Energy Calibration of the CUORE Bolometric Double Beta-Decay Experiment

Karsten M. Heeger
University of Wisconsin

on behalf of the CUORE Collaboration
CUORE Double Beta Decay Experiment

CUORE: Cryogenic Underground Observatory for Rare Events will be a tightly packed array of 988 bolometers with mass of ~ 200 kg of $^{130}$Te

- Operated at Gran Sasso laboratory
- Special cryostat built w/ selected materials
- Cryogen-free dilution refrigerator operated at ~ 10mK
- Shielded by several lead shields

19 Cuoricino-like towers with 13 planes of 4 crystals each

see also Y. Kolomensky “Status of the CUORE Experiment”, Tues, Oct 13
**TeO₂ Bolometers**

For $E = 1$ MeV: $\Delta T = E/C \approx 0.1$ mK

Signal size: 1 mV

- **Voltage signal** $\propto$ energy deposited
- Time constant: $\tau = C/G = 0.5$ s
- Energy resolution: $\sim 5$-10 keV at 2.5 MeV

Heat sink: Cu structure (8-10 mK)

Thermal coupling: Teflon ($G = 4$ pW/mK)

Thermometer: NTD Ge-thermistor ($dR/dT \approx 100$ kΩ/µK)

Absorber: TeO₂ crystal ($C \approx 2$ nJ/K $\approx 1$ MeV / 0.1 mK)

Deposited energy

- voltage pulses
  - amplitude is related to energy
  - non-linear relationship must be measured experimentally

790g per crystal

voltage signal amplitude

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DBD0\$
Search for 0νββ in $^{130}$Te

Experimental Signature of 0νββ
- peak at the transition Q-value
- enlarged by detector resolution over unavoidable background due to 2νββ

$Q(^{130}\text{Te}) = 2527.518 \pm 0.013$ keV
Redshaw et al. nucl-ex/0902.2139

$Q(^{130}\text{Te}) = 2527.01 \pm 0.32$ keV

→ energy is the key event signature of candidate events
→ individual energy calibration of all 988 bolometers critical for summing energy spectra
Calibration of Cuoricino/CUORE Bolometers

Gain Stabilization
For each bolometer an energy pulse generated by a Si resistor is used to correct pulse amplitudes for gain instabilities (→ every 5 min).

Voltage-Energy Conversion
Fit of a calibration measurement with a gamma source (e.g. $^{232}$Th) of known energy. Energy calibration performed regularly. (~ monthly).

Calibration of individual bolometer
- calibrate with γ-sources
- need 5+ lines visible in calibration spectrum
- energy accuracy goal: < 0.05 keV

Summed spectrum from all detectors

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>Counts/(keV kg yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>511</td>
<td>500</td>
</tr>
<tr>
<td>911</td>
<td>1000</td>
</tr>
<tr>
<td>1592</td>
<td>2000</td>
</tr>
<tr>
<td>1912</td>
<td>3000</td>
</tr>
<tr>
<td>2515</td>
<td>3000</td>
</tr>
<tr>
<td>2615</td>
<td>208 Tl</td>
</tr>
<tr>
<td>3820</td>
<td>228 Ac</td>
</tr>
<tr>
<td>4040</td>
<td>228 Ac</td>
</tr>
<tr>
<td>4149</td>
<td>228 Ac</td>
</tr>
</tbody>
</table>
Calibration Source Simulations

Optimization of Source Strength, Position, and Distribution

- achieve uniform illumination of all crystals with internal/external sources
- determine max source activity, minimize calibration time

Max hit rate of 150 mHz per crystal to avoid pile-up, based on Cuoricino experience

Activity per discrete source:
- internal/external sources: 87 mBq/430 mBq
- internal/external sources edges: 126 mBq/1010 mBq

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Calibration Source Simulations

radioactive sources: 
$^{56}\text{Co}$ and/or $^{232}\text{Th}$

$^{56}\text{Co}$: proton activated Fe wire; $^{232}\text{Th}$: Thoriated Tungsten wire

both have been used in Cuoricino

Simulated calibration spectrum of a CUORE detector with $^{56}\text{Co}$ source

$\sim$100 events over background per peak are required for successful calibration
Detector Calibration System

Key Issues
- **Thermal loads** meet heat load requirements of cryostat
- **Calibration rate** of < 150mHz for each bolometer to avoid pile-up
- **Sources can be replaced.** Other source isotopes can be used if necessary (e.g. $^{56}\text{Co}$ has been studied)
- **Calibration time** does not significantly affect detector live time
- Negligible contribution to radioactive background in the $\beta\beta0\nu$ region
- **Minimize the uncertainty** in the energy calibration (< 0.05 keV)
- reasonable **calibration time** (< 1 week), minimize loss in detector livetime

