# Cryogenic Verification of the CUORE Detector Calibration System


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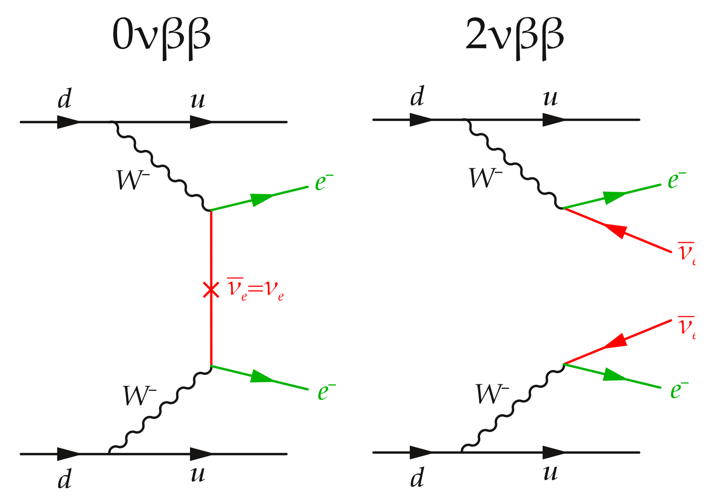
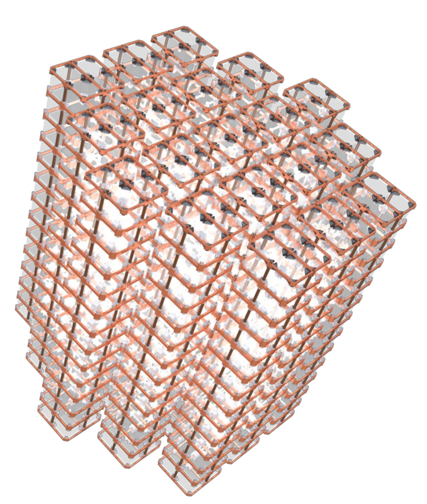
## Overview

### Neutrinoless Double Beta Decay

- The search for neutrinoless double beta decay ($0\nu\beta\beta$) is the only currently feasible way to test the hypothesis that neutrinos are Majorana particles.
- The total energy of the electrons in $0\nu\beta\beta$ events is fixed at a specific value, the Q-value, which is the difference in binding energy between the initial and final nuclei.
- If the $0\nu\beta\beta$ half-life can be measured in any nuclide, the effective Majorana mass of the electron neutrino can also be deduced, by way of various theoretical models.



