic potential } -U_0: \text{ electrons transit if}

\[ T_z(B_1) = T_0 - 2 \times 10^{-4}T_{\perp}(B_0) \geq eU_0 (= T_{\text{min}}) \]
\[ T_z(B_1) = T_0 - 2 \times 10^{-4} T_{\perp}(B_0) \geq eU_0 (= T_{\text{min}}) \]

\[ T \geq T_{\text{min}} (1 - 2 \times 10^{-4}) \]

\[ \Delta T = 2 \times 10^{-4} T_{\text{min}} \]

For \( T_{\text{min}} = 18.6 \text{ KeV} \) detector resolution is \( \Delta T \simeq 3.7 \text{ eV} \).

- Excellent energy resolution
- Large geometrical acceptance: great luminosity.
- INTEGRAL spectrometer: no direct spectral information.
The negative mass square problem

The first data of the two most sensitive experiments: Mainz and Troitsk, showed a count excess close to the end point: \( \Rightarrow \) fit to a negative \( m_\nu^2 \).

To solve the problem:

- Add additional arbitrary parameters to the fit
- Invoke new exotic physics to explain the problem
- Fix the experimental problem

*Particle Data Book 1998*: “...Unexpected effects have resulted in significantly negative \( m_\nu \) in the new, precise tritium beta decay experiments. It is felt that a real neutrino mass as large as 10-15 eV would cause observable spectral distortions even in the presence of the end-point count excess.
Mainz: (final) neutrino mass results 1998-2001

detailed investigations of systematic effects

- Roughening transition of $T_2$ film avoided by keeping film $T < 2K$
  

- Inelastic scattering in $T_2$ film
determination of cross section and energy loss function
  

- Self charging of $T_2$ film
determination of critical field
  

- New: neighbour excitation amplitude fitted with data
  agrees with calculations

M. Mezzetto, Lezioni Dottorato Ricerca 2008
Mainz: neutrino mass limits

final $\nu$-mass analysis from 1998-2001 measurements

(119 days, 6 runs: Q5-8,Q11,Q12)

1998/99 : 15 weeks
2001: 5.5 weeks

Signal: x5 improved
Background: x2 reduced
S/B ratio: x10 improved

detailed investigations:

improvements for many systematic effects
Katrin Experiment (Karlsruhe, start in 2008)

Present Mainz Setup:

Improve $m_\nu$ sensitivity by one order of magnitude (2 eV → 0.2 eV) ⇒ two orders of magnitude on $m_\nu^2$ (4 ev$^2$ → 0.04 eV$^2$)

PROBLEM: endpoint count rate falls very rapidly ($\propto \delta E^3$)

- Improve statistics: more powerful tritium source ($\times 80$) and longer running time (100 days → 1000 days)
- Improve energy resolution: Large electrostatic spectrometer with $\delta E = 1$ eV ($\times 4$)
- Better control of systematics: two independent tritium sources (molecular and gaseous), decrease energy losses by one order of magnitudes.
The KArlsruhe TRItium Neutrino Experiment

Klaus Eitel, Forschungszentrum Karlsruhe

A different approach: microbolometers

Measure total decay energy with (micro)bolometers instead that electron momentum with spectrometers

Good: No problem with nuclei final states: the whole energy is measured
Completely different systematic effects (no backscattering, energy losses in the source, solid state excitations …)
Only limit on detector mass: how many microbolometers can be assembled

Bad: Slow detectors sensitive to all the decays ⇒ pile-up problems
Energy dependent backgrounds
Worse resolution
Calibration and stability of all the detectors

Microbolometers array, each sensor is $\sim 500 \mu g$
Very low $Q$ material: Rhenium ($Q=2460$ eV, $\tau_{1/2} = 4.3 \cdot 10^{10}$ years).
Milano $\mu$-calorimeters for $^{187}\text{Re}$ $\beta$ decay study

Neutrino mass measurement with arrays of 10 AgReO$_4$ $\mu$-calorimeters.

