THE ROLE OF LOW TEMPERATURE DETECTORS IN NEUTRINO PHYSICS

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Neutrinos are...
Mysteries about Neutrinos

- Why are neutrinos so light?
- Are neutrinos their own anti-particles?
- Is there a fourth neutrino type?
- Are there non-standard interactions?
Current knowledge on neutrino properties

Neutrinos have mass and mix

From oscillation experiments:

\[ |\nu_i\rangle = \sum_k U_{ik} |\nu_k\rangle \]

- 2 mass square differences
- 3 mixing angles
- hints of CPV
- indications in favor of Normal Ordering

\[ \Delta m^2 = (\Delta m_{13}^2 + \Delta m_{23}^2)/2 \]

Capozzi et al., Prog. Part. Nucl. Phys. 102 (2018) 48

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There are at least 3 massive neutrinos

Neutrino masses

\[ |\nu_i\rangle = \sum_k U_{ik} |\nu_k\rangle \]

Neutrino mixing matrix

Neutrino mass eigenstate

Neutrino flavor weak eigenstate

Mass eigenstates: \( \nu_1, \nu_2, \nu_3 \)

Missing puzzle pieces:

- mass scale (i.e. mass of the lightest \( \nu \))
- mass ordering
  - \( m_1 < m_2 \ll m_3 \) or \( m_3 \ll m_1 \approx m_2 \)?
- Dirac or Majorana particle?
- CP violation in the lepton sector
Neutrino mass observables

### Tool
- **Cosmology (CMB only)**
  - Measured quantity: $m_\Sigma \equiv \sum m_i$
  - Sensitivity (eV):
    - Present: 0.6
    - Future: 0.06
    - Yes

- **0ν double beta decay**
  - Measured quantity: $m_{\beta\beta} \equiv |\sum m_i|U_{ei}|^2 e^{i\alpha_e}$
  - Sensitivity (eV):
    - Present: 0.1
    - Future: 0.01
    - Yes

- **Beta decay**
  - Measured quantity: $m_\beta \equiv (\sum m_i^2 |U_{ei}|^2)^{1/2}$
  - Sensitivity (eV):
    - Present: 2
    - Future: 0.2
    - No

### Model dependency
- NO
- IO

(2σ and 3σ)

Capozzi et al., Prog. Part. Nucl. Phys. 102 (2018) 48

Complementarity of informations from experimental observables
Summed mass of active neutrinos have specific effects on Cosmic Microwave Background anisotropies and on Large Scale Structure formation.

95% CL upper bounds on \( \Sigma m_i \) for 7 parameters:

- CMB only: Planck, w/o high-l polarisation and lensing...
  \( \Sigma m_i < 590 \text{ to } 140 \text{ meV (95\% CL)} \)

- CMB + conservative LSS:
  - Planck 2016 \{TT+SIMLlow+lensing\} + BAO:
    \( \Sigma m_i < 170 \text{ meV (95\% CL)} \)
  - Planck 2016 \{TTTEEE+SIMLlow\} + BAO:
    \( \Sigma m_i < 120 \text{ meV (95\% CL)} \)

- Planck 2015 + Lyman-\( \alpha \):
  \( \Sigma m_i < 120 \text{ meV (95\% CL)} \)

[Planck col.] 1605.02985; Cuesta et al. 2016; Palanque-Delabrouille et al. 1506.05976; Vagnozzi et al. 1701.08172; PDG “Neutrino Cosmology” [JL & Verde]

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http://doi.org/10.5281/zenodo.1287028

J. Lesgourgues, Neutrino 2018
Double Beta Decay

second order weak decay of even-even nuclei in $A$ even multiplets

$^{48}$Ca, $^{76}$Ge, $^{100}$Mo, $^{116}$Cd, $^{130}$Te, $^{136}$Xe ...

