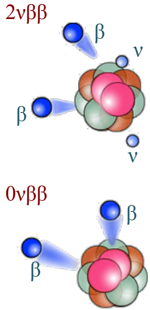
Large Mass Bolometers for Rare Event Searches

Ke Han for CUORE Collaboration

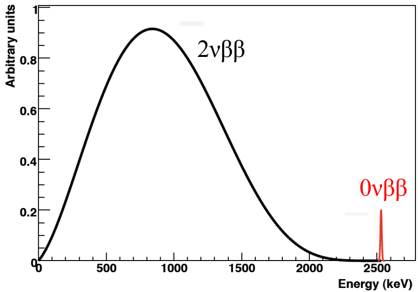
Berkeley Lab

February 23, 2011

Neutrinoless double beta decay



$$(A, Z) \to (A, Z+2) + 2e^- + \cancel{2\bar{\nu}_e}$$



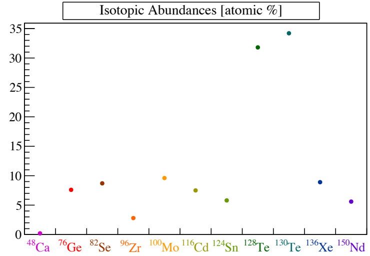
- Extremely rare process ($T_{1/2} > 10^{24}$ y), if occurs at all.
- Detect the two decay electrons and sum the energy.
- $0\nu\beta\beta \Leftrightarrow E_{total}$=Q-value

Sensitivity to rare decay events

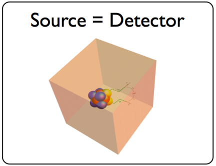
$$\text{Half life sensitivity} \propto \eta \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

Isotopic abundance | Detecting efficiency | Detector mass | Background rate | Energy resolution | Measuring time

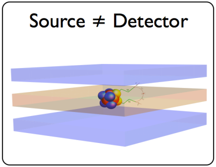
Isotopic abundance η:



Detecting efficiency ϵ:

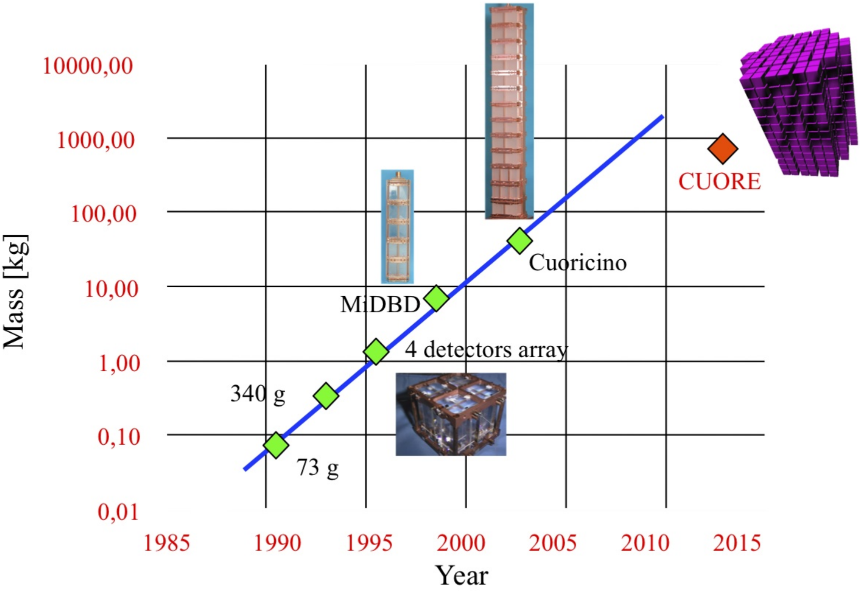


high efficiency



low efficiency

Pursuit of rare decay events with bolometers



Outline

- Single bolometer module
  - Principles and characteristics
  - Resolution and noise
- Bolometer arrays
  - Cuoricino
  - Anti-Coincidence cut; self-shielding
  - Background level
- Road to CUORE
  - TTT; CCVR; CUORE-0
  - Cryostat; Calibration system
- Next generation bolometer R&D
  - Scintillating bolometers
  - Bolometers with ionization.