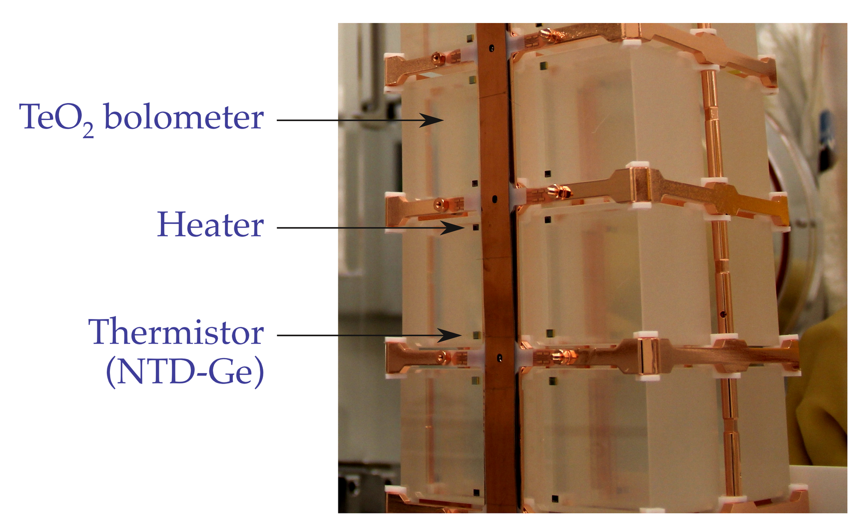

### CUORE



CUORE Detector Towers

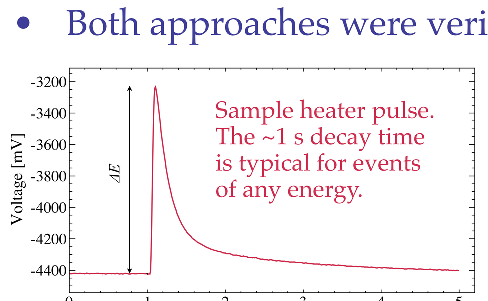
- The Cryogenic Underground Observatory for Rare Events (CUORE) will search for $0\nu\beta\beta$ in $^{130}$Te.
- The experiment is located deep underground at the Laboratori Nazionali del Gran Sasso (LNGS) in Assergi, Italy.
- CUORE is composed of 988 $TeO_2$ crystals, which serve as both the $0\nu\beta\beta$ sources and as bolometric detectors, ultra-low temperature devices that measure the energy of incident particles via a rise in temperature.
- The high-resolution crystal bolometers, with a total mass of 741 kg and 206 kg of $^{130}$Te, will be operated at 10 mK.
- CUORE is distinguished from other $0\nu\beta\beta$ searches by the high natural isotopic abundance of $^{130}$Te, the Q-value of $^{130}$Te decay above the Compton edge of the dominant gamma background (2615 keV from $^{208}$Tl), and the high resolution of $TeO_2$ bolometers.

- Each $TeO_2$ bolometer crystal is instrumented with a resistive heater and a Neutron Transmutation Doped germanium (NTD-Ge) thermistor.
- CUORE is composed of 19 towers, each with 13 floors of 4 crystals each, for a total of 988 crystals.
- The frame of each tower is OFHC copper, and the crystals are thermally coupled to the copper with PTFE supports.




### Energy Calibration

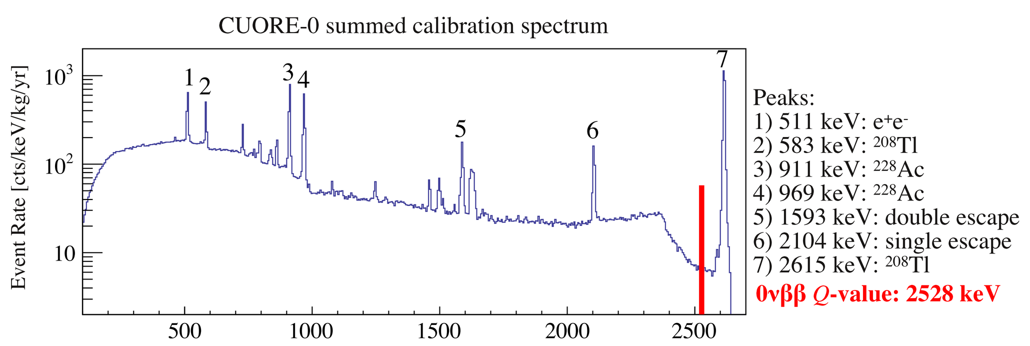
- Voltage signals from the thermistors must be calibrated to determine the energy of each event.
- A two-step calibration process will be used: first the thermistor gain is stabilized and then the thermistor readings area calibrated to absolute energies.
- Both approaches were verified in the operation of CUORE-0, a predecessor experiment.



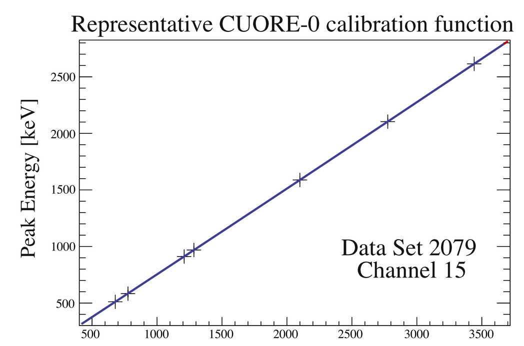

- The response of each bolometer over short time scales is measured with the use of periodic fixed-energy heater pulses
- Using these pulses, all thermister signal amplitudes are converted to arbitrary-unit gain-corrected stabilized amplitudes.