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

- allowed by the Standard Model
- observed with $\tau_{1/2} > 10^{18}$ years

Neutrinoless Double Beta Decay

$0\nu\beta\beta$: $(A, Z) \rightarrow (A, Z+2) + 2e^-$
- not allowed in Standard Model ($\Delta L=2$)
- expected $\tau_{1/2} > 10^{25}$ years

- The decay occurs only if neutrinos are **Majorana particles**
- The decay rate depends on the “**effective Majorana mass**”

\[ 0\nu\beta\beta \iff m_\nu \neq 0 \]

\[ \nu \equiv \bar{\nu} \]
Neutrinoless Double Beta Decay

$0\nu\beta\beta$: $(A, Z) \rightarrow (A, Z+2) + 2e^-$
- not allowed in Standard Model ($\Delta L=2$)
- expected $\tau_{1/2} > 10^{25}$ years

✔ The decay occurs only if neutrinos are Majorana particles

✔ The decay rate depends on the “effective Majorana mass”

$0\nu\beta\beta$ is a test for Lepton Number Violation at low energy

Lepton Number Violation is a necessary condition for Leptogenesis
(matter – antimatter asymmetry of the Universe)
Neutrinoless Double Beta Decay

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

- not allowed in Standard Model (\(\Delta L=2\))
- expected \(\tau_{1/2} > 10^{25}\) years

✔ The decay occurs only if neutrinos are **Majorana** particles

✔ The decay rate depends on the “**effective Majorana mass**”

**light Majorana** \(\nu\) **mediated** \(\beta\beta-0\nu\) decay rate:

\[
\frac{1}{\tau_{1/2}^{0\nu}} = \frac{|m_{\beta\beta}|^2}{m_e^2} \cdot F_N
\]

- phase space \(G^{0\nu}(Q_{\beta\beta}, Z) \propto Q_{\beta\beta}^5\) can be calculated with reasonable accuracy
- matrix element \(|M^{0\nu}|\) contains details of nuclear physics \(\rightarrow\) source of uncertainties (a factor \(\approx 3\))

\(0\nu\beta\beta \iff m_\nu \neq 0\)
0νββ experimental sensitivity

\[
S^{0\nu}(\tau_{1/2}) \propto \epsilon \cdot \frac{\eta}{A} \sqrt{\frac{M \cdot t_{\text{meas}}}{\Delta E \cdot bkg}} \quad bkg \neq 0
\]

- \(\epsilon\) detector efficiency
- \(\eta\) 0νββ isotope abundance
- \(A\) atomic mass
- \(bkg\) background @ ROI in counts/keV/kg/y
- \(M\) total active mass
- \(t_{\text{meas}}\) measuring time
- \(\Delta E\) FWHM resolution

For \(bkg = 0\):

\[
S^{0\nu}(\tau_{1/2}) \propto \frac{\epsilon \cdot \eta}{A} M \cdot t_{\text{meas}}
\]

\[
m_{\beta\beta} \propto \sqrt{\frac{1}{\tau_{1/2}^{0\nu}}}
\]
# 0νββ experimental sensitivity

\[ S^{0\nu}(\tau_{1/2}) \propto \epsilon \cdot \frac{\eta}{A} \sqrt{\frac{M \cdot t_{\text{meas}}}{\Delta E \cdot bkg}} \quad bkg \neq 0 \]

- **ε** detector efficiency
- **η** 0νββ isotope abundance
- **A** atomic mass
- **M** total active mass
- **t_{meas}** measuring time
- **bkg** background @ ROI in counts/keV/kg/y

For bkg = 0:

\[ S^{0\nu}(\tau_{1/2}) \propto \epsilon \frac{\eta}{A} M t_{\text{meas}} \]

\[ m_{\beta\beta} \propto \sqrt{\frac{1}{\tau^{0\nu}_{1/2}}} \]

## 2ν rate in ROI

### Isotope
- **Q_{ββ} [keV]**
- **η [%]**
- **T^{2\nu}_{1/2} [y]**
- **R_{2ν}(50 keV) [c/y/ton_iso]**
- **R_{0ν}(m_{ββ} = 50 meV) [c/y/ton_iso]**
- **R_{0ν}(m_{ββ} = 10 meV) [c/y/ton_iso]**