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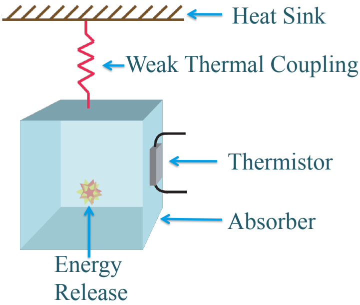

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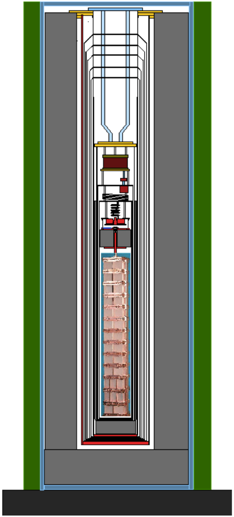

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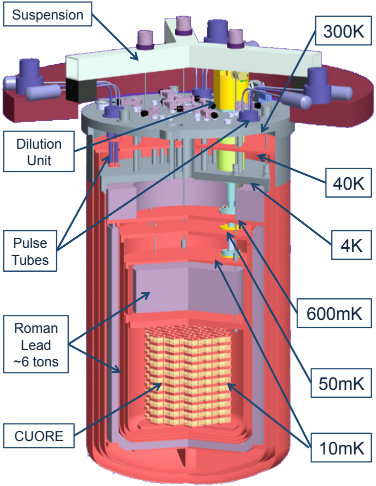

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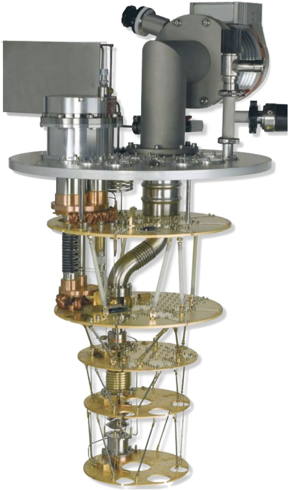
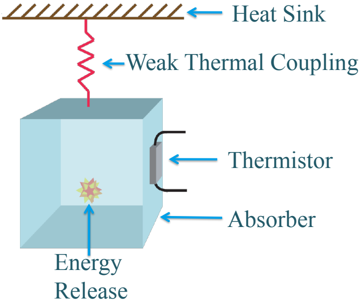
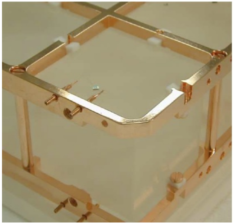


A large mass bolometer module

- Measuring the energy through a corresponding temperature rise.
- Tiny temperature rise read out by a thermistor.
- Back to base temperature via the thermal coupling to heat sink.
- Small phonon excitation energy; excellent intrinsic energy resolution.
- Large absorber mass $\Rightarrow$ large heat capacity $\Rightarrow$ large time constant

$$T = \frac{C}{G} \propto m$$





Crystal – the absorber

- Material choice:

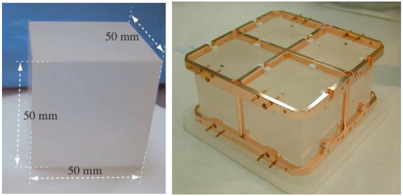
$$c(T) = c_r(T) + \cancel{c_e(T)}$$

- High Debye temperature, small specific heat capacity

$$c_r(T) = \frac{12}{5}\pi^4 k_B N_A \left(\frac{T}{\Theta_D}\right)^3$$

- Large crystals desired but still cost effective to grow.
- Survives the heat cycling.