- Monthly, the crystals are exposed to $^{232}$Th $\gamma$-ray sources, which provide several strong peaks in the energy spectrum, including a $^{208}$Tl peak at 2615 keV, very close to the $0\nu\beta\beta$ Q-value.
- An energy vs. stabilized amplitude curve is determined for each channel.
- The hardware for this monthly calibration is the CUORE Detector Calibration System.

CUORE-0 summed calibration spectrum




Representative CUORE-0 calibration function




## Detector Calibration System

### Calibrating a Large Bolometer Array

- Bolometers require independent energy calibration.
- Calibration sources must be inside cryostat only during calibration.
- Inserting sources must not affect bolometer temperature.
- Procedure must be stable over expected 5-year lifetime of the experiment.
- Background contribution of calibration hardware must be low (<< 0.01 counts/keV/kg/year).

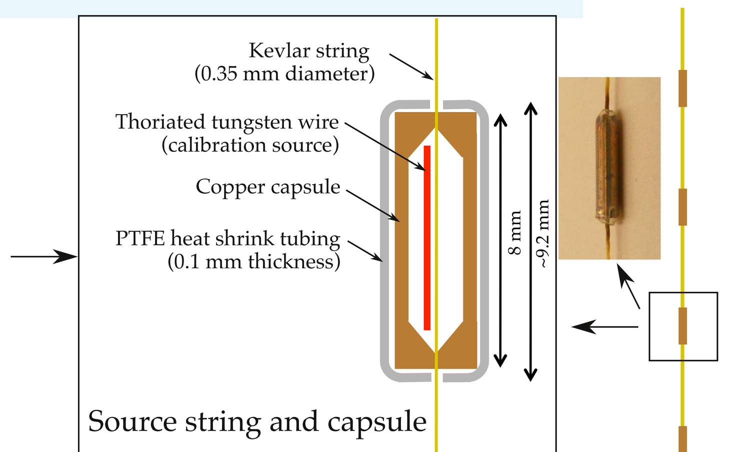
### Design and Implementation

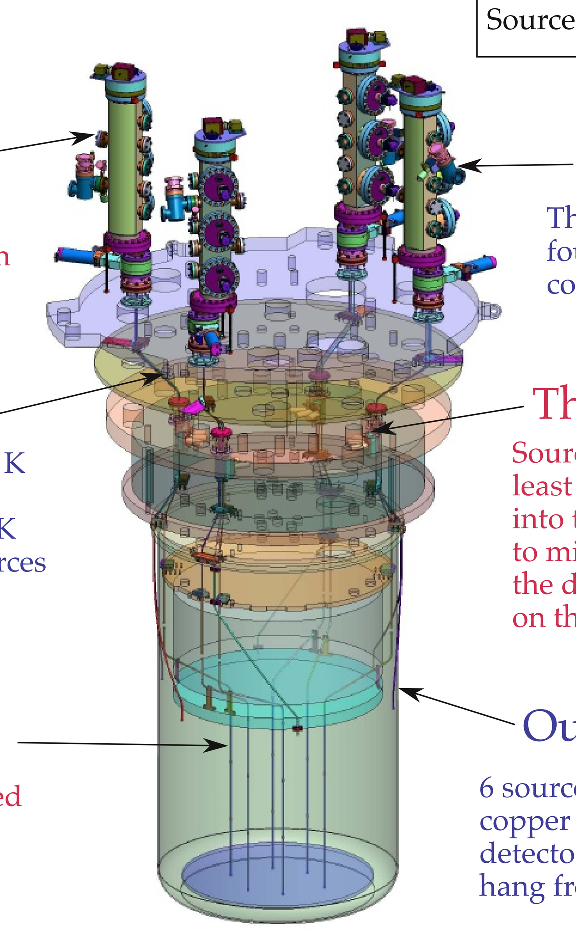
Twelve source strings:

- Move under their own weight
- Lowered into the cryostat during operation
- Cooled from 300 K to the bolometer region at ~10 mK

Each source string contains:

- 25 source capsules of thoriated tungsten wire (containing $^{232}$Th)
- 8 weight capsules
- PTFE guide ball



**Motors and spools**

Each source string is wound around a spool and connected to a motor, which turns the spool to raise and lower the calibration sources.