<table>
<thead>
<tr>
<th>Isotope</th>
<th>Q_{ββ} [keV]</th>
<th>η [%]</th>
<th>T^{2\nu}_{1/2} [y]</th>
<th>R_{2ν}(50 keV) [c/y/ton_iso]</th>
<th>R_{0ν}(m_{ββ} = 50 meV) [c/y/ton_iso]</th>
<th>R_{0ν}(m_{ββ} = 10 meV) [c/y/ton_iso]</th>
</tr>
</thead>
<tbody>
<tr>
<td>48Ca</td>
<td>4274</td>
<td>0.2</td>
<td>4.4 \times 10^{19}</td>
<td>4.0 \times 10^{-2}</td>
<td>1.4–23.1</td>
<td>0.1–0.9</td>
</tr>
<tr>
<td>76Ge</td>
<td>2039</td>
<td>7.6</td>
<td>1.8 \times 10^{21}</td>
<td>2.5 \times 10^{-2}</td>
<td>1.2–12.2</td>
<td>0.05–0.5</td>
</tr>
<tr>
<td>82Se</td>
<td>2996</td>
<td>8.7</td>
<td>9.2 \times 10^{19}</td>
<td>6.8 \times 10^{-2}</td>
<td>4.4–38.7</td>
<td>0.2–1.5</td>
</tr>
<tr>
<td>96Zr</td>
<td>3348</td>
<td>2.8</td>
<td>2.3 \times 10^{19}</td>
<td>1.3 \times 10^{-1}</td>
<td>3.9–50.7</td>
<td>0.2–2.0</td>
</tr>
<tr>
<td>100Mo</td>
<td>3034</td>
<td>9.6</td>
<td>7.1 \times 10^{18}</td>
<td>6.8 \times 10^{-1}</td>
<td>8.9–71.3</td>
<td>0.4–2.9</td>
</tr>
<tr>
<td>116Cd</td>
<td>2814</td>
<td>7.5</td>
<td>2.8 \times 10^{19}</td>
<td>2.1 \times 10^{-1}</td>
<td>6.8–23.8</td>
<td>0.3–1.0</td>
</tr>
<tr>
<td>130Te</td>
<td>2528</td>
<td>34.2</td>
<td>6.8 \times 10^{20}</td>
<td>1.3 \times 10^{-2}</td>
<td>3.6–24.9</td>
<td>0.1–1.0</td>
</tr>
<tr>
<td>136Xe</td>
<td>2458</td>
<td>8.9</td>
<td>2.1 \times 10^{21}</td>
<td>4.8 \times 10^{-3}</td>
<td>2.5–14.0</td>
<td>0.1–0.6</td>
</tr>
<tr>
<td>150Nd</td>
<td>3368</td>
<td>5.6</td>
<td>8.2 \times 10^{18}</td>
<td>2.3 \times 10^{-1}</td>
<td>9.1–42.7</td>
<td>0.4–1.7</td>
</tr>
</tbody>
</table>
0νββ detection techniques “MUSTs”

- Negligible radioactive background
- Large detector mass
- High energy resolution
- Favorable 0νββ candidate (high $Q_{0νββ}$, large $R_{0ν}/R_{2ν}$ in the ROI)
LTDs for $0\nu\beta\beta$ searches

- excellent energy resolution
- true calorimeters
- wide material choice
- low threshold
- high efficiency
- large masses
- radiopure absorbers
- fully sensitive to recoils
- segmentation to reduce background
- double-readout detectors with particle identification capabilities (i.e. $e/\gamma$ - recoil, $e/\gamma$ - $\alpha$)

- slow time responses
- fully sensitive to surface radioactivity
- difficult to reduce close materials (holders, wires, cryostats,...)
- not easy to run stable

Most common thermometer technologies:
- Neutron Transmutation Doped Ge (NTD)
- Transition Edge Sensors (TES)
- Metallic Magnetic Calorimeters (MMC)
- Microwave Kinetic Inductance Det (MKIDs)

Example of double read-out (phonons + scintillation photons)
The CUORE TeO$_2$ thermal detectors

Cryogenic Underground Observatory for Rare Events

TeO$_2$ absorbers + Ge-NTD thermistors:
- $T \sim 10$ mK
- $\Delta T/\Delta E \sim 0.1$ mK/MeV
- $\Delta V/\Delta E \sim 0.3$ mV/MeV
- $\tau = C/G \sim 1$ s
- $C \sim 2 \times 10^{-9}$ J/K
- FWHM $\sim 0.2$ %