$\surd$ TeO_2 $\times$ Te



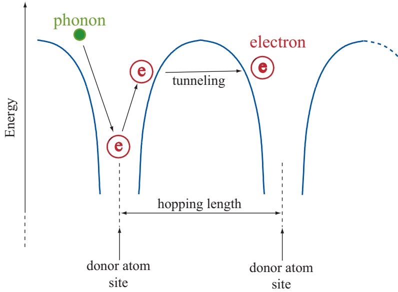
CUORICINO/CUORE TeO_2 crystal

- 5x5x5 cm^3, 750g
- had 3x3x6; tried 6x6x6
- $C_r = 2.3 \times 10^{-3} T^3$ J/K
  - ΔT=0.1 mK/MeV at 10mK
- for $0\nu\beta\beta$: radiopure

Neutron Transmutation Doped (NTD) Germanium

- Phonon induced tunneling (hopping) between impurity sites.
- Variable range hopping to match phonon energy at low temperature:

$$\rho = \rho_0 e^{\sqrt{T_0/T}}$$



Controlled, homogeneous neutron doping

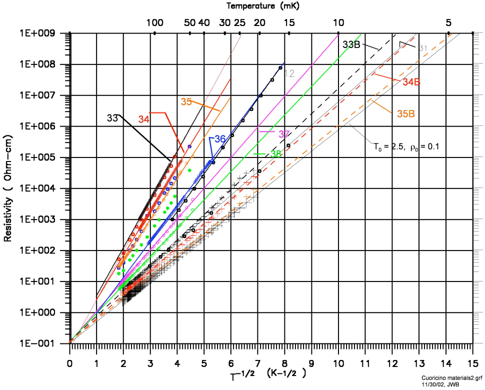
$^{70}Ge + n \rightarrow ^{71} Ge \rightarrow ^{71} Ga$, Acceptor

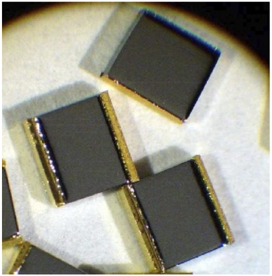
$^{74}Ge + n \rightarrow ^{75} Ge \rightarrow ^{75} As$, Donor

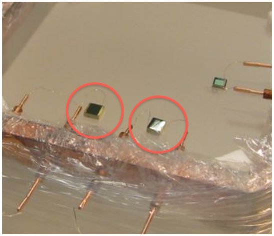
$^{76}Ge + n \rightarrow ^{77} Ge \rightarrow ^{77} Se$, Double Donor

CUORE Thermistors

- $\rho = \rho_0 e^{\sqrt{T_0/T}}$; ρ_0, T_0 determined by dosage.
- For standard CUORE thermistors, $3 \times 3 \times 1$ mm^3 size, $R_0 \sim 1\Omega$, $T_0 \sim 3K$
- 100 MΩ at 10 mK.







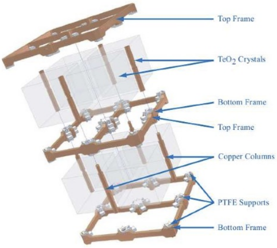
Copper Frame and Teflon Holders

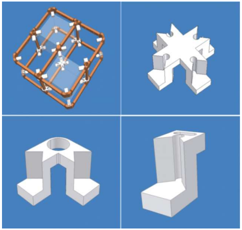
Copper Frame:

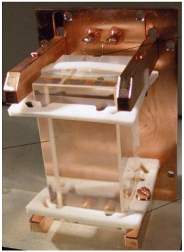
- Heat bath
- Major background source

Teflon holders

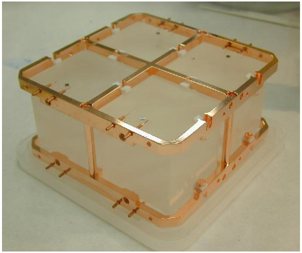
- The weak thermal link
- Reduce vibration noise