**Motion Box**

The motors are contained within four motion boxes, each of which controls three source strings.

**S-tubes**

Each source string is guided from 300 K to 4 K in a PTFE-coated stainless steel bellows ("S-tube") anchored to the 40 K plate. Bends in the tube allow the sources to thermalize with the tube.

**Thermalizers**

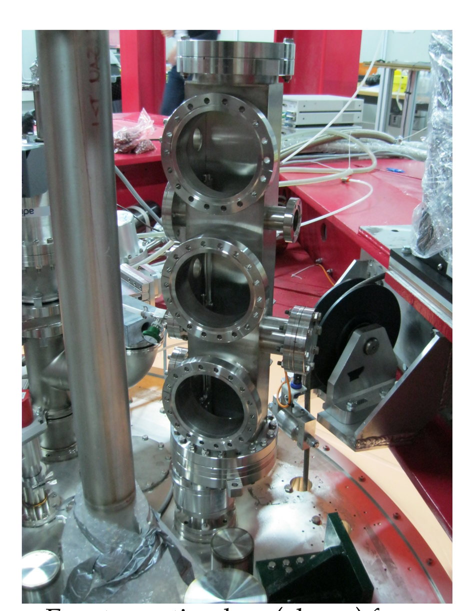
Source strings must be cooled to at least 4 K before being lowered further into the cryostat. 4 K is cold enough to minimize blackbody radiation in the detector region and the heat load on the inner guide tubes.

**Inner guide tubes**

6 source strings (27 Bq each) are guided between the $TeO_2$ detector towers in copper tubes to illuminate the inner bolometers.

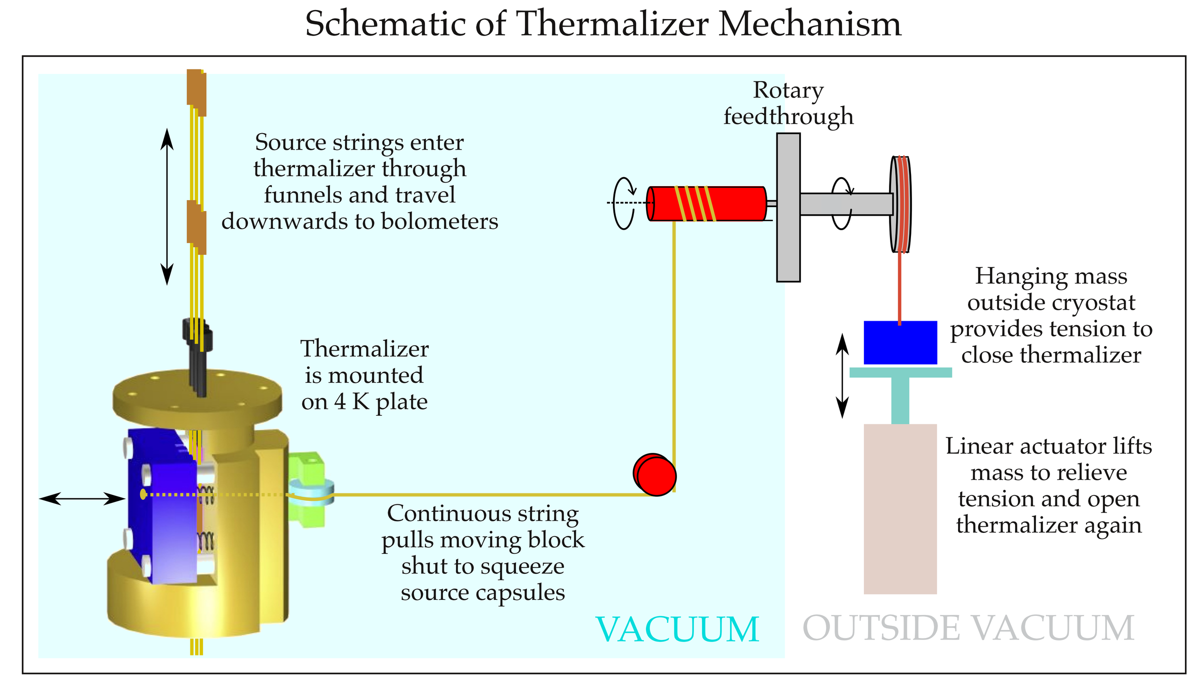
**Outer guide tubes**

6 source strings (4.4 Bq each) are guided in copper tubes to the region outside of the detector towers and then are allowed to hang freely.