$^{130}$Te as $\beta\beta$0v candidate
- high natural isotopic abundance: 34.2 %
- transition energy: $Q = 2527.52$ keV

$\text{TeO}_2$ Absorbers
- low specific heat
- large crystals available
- radiopure

Ge-NTD thermistors
- high dynamic range
- high linearity
- microphonic
- slow

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- $C \sim 2 \times 10^{-9}$ J/K
- FWHM $\sim 0.2\%$

High energy resolution

Radiopurity of close materials
- strict control of the contamination content of Cu, PTFE, Ge-NTDs, Si heaters, PEN wires and TeO$_2$ crystals themselves
CUORE is the latest evolution of a long series of TeO$_2$ detector arrays.

CUORE projected sensitivity (5 years): $S^{0\nu}(\tau_{1/2}) = 9 \times 10^{25}$ y (90% C.L.)
CUORE first results

CUORE cryogenic system: the most powerful cryostat ever commissioned

Background Index is consistent with expectations:
BI ~ 10^{-2} counts/keV/kg/y


CUORE count rate in the ROI is dominated by surface contaminations (alpha background)
CUORE first results

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CUORE cryogenic system:
the most powerful cryostat ever commissioned

CUORE count rate in the ROI
is dominated by surface contaminations
(alpha background)
CUORE Upgrade with Particle IDentification

- Scintillating crystals and light detectors operated @ 10mK
- Absorbers may be grown from various $\beta\beta$ emitters
- Availability of isotopes with $Q_{\beta\beta}$ in the $\gamma$-free region ($^{82}\text{Se}$, $^{100}\text{Mo}$)
- Excellent energy resolution at $Q_{\beta\beta}$ (< 1%)
- Particle ID capability in the heat and light channels
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<table>
<thead>
<tr>
<th>Nucleus</th>
<th>A.I.</th>
<th>Q-value</th>
<th>Good materials</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>7.8</td>
<td>2039</td>
<td>Ge</td>
</tr>
<tr>
<td>$^{130}\text{Te}$</td>
<td>33.8</td>
<td>2527</td>
<td>TeO2</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>7.5</td>
<td>2802</td>
<td>CdWO4, CdMoO4</td>
</tr>
<tr>
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<td>9.2</td>
<td>2995</td>
<td>ZnSe</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>9.6</td>
<td>3034</td>
<td>PbMoO4, CaMoO4, SrMoO4, CdMoO4, ZnMoO4, Li2MoO4, MgMoO4</td>
</tr>
<tr>
<td>$^{96}\text{Zr}$</td>
<td>2.8</td>
<td>3350</td>
<td>ZrO2</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$</td>
<td>5.6</td>
<td>3367</td>
<td>NONE</td>
</tr>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>0.187</td>
<td>4270</td>
<td>CaF2, CaMoO4</td>
</tr>
</tbody>
</table>
CUPID: the present ...

CUORICINO

- Scintillating crystals and light detectors operated @ 10mK
- Absorbers may be grown from various ββ emitters
- Availability of isotopes with Qββ in the γ-free region (82Se, 100Mo)
- Excellent energy resolution at Qββ (< 1%)
- Particle ID capability in the heat and light channels

*possible only with LTDs*

CUPID-0: the first array of scintillating LTDs for 82Se 0νββ search

Zn82Se (95% enrich)

- NTD thermistor (phonons)
- Ge-wafer + NTD (light)

ROI bkg: 3.5 × 10⁻³ c/keV/kg/y best ever achieved with LTDs
CUORICINO: Scintillating crystals and light detectors operated @ 10mK
Absorbers may be grown from various ββ emitters
Availability of isotopes with $Q_{\beta\beta}$ in the γ-free region ($^{82}$Se, $^{100}$Mo)
Excellent energy resolution at $Q_{\beta\beta}$ (< 1%)
Particle ID capability in the heat and light channels

CUPID-Mo: 20 Li$_2^{100}$MoO$_4$ (96% enrich) operated in EDELWEISS setup

- NTD thermistor as phonon sensor
- Ge-wafer with SiO coating + NTD as light detector
CUPID: the future