- lower pile-up
- higher statistics

Absorbers
AgReO$_4$ single crystals
$^{187}\text{Re}$ fraction $\sim$0.32
$A_\beta \approx 5.4 \times 10^{-4}$ Hz/µg
Mass 250 $\sim$ 300 µg
6.2 \cdot 10^6 \^{187}Re \text{ decays above } 700 \text{ eV} \\
8751 \text{ hours mg (of AgReO}_4\text{)}

Fit with the following free parameters:

1. $\beta$ end - point.
2. $m_\nu^2$
3. spectrum normalization
4. pile-up normalization
5. background rate

\begin{align*}
\text{RESULTS} \\
Q &= 2465.3 \pm 0.5_{\text{stat}} \pm 1.6_{\text{sys}} \text{ eV} \\
\tau_{1/2} &= 43.2 \pm 0.2_{\text{stat}} \pm 0.1_{\text{sys}} \text{ Gy} \\
m_\nu^2 &= -112 \pm 207_{\text{stat}} \pm 90_{\text{sys}} \text{ eV}^2 \\
m_\nu &= 15 \text{ eV (90\% CL)}
\end{align*}
**MANU-2: sensitivity**

- **Calorimeter c#28 c#31 c#35 c#55**
  - $R_{\text{Re}}$ (g) 310 210 215 215
  - $C_{\text{Re}}$ (pJ/K) 3.3 0.75 0.5 0.5
  - $C_{\text{sensor}}$ (pJ/K) 3.6 1.8 1.8 0.02
  - $R_{\text{sensor}}$ (M) 4.9M 7.8M 6.6M 1
  - $V_{\text{noise}}$ (extim.) (mV) 4.5 5.2 4.7 *
  - Baseline noise (mV) 4.5(.2) 4.0 5.4(.2) 650pA
  - Extim. $E_{\text{eV}}$ FWHM@5.9keV 28.2 82.3 44.7 5.8
  - $E_{\text{eV}}$ FWHM@5.9keV 77.6 44.7 37.6 11

---

**Graphs:**

- **Data 5**
  - 5 eV fwhm, $F(p.p.)=7e-8$
  - 10 eV fwhm - $F(p.p.)=1.4e-7$

- **Energy vs. Counts:**
  - 11 eV FWHM

---

**IFAE, Pavia**

April, 19th, 2006

Flavio Gatti
Proposal MARE, down to 0.2 eV

Sensitivity at 90% c.l. [eV]

0.6
0.5
0.4
0.3
0.2
0.1

0 2 4 6 8 10
Measurement live time [y]

10000 detectors deployed per year

(2.5, 2, 5)
(5.0, 5, 20)
(5.0, 1, 10)
(2.5, 1, 10)
mν in the future

**Spettrometri**

- **1990**: 20 eV
- **1995**: 20-10 eV
- **2000**: 2.2 eV
- **2005**: 2 eV
- **2010**: 0.2 eV

**Calorimetri**

- **Sandro Vitale**: 1985, 187 Re
- **1990**: 26 eV
- **1995**: 15 eV
- **2000**: 20 eV
- **2005**: 2 eV
- **2010**: 0.2 eV
- **2015**: (O. Cremonesi)
Neutrinoless Double Beta Decays

Another way to measure neutrino mass:

\[ \beta\beta_{0\nu} \, (A,Z) \rightarrow (A,Z+2) + e^- + e^- \]

\[
\left( T_{1/2}^{0\nu} \right) = G_{0\nu}^{0\nu}(E_0, Z) |M_{0\nu}^{0\nu} gV^2_{A} M_{F}^{0\nu}|^2 \langle m_{\nu} \rangle^2
\]

To happen it needs:

- Violate by 2 units lepton number conservation \((\Delta L = 2)\)
- Majorana neutrinos: neutrino = antineutrino.
- Massive neutrinos

M. Mezzetto, Lezioni Dottorato Ricerca 2008
Similar processes are allowed:

\[ \beta\beta 2\nu: (A,Z) \rightarrow (A,Z+2) + e^- + e^- + \nu_e^c + \nu_e^c \quad (\Delta L = 0) \]

\[ \left( T^{2\nu}_{1/2} \right) = G^{2\nu}(E_\circ, Z)|M^{2\nu}_{GT}|^2 \]

\[ \beta\beta \chi^0: (A,Z) \rightarrow (A,Z+2) + e^- + e^- + \chi^0 \]

\[ \left( T^{\chi^0}_{1/2} \right) = G^{\chi^0}(E_\circ, Z)|M^{0\nu}_{GT} - \frac{g_Y^2}{g_A^2} M^{0\nu}_{F}|^2 < g_{e\nu}^2 \]

\[ \beta\beta \text{ SUSY: } (A,Z) \rightarrow (A,Z+2) + e^- + e^- \]
Beta and Double Beta mass measurement interplay