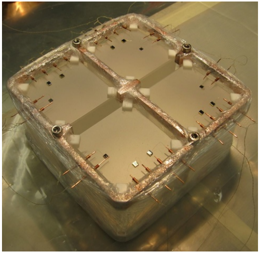




MiDBD

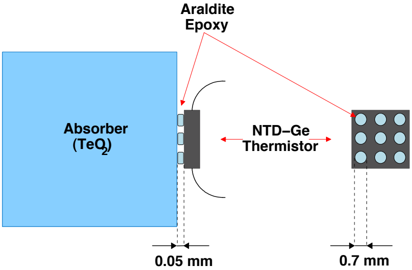


CUORICINO



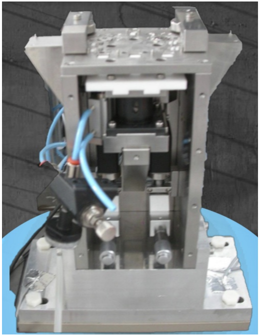
CCVR

Gluing

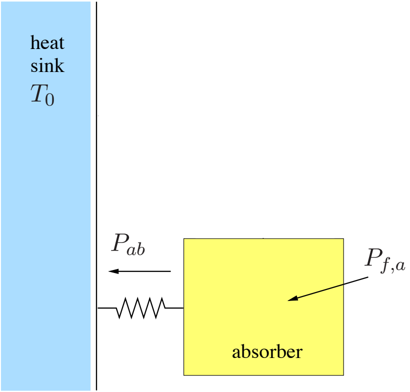


Araldite
Epoxy
Absorber
(TeO_2)
NTD–Ge
Thermistor
0.05 mm
0.7 mm

ABB
Clean Room
ABB



Thermal Model



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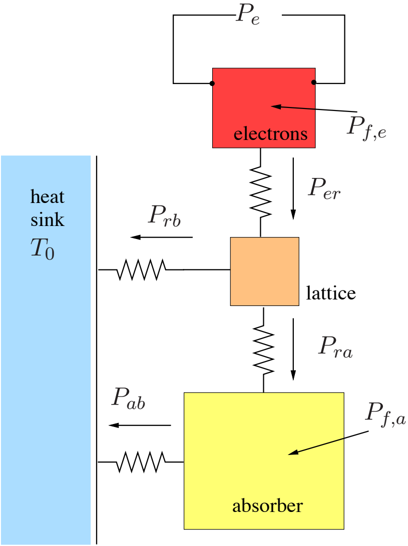

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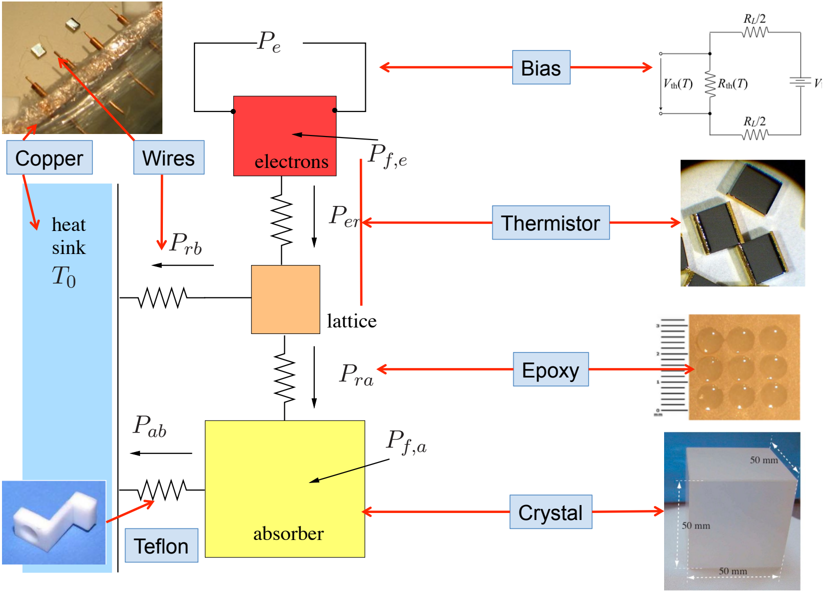
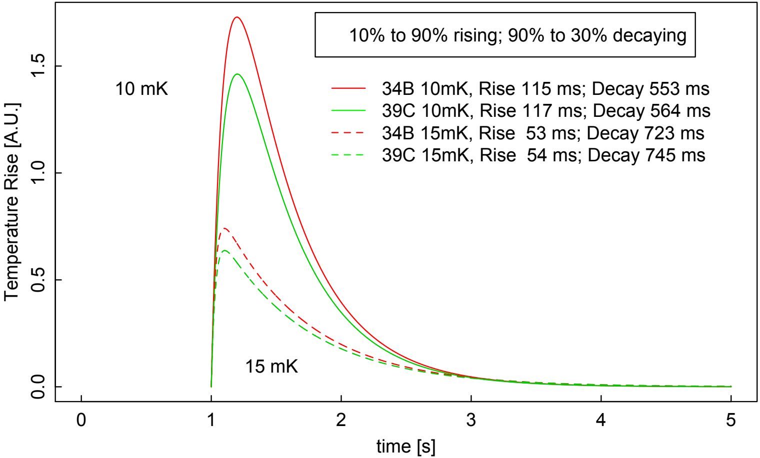