CUORE Upgrade with Particle IDentification

Goal: explore the entire inverted ordering neutrino mass region down to 10 meV

Strategy: merge the CUORE cryogenic infrastructure with CUPID particle ID

Option for multiple isotopes with the same technique

Active background rejection to reach almost zero-background condition

Expected BI $10^{-4}$ counts/keV/kg/y in the ROI

Baseline: Li$_2^{100}$MoO$_4$ scintillating absorbers (1500 crystals for 250 kg of $^{100}$Mo)

NTD-Ge phonon sensors
Ge wafer + NTD-Ge light detector

TDR and construction readiness in 2021

CUPID CDR available soon
CUPID: the future

CUORE Upgrade with Particle Identification

Goal: explore the entire inverted ordering neutrino mass region down to 10 meV

CUPID: the future

Strategy:

Baseline: Li
Active background rejection to reach almost zero-background condition
Option for multiple isotopes with the same technique

Other light detector technologies like Neganov-Luke-assisted NTDs, Transition Edge Sensors (TES) and microwave Kinetic Inductance Detectors (KID) are under study for their superior signal-to-noise ratio and speed.

These technologies might be suitable also to read the feeble Cerenkov light emitted by TeO₂ enriched detectors (CUPID alternative solution).

**CUPID: the future**

**CUORE Upgrade with Particle IDentification**

Other light detector technologies like Neganov-Luke-assisted NTDs, Transition Edge Sensors (TES) and microwave detectors (KID) are under study for their potential-to-noise ratio. Baseline: Li

**Optics**

*CALDER*

N. Casali, talk ID 143

*CROSS*

H. Khalife, poster ID 47
P. Carniti, poster ID 390

**R&Ds**

V. Singh, poster ID 248
J. Zhang, poster ID 329
G. Wang, poster ID 269
Advanced Mo-based Rare process Experiment

- MMC as phonon sensor
- Ge-wafer + MMC as light detector

AMoRE pilot: 6 detector modules with $^{48}\text{depl}^{100}\text{Ca}^{100}\text{MoO}_4$ absorbers

<table>
<thead>
<tr>
<th>Crystal Mass (kg)</th>
<th>Backgrounds(ckky)</th>
<th>$T_{1/2}$ (year)</th>
<th>$m_{bb}$ (meV)</th>
<th>Schedule</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMoRE-Pilot</td>
<td>AMoRE-I</td>
<td>AMoRE-II</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.5</td>
<td>$\sim 10^{-2}$</td>
<td>$1.0 \times 10^{24}$</td>
<td>380-719</td>
<td>2017</td>
</tr>
<tr>
<td>5</td>
<td>$\sim 10^{-3}$</td>
<td>$8.2 \times 10^{24}$</td>
<td>130-250</td>
<td>2018</td>
</tr>
<tr>
<td>200</td>
<td>$10^{-4}$</td>
<td>$8.2 \times 10^{26}$</td>
<td>13-25</td>
<td>2020-2023</td>
</tr>
</tbody>
</table>
**AMoRE**

**Advanced Mo-based Rare process Experiment**

- MMC as phonon sensor
- Ge-wafer + MMC as light detector

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**AMoRE Pilot**

<table>
<thead>
<tr>
<th>Detector Modules</th>
<th>Crystals</th>
<th>Backgrounds (ckky)</th>
<th>$T_{1/2}$ (year)</th>
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<td>48 depl $^{100}$CaMoO$_4$ absorbers</td>
<td></td>
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</tr>
</tbody>
</table>

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**AMoRE**

C.S. Khang, talk ID 236
D. Kwon, poster ID 278
K. Woo, poster ID 264
H.B. Kim, poster ID 245
S.G. Kim, poster ID 268
0νββ searches: outlook

Present results

Proposed experiments

Far future

Discovery potential of proposed projects

Experimental state-of-the-art

Next-generation goal

CUORE final sensitivity

CUPID baseline projected sensitivity

Inverted ordering

Direct ordering

\[ m_{\beta\beta} \text{ [eV]} \]

\[ \text{Lightest neutrino mass [eV]} \]