$\beta$ and $0\nu2\beta$ observables in terms of the mass eigenstates $m_i$, the mixing angles $\theta_{ij}$ and the Majorana phases $\alpha$ e $\beta$:

\[
m_{\nu e} = \left( \sum_i |V_{ei}|^2 m_i^2 \right)^{1/2} = \left( \cos^2 \theta_{13} (m_1^2 \cos^2 \theta_{12} + m_2^2 \sin^2 \theta_{12}) + m_3^2 \sin^2 \theta_{13} \right)^{1/2}
\]

(1)

\[
|m_{ee}| = \left| \sum_i V_{ei}^2 m_i \right| = \left| \cos^2 \theta_{13} (m_1 \cos^2 \theta_{12} + m_2 e^{2i\alpha} \sin^2 \theta_{12}) + m_3 e^{2i\beta} \sin^2 \theta_{13} \right|.
\]

(2)
\(0\nu\) and \(2\nu\beta\beta\) decays have different electron spectra. Nuclei are needed where:

- Single beta decays are suppressed
- \(0^+ \rightarrow 0^+\) transitions
- Abundant isotopes in nature.

**Experimental merit factor**

\[
T_{1/2}^{0\nu} \propto \frac{a}{A} \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} \cdot \epsilon
\]

- \(a\): isotopic abundance
- \(A\): atomic mass
- \(M\): mass
- \(t\): running time
- \(B\): background rate
- \(\epsilon\): efficiency
- \(\Delta E\): energy resolution

Extremely rare process: \(T_{1/2}^{0\nu} > 10^{24}\) years for \(\langle m_{\nu_e} \rangle = \mathcal{O}(1\, eV)\), \(\Rightarrow\) low noise techniques

- Deep underground experiments
- Very efficient active and passive radiation shields.
Experimental techniques

Geochemical Experiments Look for an abnormal abundance of the nucleus (A,Z+2) produced in geological times by the $\beta\beta$ decay of the nucleus (A,Z).

GOOD $\Rightarrow$ Very long integrated decay time and large samples

BAD $\Rightarrow$ No way to separate neutrinoless and two neutrino decays. Heavy assumptions on the geological history of the sample. Evidence of $\beta\beta$ decays in $^{82}Se$, $^{96}Zr$, $^{128}Te$, $^{130}Te$.

Radiochemical Experiments Store a $\beta\beta$ candidate material. After a while, count the nuclei produced by $\beta\beta$ decays.

Again, impossible to separate neutrinoless $\beta\beta$ from 2 neutrino $\beta\beta$. Successfully used to measured 2 neutrino $\beta\beta$ decays in $^{238}U$ in $^{238}Pu$.

Direct measurements The only way to identify neutrinoless double beta decays. Two possible experimental techniques:

Spectrometers (source $\neq$ detector), a passive source of $\beta\beta$ emitters is embedded within an electron tracker. All the candidate nuclei can be tested but limited experimental resolution.

Calorimeters :source = detector. Limited choice of materials but excellent experimental resolution and reduction of backgrounds.
Big systematic errors in the computation of the nuclear matrix elements ⇒ search the process in different nuclei.

Double beta decays with 2 neutrinos signals are used as a control sample to check the estimations of the nuclei matrices (the process involved has however a completely different set of intermediate states).

\[ T^{0\nu} = S^{0\nu} \langle m_\nu \rangle^2 \]

\( S^{0\nu} \): Nuclear sensitivity = \( G^{0\nu} |M^{0\nu}|^2 \)

\( G^{0\nu} \): Phase space volume \( \propto Q_{\beta\beta}^5 \) ⇒ High z nuclei

\( M^{0\nu} \): Nuclear matrix element
Nuclear Matrix Element Calculations

\[ T^{0\nu}_{1/2} = \frac{1}{\Gamma(Q^{5}_{\beta\beta})} \frac{M^2}{<m_{ee}>^2} \]

- $^{76}$Ge $\rightarrow^{76}$Se \hspace{1cm} Q_{\beta\beta} = 2039 \text{ keV} \hspace{1cm} \text{nat. abund.} = 7.4\%
- $^{100}$Mo $\rightarrow^{100}$Ru \hspace{1cm} Q_{\beta\beta} = 3034 \text{ keV} \hspace{1cm} \text{nat. abund.} = 9.6\%
- $^{130}$Te $\rightarrow^{130}$Xe \hspace{1cm} Q_{\beta\beta} = 2529 \text{ keV} \hspace{1cm} \text{nat. abund.} = 34\%
- $^{136}$Xe $\rightarrow^{136}$Ba \hspace{1cm} Q_{\beta\beta} = 2479 \text{ keV} \hspace{1cm} \text{nat. abund.} = 8.9\%