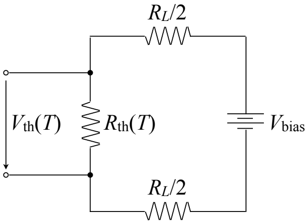
Temperature Rise

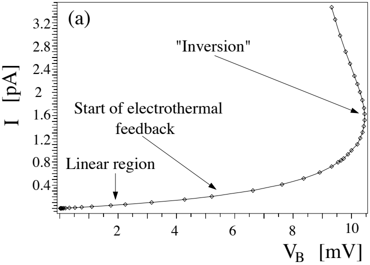


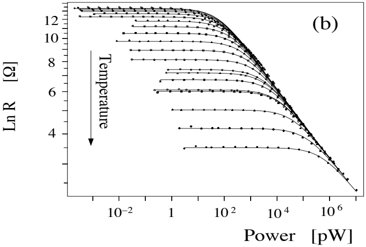
◇ Time scale ◇ Pulse height ◇ Pulse shape

Bias Circuit and Electrothermal Feedback

- Programmable bias voltage and load resistance.
- $R_L \gg R_{th}$, constant current bias $\Rightarrow$ Electrothermal feedback.
- Optimum point (with max S/N) is close to maximum signal pulse height point.







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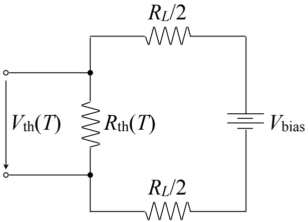
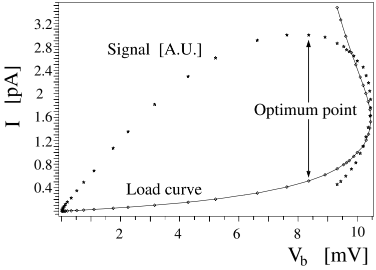
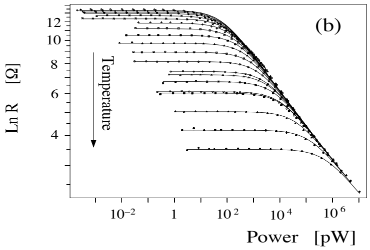
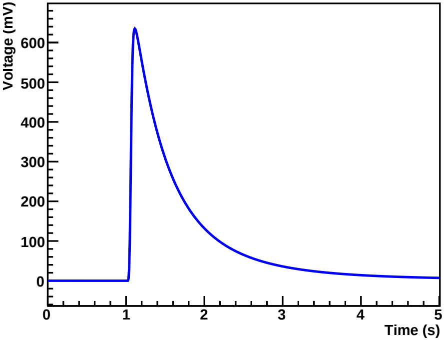






Data Acquisition System

- High accuracy M series digitizer from NI
- 18-bit, 500kS/s
- Fiber-optic for electrical isolation from PXI crate to PC.



