The energy calibration system of the CUORE double beta decay bolometric experiment

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on behalf of the CUORE collaboration
Status of neutrino physics

- Neutrino oscillation experiments proved that neutrinos are massive particles

- Neutrinos’ open questions:
  - absolute neutrino mass scale
  - neutrino mass hierarchy
  - $\nu_e \neq \bar{\nu}_e$ or $\nu_e = \bar{\nu}_e$ nature
  - $\theta_{13}$ and values of the CP phases
**ββ0ν decay for neutrino physics**

- Neutrinoless double beta decay $ββ0ν$ could be the key to answer some of these questions.

$$ββ2ν : (A, Z) \rightarrow (A, Z+2) + 2e^- + 2ν_e$$

$$ββ0ν : (A, Z) \rightarrow (A, Z+2) + 2e^-$$

- $ββ0ν$ observation would imply:
  - Lepton number non conservation
  - Majorana nature of the neutrinos

NEW PHYSICS BEYOND THE STANDARD MODEL
The search for $\beta\beta 0\nu$

- Experimentally challenging: must measure half-lifes $\gtrsim 10^{25}-10^{27}$ y
  - strong background reduction
  - large mass experiments

Experimental signature:
peak at the transition $Q$ value, enlarged by detector resolution, over the unavoidable background due to $\beta\beta 2\nu$

Our candidate: $^{130}\text{Te}$

\[ Q_{\beta\beta 0\nu}(^{130}\text{Te}) \approx 2527.5 \text{ keV} \]
TeO$_2$ bolometers

The absorber is a 5x5x5 cm$^3$ (790 g) crystal of TeO$_2$ which contains the $\beta\beta0\nu$ candidate $^{130}$Te.

Temperature sensor

The thermal signal is measured by means of an NTD Ge Thermistor.

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

An electrical read-out converts resistance changes into voltage pulses.

$R(T) = R_0 e^{\sqrt{T_0/T}}$
CUORE: Cryogenic Underground Observatory for Rare Events will be a tightly packed array of 988 bolometers - $M \sim 200$ kg of $^{130}$Te

- Operated at Gran Sasso Underground laboratory (Italy)

CUORE Goals

- Average FWHM resolution: 5 keV
- Background in DBD region: 0.01 counts/kev/kg/y
- Predicted limit after ~5 years of running:

$$T_{1/2} \sim 2.1 \times 10^{26} \text{ yr} \quad \rightarrow \quad <m_\nu> \leq (24 - 83) \text{ meV}$$

Calibration of bolometers

- Bolometer are operated as perfect calorimeters
  - energy is the most relevant information extracted
- For each bolometer:
  - Voltage vs Energy relationship is needed
  - Calibration with $\gamma$ sources of known energies (e.g. $^{232}$Th)
  - The pairs $(E_i, V_i)$ are fitted with a proper calibration function
  - The calibration measurement is performed regularly (~ monthly)

- The calibration uncertainty
  - affects the resolution of the detectors
  - is one of the systematic errors in the determination of the $\beta\beta 0\nu$ half life

![Diagram]
CUORE calibration

- **Uniform illumination** of all detectors with 5 calibration lines clearly identified in the energy spectrum between 511 keV and 2615 keV.

- **Sources can be replaced.** Other source isotopes can be used if necessary (e.g. $^{56}$Co has been studied).

- **Calibration time** does not significantly affect detector live time.

- Negligible contribution to radioactive background in the $\beta \beta 0\nu$ region.

- **Minimize the uncertainty** in the energy calibration. Goal: residual calibration uncertainty in $\beta \beta 0\nu$ region < 0.05 keV.
CUORE calibration system

Insertion of 12 γ sources that are able to move, under their own weight, through a set of guide tubes that route them from the deployment boxes on the 300K flange down into position in the detector region.

**Source locations**

- top view of detector array with source positions
- guide tubes
- detectors
- Lead shield

**Computer controlled motion box for source deployment**

- Drive assembly

**Radioactive capsules** crimped on a Kevlar string

- 232Th
- 56Co

**Source locations**

- 40K
- 300K
- 4K
- 0.7K
- 70mK
- 10mK
- Teflon cover

- ~1.6mm
- ~10mm
Prototype tests

Lab mock up of a representative guide tube routing

- reliable motion, little fraying
- >10,000 cycles

- load cell
  - tracks tension in string

- USB camera integrated with LabView control software
  - takes snapshot of source after given number of turns of the spool

- proximity sensor
  - counts capsules passing by

- reproducible profile allows monitoring of source’s travel through the tubes

- positioning accuracy of ~0.5 mm
## Cryogenic considerations

### Sources of heat load:

- Conductance of the guide tubes
- Radiation funneled by guide tubes
- Conductivity of source string
- Radiation emitted by the source string
  - cooling mechanism required
- Friction during insertion/extraction
  - low friction materials + speed adjustment

### Scheme of guide tube materials and thermal couplings

<table>
<thead>
<tr>
<th>Stage</th>
<th>T [K]</th>
<th>Cooling power available to calibration [W]</th>
<th>Static heat load from guide tubes</th>
<th>Radiation from source string at 4K</th>
</tr>
</thead>
<tbody>
<tr>
<td>40K</td>
<td>40 – 50</td>
<td>~1</td>
<td>~1</td>
<td>--</td>
</tr>
<tr>
<td>4K</td>
<td>4 – 5</td>
<td>0.3</td>
<td>0.02</td>
<td>--</td>
</tr>
<tr>
<td>0.7K</td>
<td>0.6 – 0.9</td>
<td>0.55m</td>
<td>0.13m</td>
<td>0.08 µ</td>
</tr>
<tr>
<td>70mK</td>
<td>0.05 – 0.1</td>
<td>1.1 µ</td>
<td>negligible</td>
<td>0.3 µ</td>
</tr>
<tr>
<td>10mK</td>
<td>0.01</td>
<td>1.2 µ</td>
<td>1.07 µ</td>
<td>0.08 µ</td>
</tr>
<tr>
<td>detector</td>
<td>0.01</td>
<td>&lt; 1 µ</td>
<td>--</td>
<td>0.25 µ</td>
</tr>
</tbody>
</table>
Cooldown of the sources

- Sources must be cooled to < 4K to meet heat load requirements
- Strong mechanical contact is needed between the source carrier and a heat sink at 4K
Friction during source insertion/extraction

Sliding friction

Friction of a string on a fixed rod

\[ \frac{T_2}{T_1} = e^{\mu_k \beta} \]

Exponential dependence on angle and friction coefficient

Each guide tube routing has several bends and sloped sections

Optimal sequence of staggered source extraction at variable speed to meet heat load requirements

Simulated heat load

Source speed = 0.1 mm/s

Power dissipated [W]

Distance traveled by source [m]

During extraction at constant speed
Conclusions

• Neutrinos could be the key to unravel physics beyond the standard model.

• The successful operation of CUORE, in the search for neutrinoless double beta decay, requires a reliable and efficient energy calibration system.

• The design of the calibration system is technically challenging and stringent requirements must be met, in particular when it comes to the integration in the unique CUORE cryostat.

• The design of the calibration system for CUORE is being finalized and prototype parts are currently being tested.

• Commissioning of the calibration system is expected for early 2010.