$T_{1/2}$ for nuclear matrix element calculations

- \( <m_{ee}> = 50 \text{ meV} \)
- truncated shell model
  - Hoxton (1984)
- nuclear shell model
  - Caurier (1999)
- QRPA, schematic \( \delta \) force
  - Vogel (1988)
- QRPA, G–matrix inter.
  - Staudt (1990)
- renormalized QRPA
  - Toivanen (1995)
- QRPA, no p–n pairing
  - Faessler (1996)

Selection of calculations from Elliott & Vogel, hep-ph/0202264

Need more than one isotope to get information about \( <m_{ee}> \)

- 11 kG of enriched (86%) $^{76}\text{Ge}$, in 5 crystals.
- Germanium is both the emitter and the detector.

Background rate: 0.11 counts/KeV/kg/yr
Signal efficiency: $\sim 100\%$
Energy resolution: $\sim 3.5$ keV
Duty cycle: $\sim 80\%$

$T^{0\nu}_{1/2} > 1.3 \cdot 10^{25}$ years ($90\% C.L.$) $\Rightarrow \langle m_\nu \rangle \leq 0.35(0.42) eV$

$T^{2\nu}_{1/2} \approx 1.55 \cdot 10^{21}$ years
Evidence of neutrinoless double beta decays

71.7 Kg yr
\[ T_{1/2}^{0\nu} = (0.69 - 4.18) \times 10^{25} \text{ years} \]
\[ m_\nu = 0.44(0.24 - 0.58) \text{ eV} \]
Significance: 4.2\( \sigma \)
Events in the \( \beta\beta \) peak: 29
Pulse shape analysis of events confined in just one crystal.
Select events compatible with the $\beta\beta$ shape.
The bolometric technique for the study of DBD was proposed by E. Fiorini and T.O. Niinikoski in 1983.

**Source = detector**

**Bolometric technique:**

- 0ν DBD is a factor 5-10 faster than in 76Ge
- A.I.: 34% ⇒ enrichment not necessary

**Nuclide under study: 130Te**

**CUORICINO source**

$$6.4 \times 10^{25} \text{ 130Te nuclei}$$

**Bolometric technique:** the nuclear energy is measured as a temperature increase of a single crystal

$$\Delta T = \frac{E}{C}$$

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
Cryogenic Detectors

Heat bath (~8 mK)

Weak thermal coupling (G~4 pW/mK)

Thermometer (NTD Ge, R~100 MΩ)

Adsorber crystal (TeO₂, C~10⁻⁹ J/K)

Cryodet features
- wide choice of detector materials
- good energy resolution
- true calorimeters
- velocity

ΔT = E/C

Amplitude [a.u.] vs. Time [s]
CUORICINO bolometers

**Absorber crystal**
The absorber is a 5x5x5 cm\(^3\) crystal of TeO\(_2\) which contains the neutrinoless DBD candidate \(^{130}\text{Te}\).

**Temperature sensor**
The thermal signal is measured by means of an NTD Ge Thermistor

\[
R(T) = R_0 \exp \sqrt{\frac{T_0}{T}}
\]
Cuoricino result on $^{130}\text{Te}$ $\beta\beta$–0ν decay

Anticoincidence background spectrum of the 5x5x5 cm$^3$ crystals around the 1ν–0ν region

$\tau_{1/2}^{0\nu} \geq 1.86 \cdot 10^{24}$ y [90% CL]  \quad \Rightarrow \quad \langle m_{\nu} \rangle \leq 0.20 – 1.05$ eV* [90% CL]