<table>
<thead>
<tr>
<th>Project</th>
<th>3σ discovery sensitivity on ( m_{\beta\beta} ) [eV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUPID</td>
<td></td>
</tr>
<tr>
<td>CUPID-teach</td>
<td></td>
</tr>
<tr>
<td>CUPID-1T</td>
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<td>LEGEND-1000</td>
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<td>nEXO</td>
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<td>NEXT-HD</td>
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<td>NEXT-BOLD</td>
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<td>PandaX-III-1000</td>
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<td>KamLAND-2</td>
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<tr>
<td>SNO+I</td>
<td></td>
</tr>
</tbody>
</table>

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**Direct neutrino mass measurement**

- Kurie plot near $E_0$

**General experimental requirements**

- Low endpoint energy $E_0$
- High statistics at the $\beta$ spectrum end-point
- High energy resolution $\Delta E$
- High signal-to-background ratio at the end-point
- Small systematic effects

**Effect of:**
- Detector energy resolution
- Background counts
- Other systematics...

**Effect of $m_\nu \neq 0$**

\[
N(E_\beta, m_\nu = 0) = \int_{E_0 - \delta E}^{E_0} N(E_\beta, m_\nu = 0) \, dE \\
\approx (\delta E / E_0)^3
\]

Fraction $F$ of decays below the end-point

\[
F(\delta E) = \int_{E_0 - \delta E}^{E_0} N(E_\beta, m_\nu = 0) \, dE \\
\approx 2 \times 10^{-10}
\]

for $^3$H $\beta$-decay $F(10 \text{ eV})$.
Calorimeters measure the entire spectrum at once
use low $E_0 \beta$ decaying isotopes to achieve enough statistics close to $E_0$
e.g. $^{187}$Re: $E_0 = 2.47$ keV $\Rightarrow F(\delta E = 10$ eV $) \approx (\delta E/E_0)^3 = 7 \times 10^{-8}$

Drawback:

Arrays of microcalorimeters ($\sim \mu g$)

Pile-up
time unresolved superposition of $\beta$ decays
for a source activity $A_\beta$, a time resolution $\tau_R$
and an energy resolution function $R(E_\beta)$

$N_{\exp}(E_\beta) \approx (N(E_\beta) + \tau_R A_\beta \cdot N(E_\beta) \otimes N(E_\beta)) \otimes R(E_\beta)$
Precursor $^{187}$Re experiments

**MANU (1999)**
Genova

1 crystal of metallic Re: 1.6 mg
$^{187}$Re activity $\approx$ 1.6 Hz
Ge-NTD thermistor
$\Delta E$=96 eV FWHM
0.5 years live-time
$m_{\nu}^2 = 462^{+579}_{-679}$ eV$^2$
$m_{\nu} < 26$ eV (95 % C.L.)

**MIBETA (2002-2003)**
Milano, Como, Trento

10 AgReO$_4$ crystals: 2.71 mg
$^{187}$Re activity = 0.54 Hz/mg
Si thermistors (ITC-irst)
$\Delta E$= 28.5 eV FWHM
0.6 years live time
$m_{\nu}^2 = -112 \pm 207_{\text{stat}} \pm 90_{\text{sys}}$ eV$^2$
$m_{\nu} < 15$ eV (90 % C.L.)
The $^{187}$Re project MARE was abandoned due to the impossibility to fabricate rhenium microcalorimeters matching the specifications required by a neutrino mass experiment with sub-eV sensitivity.

Electron capture calorimetric experiments

\[ ^{163}\text{Ho} + e^{-} \rightarrow ^{163}\text{Dy}^{*} + \nu_{e} \]

**electron capture from shell \( \rightarrow \) M1**


\[ m(\nu_{e}) < 225 \text{ eV} \]


Atomic de-excitation:
- X-ray emission
- Auger electrons
- Coster-Kronig transitions