**Calibration uncertainty**
- affects the **resolution of the detectors**
- is one of the **systematic errors** in the determination of the $0\nu\beta\beta$ half life
Detector Calibration System

- **insertion of 12 γ sources that move under own weight**

- **motion system:**
  - insertion and extraction of sources in and out of cryostat

- **guide tubes:**
  - no straight vertical access

- **source strings:**
  - move under own weight in guide tubes

**source locations**

**vertical cross section of the cryostat**

- top view of detector array with source positions
Detector Calibration System

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**Insertion of 12 γ sources that move under own weight**

**Lead shield**

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

**Guide tubes**

- Detector support plate

**Bolometers** @ ~10 mK
Detector Calibration System

Motion Box and Drive Spool System

- vacuum flange
- electrical feedthrough
- guide pulley
- motor
- load cell
- narrow spool for spiral winding
- vacuum feedthrough with shaft

Drive spools can be removed for individual source exchange.
Detector Calibration System

Source String
- flexible, moves under gravity in guide tube
- small mass: < 5 grams
- vertical distribution of source activity can be adjusted
- 30 capsules crimped and evenly spaced over 85 cm of Kevlar string

Guide Tubes
- stainless and/or machined from solid, low-background copper

radioactive source wire
- $^{232}$Th: Thoriated Tungsten wire
- $^{56}$Co: proton activated Fe wire
Prototype Motion Tests

Mock-up of guide tube routing and motion system

Source Motion Monitoring
- encoder
- USB camera → absolute position
- proximity sensor → senses capsules
- load cell → string tension

Motion Tests
- source moves reliably under its own weight
- position accuracy ~ 5 mm
- reproducible load cell pattern allows safe operation
Cryogenic Considerations

- Calibration system must be integrated with complex detector cryostat
- Must meet available cooling power requirements at all thermal stages

<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 (\mu)</td>
</tr>
<tr>
<td>70mK</td>
<td>0.05 – 0.1</td>
<td>1.1 (\mu)</td>
<td>negligible</td>
<td>0.3 (\mu)</td>
</tr>
<tr>
<td>10mK</td>
<td>0.01</td>
<td>1.2 (\mu)</td>
<td>1.07 (\mu)</td>
<td>0.08 (\mu)</td>
</tr>
<tr>
<td>detector</td>
<td>0.01</td>
<td>&lt; 1 (\mu)</td>
<td>--</td>
<td>0.25 (\mu)</td>
</tr>
</tbody>
</table>

- Thermal conductivity of guide tubes
- Radiation heat inflow from 300 K
- Heat radiated by the source strings
- Thermal conductivity of the source strings
- Friction heat during source string motion
Cooldown of the Source Strings

- 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

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Squeezing mechanism

- iso view
- source string
- detector region
- solenoid linear actuator
- pushing blade
- side view
- source string

Karsten Heeger, Univ. of Wisconsin  DBD09, October 12, 2009
Friction During Source Motion

Friction during source motion
- sliding friction in sloped guide tubes
- friction at bends
(exponential dependence on the bending angle and the friction coefficient)

Optimize sequence of staggered source extraction at variable speed to meet heat load requirements
CUORE and Calibration System Schedule

2009
- 3-tower test
- background R&D

2010
- CUORE-0 construction
- assembly tests
- single tower assembly (in Cuoricino cryostat)

2011
- CUORE-0 data taking

2012
- CUORE data taking

CUORE construction
- utilities
- clean room
- external shielding

cryostat assembly
- calibration system 4k test
- cryostat test cooldown

detector assembly:
- 18+1 towers
- ~1000 detectors

front-end electronics DAQ

calibration system
installation & commissioning
Conclusions

• Energy is the key event signature for $0\nu\beta\beta$ candidate events in CUORE and for discriminating backgrounds.

• Energy calibration is critical for summing the spectra from the 988 individual CUORE detectors.

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

• The design and integration of the calibration system is technically challenging and stringent requirements must be met.

• A complete design of the calibration system has been developed, prototype parts are being tested, and preparations for a 4K test of the system are under way.

• A 4K test of the system in the CUORE cryostat is planned for 2010.

• Commissioning of the full calibration system is expected for 2011.
CUORE Collaboration

18 institutions, 101 collaborators

Europe, US, China

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