* Dependent on the value for the nuclear matrix elements

Total statistic ~ 5.36 kg ($^{130}\text{Te}$) × y

b = 0.18 ± 0.02 c/keV/kg/y

Maximum Likelihood flat background + fit of 2505 peak

M. Mezzetto, Lezioni Dottorato Ricerca 2008
### Cuoricino vs Heidelberg Moscow

<table>
<thead>
<tr>
<th>Parameter</th>
<th>He-Mo</th>
<th>Cuoricino</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{\beta \beta}$ (keV)</td>
<td>2039</td>
<td>2529</td>
</tr>
<tr>
<td>Detector mass (kg)</td>
<td>11</td>
<td>40.7</td>
</tr>
<tr>
<td>Active mass (kg)</td>
<td>9.5</td>
<td>11</td>
</tr>
<tr>
<td>Duty cycle</td>
<td>80%</td>
<td>64%</td>
</tr>
<tr>
<td>Energy resolution (keV)</td>
<td>3.5</td>
<td>8</td>
</tr>
<tr>
<td>Efficiency</td>
<td>100%</td>
<td>85%</td>
</tr>
<tr>
<td>Background rate (counts/kg/keV/yr)</td>
<td>0.11</td>
<td>0.19</td>
</tr>
<tr>
<td>Merit factor</td>
<td>1</td>
<td>0.96</td>
</tr>
</tbody>
</table>
The NEMO3 detector

Fréjus Underground Laboratory : 4800 m.w.e.

Source: 10 kg of $\beta\beta$ isotopes
cyindrical, $S = 20 \text{ m}^2$, $e \sim 60 \text{ mg/cm}^2$

Tracking detector:
drift wire chamber operating
in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H$_2$O

Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs

Magnetic field: 25 Gauss
Gamma shield: Pure Iron ($e = 18 \text{ cm}$)
Neutron shield: 30 cm water (ext. wall)
40 cm wood (top and bottom)
(since march 2004: water - boron)

Able to identify $e^+$, $e^-$, and $\gamma$
decay isotopes in NEMO-3 detector

- $^{100}$Mo 6.914 kg  
  $Q_\beta = 3034$ keV

- $^{82}$Se 0.932 kg  
  $Q_\beta = 2995$ keV

- $^{116}$Cd 405 g  
  $Q_\beta = 2805$ keV

- $^{96}$Zr 9.4 g  
  $Q_\beta = 3350$ keV

- $^{150}$Nd 37.0 g  
  $Q_\beta = 3367$ keV

- $^{48}$Ca 7.0 g  
  $Q_\beta = 4272$ keV

- $^{130}$Te 454 g  
  $Q_\beta = 2529$ keV

- nat$^\text{Te}$ 491 g

- Cu 621 g

(All the enriched isotopes produced in Russia)

Xavier Sarazin for the NEMO-3 Collaboration
M. Mezzetto, Lezioni Dottorato Ricerca 2008

Neutrino 2004 Paris 14-19 June 2004
Nemo 3 results on neutrinoless double beta decays

Phys.Rev.Lett 95, 182302, 2005

\[ T_{1/2}(^{100}\text{Mo}) = 4.6 \cdot 10^{23} \text{ years} \Rightarrow m_{ee} < (0.7 - 2.8) \text{ eV} \]
\[ T_{1/2}(^{82}\text{Se}) = 1.0 \cdot 10^{23} \text{ years} \Rightarrow m_{ee} < (1.7 - 4.9) \text{ eV} \]
## Present experimental situation

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>Experiment</th>
<th>%</th>
<th>Q</th>
<th>Enr</th>
<th>Technique</th>
<th>$0 \ y$</th>
<th>$&lt;m$</th>
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<tbody>
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<td>$^{48}\text{Ca}$</td>
<td>Elegant IV</td>
<td>0.19</td>
<td>4271</td>
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<td>Heidelberg-Moscow</td>
<td>7.8</td>
<td>2039</td>
<td>87</td>
<td>ionization</td>
<td>$&gt;1.9 \times 10^{25}$</td>
<td>12 - 1</td>
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<tr>
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<td>2039</td>
<td>87</td>
<td>Ionization</td>
<td>$&gt;1.6 \times 10^{25}$</td>
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<td>2995</td>
<td>97</td>
<td>tracking</td>
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<td>1.8-4.9</td>
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<td>9.6</td>
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<td>Solotvina</td>
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<td>83</td>
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<td>$&gt;1.7 \times 10^{23}$</td>
<td>1.7 - ?</td>
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<tr>
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<td>Bernatovitz</td>
<td>34</td>
<td>2529</td>
<td></td>
<td>geochem</td>
<td>$&gt;7.7 \times 10^{24}$</td>
<td>1-4</td>
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<tr>
<td>$^{130}\text{Te}$</td>
<td>Cuoricino</td>
<td>33.8</td>
<td>2529</td>
<td></td>
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<td>$&gt;2 \times 10^{24}$</td>
<td>.2-1.</td>
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<td>$^{136}\text{Xe}$</td>
<td>DAMA</td>
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<td>1.1 -2.9</td>
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<td>Irvine</td>
<td>5.6</td>
<td>3367</td>
<td>91</td>
<td>tracking</td>
<td>$&gt;1.2 \times 10^{21}$</td>
<td>3 - ?</td>
</tr>
</tbody>
</table>