- 125 Hz sampling rate
- 5s pulse window, 1s pre-trigger
- Continuos data also recorded for offline triggering

Calibration

^{232}Th source:

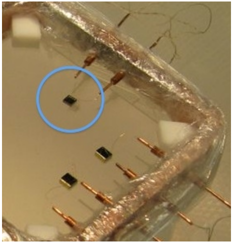
- 3 days every month
- 2615 keV γ

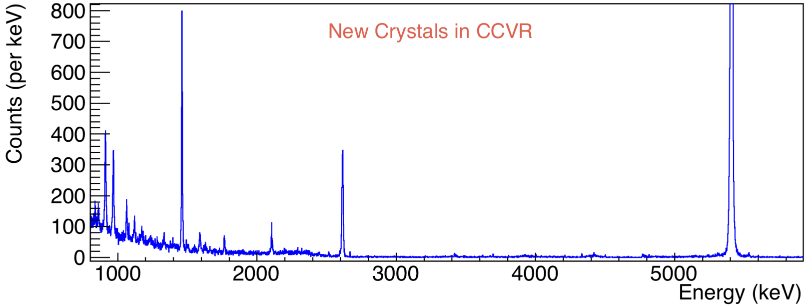
Radio-impurity

- ^{210}Po: α; ^{40}K: γ

Reference Si heater:

- One pulse per 5 min
- Negligible heat capacity
- Constant R over T
- Programmable pulser in FEE





Noise Contributions

- Intrinsic
  - Thermodynamic limit: for phonon energy $\varepsilon = k_B T$,

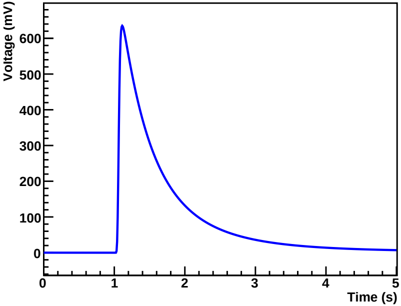
$$\Delta E = \sqrt{N} \cdot \varepsilon = \sqrt{\frac{C(T) \cdot T}{\varepsilon}} \cdot \varepsilon = \sqrt{k_B C(T) T^2} \sim 10eV$$

  - Resistor's Johnson noise due to the fluctuations of charge carriers:

$$\Delta V^2 = 4 k_B T R \Rightarrow \sim 300eV$$

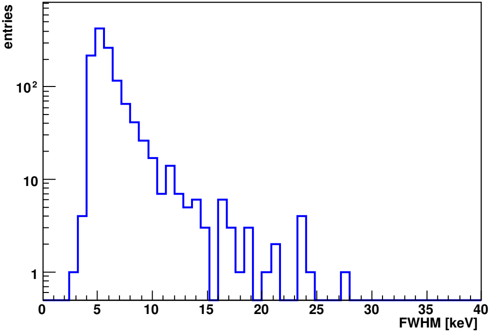
- Extrinsic
  - Vibrations
  - Microphonics
  - Pre-Amp noise

Energy resolutions



- Working T, thermistor, working point ⇒ pulse height
- Thermal links ⇒ pulse shape
- Vibrations ⇒ noise

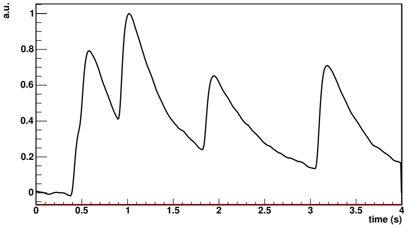
- CCVR (best): 3keV FWHM at 5.4MeV
- CUORICINO: long term stability.
- CUORE aims for 5 keV at ROI.