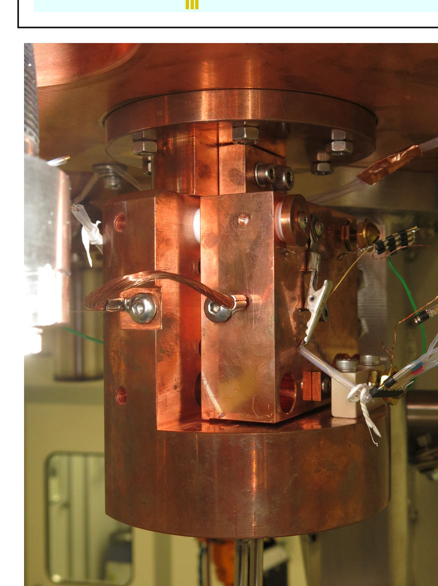


Empty motion box (above) from which sources are lowered into S-tube (below) from 300 K to 4 K

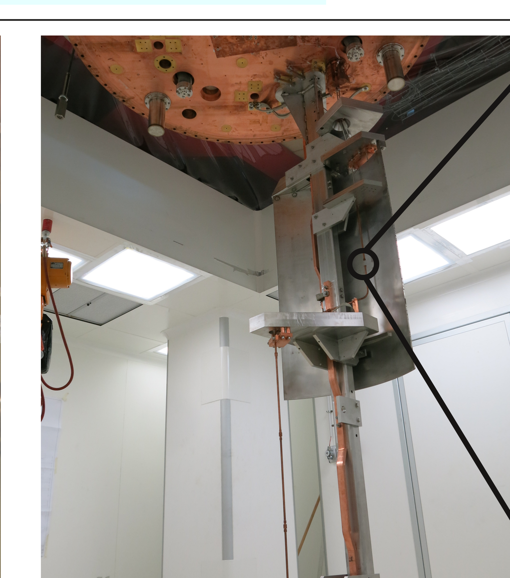
Schematic of Thermalizer Mechanism



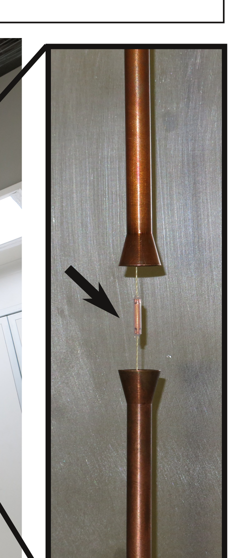

S-tube from 300 K to 4 K



Thermalizer mounted on 4 K plate



Single inner guide tube below 4 K plate



Source capsule and string

## 4 K Test Results

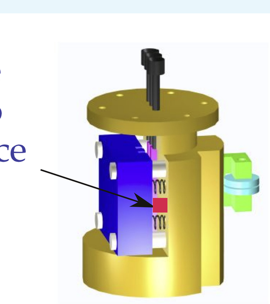
### Goals

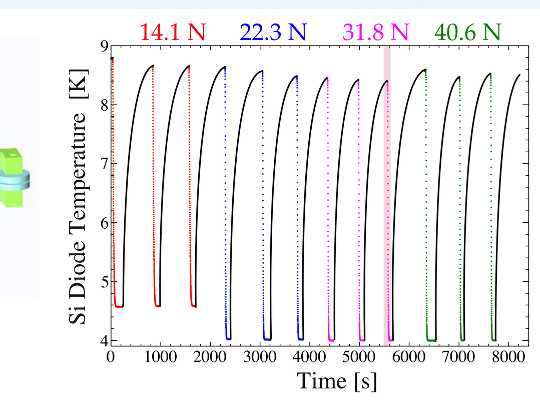
A cryogenic test of the calibration system was performed at 4 K, to:

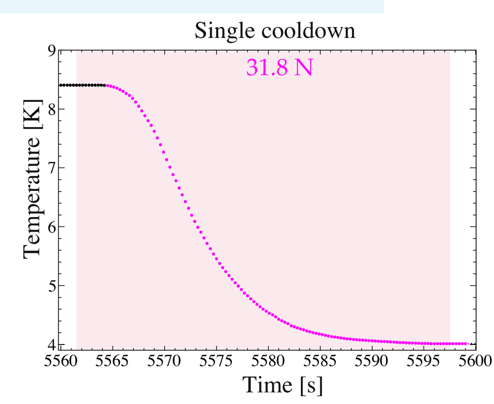
- Ensure that source strings can be lowered, cooled by mechanical squeezing, and extracted.
- Determine an appropriate squeezing force for the thermalizer.
- Estimate the time required for cooling down all of the source capsules.
- Determine whether "pre-cooling" the capsules in the upper region of the cryostat before lowering them can reduce cooling time without introducing excess background events in the detector.

### Thermalizer Squeezing Force

For testing, a Si diode thermometer made to imitate a copper source capsule was attached to the moving block and squeezed by the thermalizer.





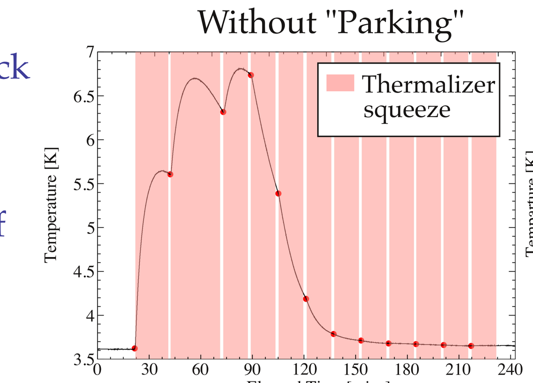

A force of 31.8 N cools the capsule to base temperature in approximately 30 seconds.

### Source Capsule Cooling

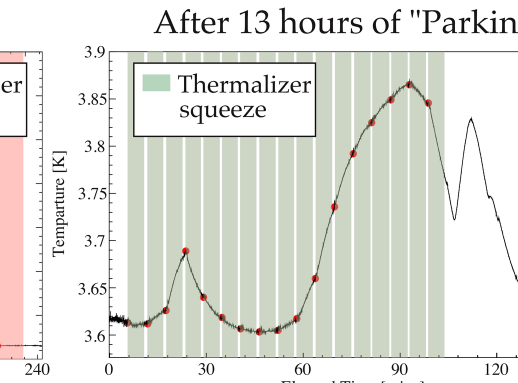
- Source strings are lowered into thermalizers and mechanically squeezed.
- Two capsules are cooled per squeezed, and the string is then lowered for the next capsules.
- This procedure was repeated with an initial 13-hour "parking" period, where the bottom of the source string was held in the thermalizer before the sources were lowered further.

The temperature of the moving block on the thermalizer was recorded as the capsules were lowered into the cold region of the cryostat (< 4 K). Red dots represent the beginning of thermalizer squeezes (shaded regions).

Without "Parking"




After 13 hours of "Parking"




Parking and pre-cooling the sources:

- Decreases the temperature rise of the thermalizer
- Decreases the time required to cool the sources before they can be lowered into the detector

### Results

- One of four complete calibration system modules was installed on the cryostat, and the sources were reliably lowered into, held in, and extracted from the detector region.
- We have verified that the thermalization mechanism cools down the source capsules to 4 K.
- We discovered that overnight pre-cooling of the source capsules reduces the time required for cooling and reduces the temperature rise of the cryostat's 4 K plate.
- We have determined the optimal squeezing force for effectively cooling down the source capsules.

### Collaboration

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