- calorimetric measurement of Dy atomic de-excitations
- \( Q = 2.83 \text{ keV} \) (determined with Penning trap in 2015)
  - end-point rate and \( \nu \) mass sensitivity depend on \( Q - E_{M1} \)
- \( \tau_{1/2} \approx 4570 \text{ years} \rightarrow 2 \times 10^{11} ^{163}\text{Ho} \text{ nuclei} \leftrightarrow 1\text{Bq} \)
Effect of the neutrino mass at the end-point of the de-excitation spectrum

\[ N(E_c) = \frac{G^2}{4\pi^2} \left( \frac{Q-E_c}{\sqrt{(Q-E_c)^2-m_\nu^2}} \right)^2 \times \sum_i n_i C_i \beta_i^2 B_i \frac{\Gamma_i}{2\pi (E_c-E_i)^2 + \Gamma_i^2/4} \]

- \( N_{ev} = 10^{14} \)
- \( \Delta E_{FWHM} = 2 \text{ eV} \)
- \( Q = 2.83 \text{ keV} \)
- \( f_{pp} = 10^{-6} \)

\( m_\nu = 0 \text{ eV} \)
\( m_\nu = 2 \text{ eV} \)
\( m_\nu = 5 \text{ eV} \)
\( m_\nu = 10 \text{ eV} \)
Pulse pile-up effect

• calorimetric measurement $\Leftrightarrow$ **detector speed is critical**

• accidental coincidences $\rightarrow$ complex pile-up spectrum

$N_{pp}(E) = f_{pp} N_{EC}(E) \otimes N_{EC}(E)$ with $f_{pp} \approx A_{EC} \tau_R$

$Q = 2800$ eV

$f_{pp} = 10^{-4}$

$N_{EC}(E)$ without higher order processes (shake up / shake off)
For a statistical sensitivity on $m_\nu$ of $\sim 1$ eV

- High statistics at the end-point region: $N_{ev} > 10^{13}$
- Unresolved pile-up fraction $f_{pp} < \sim 10^{-4}$
- High energy resolution $\Delta E_{FWHM} < 3$ eV
- Low background level $\sim 10^{-4}$ c/eV/det/day
Calorimetric $m_\nu$ measurement detector “MUSTs”

For a statistical sensitivity on $m_\nu$ of ~1 eV

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Challenges:

- $^{163}$Ho production

$^{162}$Er ($n,\gamma$) $^{163}$Er $\sigma_{\text{thermal}} \approx 20\text{b}$

$^{163}$Er $\rightarrow^{163}$Ho $+ \nu_e$ $\tau_{1/2} \approx 75\text{min}$

neutron activation
Calorimetric m_ν measurement detector “MUSTs”

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- Detector technology (ECHo, HOLMES)
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- $^{163}$Ho production
- Detector technology (ECHo, HOLMES)
- Construction of high performing detector arrays
- $^{163}$Ho embedment in the detectors
- Stable measurement in a low background environment
- Theoretical shape of the $^{163}$Ho spectrum

De Rujula et al., JHEP 05 (2016) 015
Detector technology

**HOLMES**

M. Faverzani, talk ID 404
A. Puiu, talk ID 393
E. Ferri, poster ID 408
M. Borghesi, poster ID 398
M. DeGerone, poster ID 389
A. Giachero, poster ID 397

**ECHo**

F. Mantegazzini, talk ID 149
F. Mantegazzini, Poster ID 342
O. Sander, poster ID 317
A. Refenberger, poster ID 260


Expected sensitivity of $^{163}$Ho $m_\nu$ experiments

$N_{\text{det}} t_M = 1000 \text{ det} \times 3 \text{ y}$

$A_{EC} = 300 \text{ c/s/det}$

$\nu_e$ sensitivity, 90% C.L. [eV]

- $\Delta E_{\text{FWHM}} = 1 \text{ eV}$
- $\Delta E_{\text{FWHM}} = 2 \text{ eV}$
- $\Delta E_{\text{FWHM}} = 3 \text{ eV}$
- $\Delta E_{\text{FWHM}} = 5 \text{ eV}$
- $\Delta E_{\text{FWHM}} = 10 \text{ eV}$

$A \approx 100 \text{ kBq}$
$t = 3 \text{ y}$

$m(\nu_e) < 1.5 \text{ eV} \ 90\% \ C.L.$

Activity per pixel 10 Bq
Number of detectors 12000
Readout: microwave SQUID multiplexing
... to be compared with KATRIN