E.Fiorini - NOVE 2006
How to improve by one order of magnitude the sensitivity on the neutrino mass?

\[ m_{ee}^2 \propto T_{1/2}^{0\nu} \propto a \sqrt{\frac{M \cdot t}{B \cdot \Delta E}} \]

4 orders of magnitude on \( \frac{M \cdot t}{B \cdot \Delta E} \) are needed (!!!)

**The CUORE way:**

- Factor 20 in mass (\( \sim 1 \) ton) \( \Rightarrow \) Money
- Factor 20 in useful running time (10 years) \( \Rightarrow \) Longevity
- Factor 20 in background rate \( \Rightarrow \) Skill
The **CUORE** project
(approved by the S.C. of Gran Sasso Laboratory and by INFN)

**CUORE** is an array of 988 bolometers grouped in 19 columns with 13 floors of 4 crystals

\[
750 \text{ kg TeO}_2 \Rightarrow 600 \text{ kg Te} \\
\Rightarrow 203 \text{ kg } ^{130}\text{Te}
\]

Crystals are separated by a few mm, only, with little material among them
RAD tests

An array of **8 detectors cleaned** with **ultrapure materials and procedures**

**Copper**
- Etching
- Electro polishing
- Passivation procedure

**Crystals**
- Crystal etching (Nitric acid)
- Lapping with clean powder (2µ SiO₂)
RAD tests results

• Reduction of a factor ~ 4 on crystal surface contaminations
• Reduction of a factor ~ 2 on copper surface contaminations
» new tests are ongoing in GranSasso
IONIZATION

- **goal**: analyse HM evidence in a short time using existing $^{76}\text{Ge}$ enriched detectors (HM, Igex)
- approach similar to GENIUS but less LN2
  - naked Ge crystals in LN2 or LAr
- more compact than GENIUS
  - 1.5 m LN2(LAr) + 10 cm Pb + 2 m water
  - 2-3 orders of magnitude better bkg than present Status-of-the-Art
  - active shielding with LAr scintillation
- 3 phases experiment
- **Phase I**:
  - radioactivity tests
  - $\approx 20$ kg $^{76}\text{Ge}$ from HM and Igex
  - expected bkg 0.01 c/keV/kg/y (intrinsic)
  - check at 5$\sigma$ HM evidence
  - 15 kg$\times$y $6\pm 1$ $\beta\beta$ events on 0.5 bkg events
- **Phase II**:
  - add new enriched segmented detectors with special care for activation
  - expected background $\approx 0.001$ c/keV/kg/y
  - $2\times 10^{26}$ y with 100 kg$\times$y
  - $<m> = 0.09 \div 0.29$ eV
- **Phase III**: $0.01$ eV with 1 ton Ge
  - worldwide collaboration

- Approved by LNGS S.C.
  - site: Hall A northern wing
- funded 40 kg enriched $^{76}\text{Ge}$
  - phase II
- aggressive time schedule
$^{60}$Co background spectrum

![Graph showing $^{60}$Co background spectrum with energy (MeV) on the x-axis and counts/keV on the y-axis. The graph includes peaks at different energies labeled with $\gamma_1$, $\gamma_2$, and $\beta\beta$. The $Q$MC simulation is also indicated.]
$^{60}$Co: suppression by segmentation

Illustration:
Simple 7-fold segmentation

$N_{hit} = 3$

$N_{seg} = 1$

$\sim 10$ (7 seg.)
$^{60}$Co: suppression by Lar-Ge anticoincidence

Liquid Argon

MC simulation

LAr anticoinc.

$\sim 100$

~100
LIETEKE HITRIN. VEENCE. FEBRUARY 10. 2006

ANTI-NEUTRINOS - DIRAC OR MAJORIZATION
## Next generation experiments

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<th>%</th>
<th>Q</th>
<th>% E</th>
<th>B c/y</th>
<th>T (year)</th>
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E.Fiorini - NOVE 2006