Current upper limit on anti-neutrino mass from spectrometer experiments: 2.2 eV

KATRIN overview: 70 m long beamline

sensitivity goal: 0.2 eV

First results to be published soon
Neutrinos and the precision era

Oscillation experiments have entered the precision era
Oscillation experiments have entered the precision era

Future goals are:

- Establishing the robustness of the three-flavor oscillations with respect to new physics beyond the Standard Model
Heavy neutrino emission in $^{187}$Re $\beta$ decay

$$\nu_e = \nu_L \cos \theta + \nu_H \sin \theta$$

$$N_\beta(E, m_L, m_H, \theta) = \cos^2 \theta N_\beta(E, m_L) + \sin^2 \theta N_\beta(E, m_H)$$
Sterile neutrinos with LTDs

Heavy neutrino emission in $^{187}$Re $\beta$ decay

$$\nu_e = \nu_L \cos \theta + \nu_H \sin \theta$$

Heavy neutrino emission in $^{163}$Ho EC decay

calculation to be updated with actual Q-value

$$0 < m_H < Q - E_{th}$$

$Q - m_H$

$Q$

$m_L = 0$

$m_H = 1$ keV

$\sin^2 \theta = 0$

$\sin^2 \theta = 0.2$

$\sin^2 \theta = 0.5$

$Q_{EC} = 2.2$ keV
Neutrinos and the precision era

Future goals are:

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- Determination of the CP-violating phase and the neutrino mass ordering
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Oscillation experiments have entered the precision era.

e.g.: JUNO
Neutrinos and the precision era

Future goals are:

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Additional interactions beyond the SM ones affecting the neutrino sector — Non Standard Interactions (NIS) — may have severe consequences on future experiments.

Scattering experiments are important to constrain this scenario.

Coherent elastic $\nu$-nucleus scattering (CEvNS)

Challenge: very low energy nuclear recoils

strongly enhanced cross-section

Inverse Beta Decay

no energy threshold
Coherent elastic $\nu$-nucleus scattering (CEvNS)

Challenge: very low energy nuclear recoils

First observation by COHERENT @ neutron spallation source (Oakridge) with 14.6 kg CsI[Na] scintillating crystals + PMTs

Akimov et al., Science 357 (2017) 1123
CevNS with LTDs

Goal: study neutrino physics at low energy with high precision

COHERENT – great!

Why NU–CLEUS?

Error budget

<table>
<thead>
<tr>
<th>Observed: 134±22 events</th>
<th>Expected (SM): 173±48 events</th>
</tr>
</thead>
<tbody>
<tr>
<td>stat. 16%</td>
<td>syst. 30%</td>
</tr>
</tbody>
</table>

Neutrino source

Stopped-pion-source

Nuclear power reactor

"conventional"

Detector

cryogenic detector

Threshold: A few keV

Threshold: A few 10’s of eV

Raimund Strauss, GSI Seminar, 2018
v-CLEUS

**NU-CLEUS detector prototype:**

0.5 g Al$_2$O$_3$ detector

**NU-CLEUS 1g demonstrator**

- Sapphire and CaWO$_4$ crystals
- Flexible Si wafers as inner veto detectors

---


$$E_{th} = 19.7 \pm 1 \text{ eV}$$
**v-CLEUS**

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**Trigger Efficiency**

**NU-CLEUS**

J. Rothe, talk ID 100

RICOCHET

A Coherent Neutrino Scattering Program

Q-Array
Superconducting bolometers
Zn & Al

Neutrino

CryoCube
Semi-conducting & superconducting bolometers
Ge & Zn

J. Billard, talk ID 360
A. Juillard, poster ID 373
S. Marnieros, poster ID 376
CevNS with LTDs

Other ongoing detector developments:

BULLKID
I. Colantoni,
poster ID 290

BASKET
C. Nones,
poster ID 366
Conclusions

Low Temperature Detectors have become mature devices with strong potentialities in neutrino physics experiments.

Ongoing R&Ds will surely confirm the leading role of this technique also for next generation experiments!
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Low Temperature Detectors have become mature devices with strong potentialities in neutrino physics experiments. Ongoing R&Ds will surely confirm the leading role of this technique also for next generation experiments!

THANKS!

... and apologies for those contributions I forgot to mention...