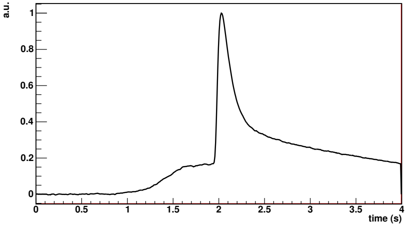
CUORICINO FWHM at 2615 keV

Rejecting spurious pulses

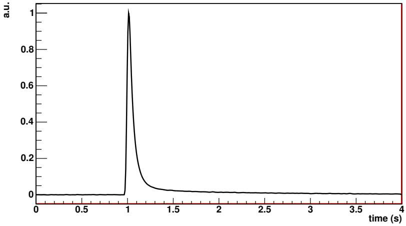
- Number of pulses
- Baseline slope
- Decay time
- Max points position



multiple event pile-up

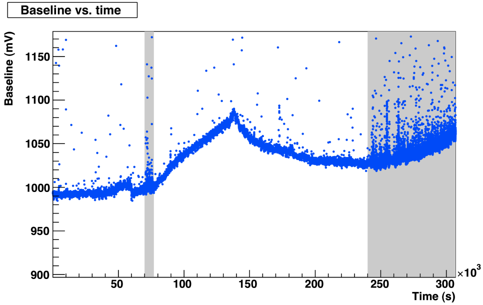


pile-up with a non-particle event

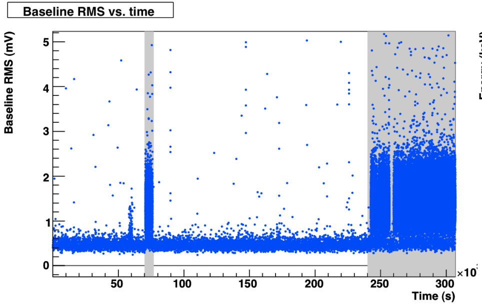


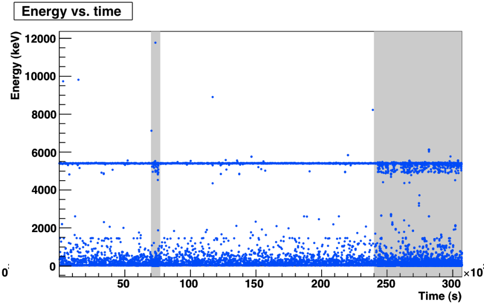
Spike (possibly decay in thermistor)

Rejecting bad intervals

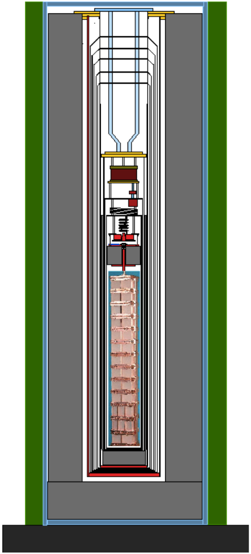


- Can correct for (small) baseline drift.
- But not for baseline noise: dead time of the measurement
- Noisy intervals tagged in database.





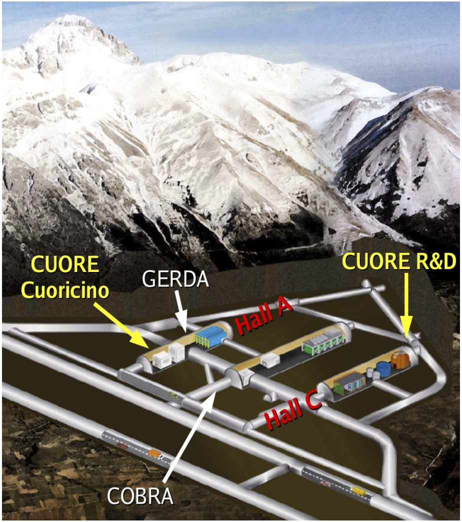
Cuoricino – little CUORE



- March 2003 to May 2008
- 44 (11 $\times 4$) 5x5x5 cm^3, 790 g TeO_2, natural I.A. of 34% of ^{130}Te.
- 18 (2 $\times 9$) 3x3x6 cm^3, 330 g TeO_2. From MiDBD.
  - Two enriched to 75% of ^{130}Te (I.A.)
  - Two enriched to 82% of ^{128}Te (I.A.)
- Totally 40.7 kg of TeO_2, including 11 kg of ^{130}Te.
- Total exposure 19.8 kg·y.
- Average energy resolution 8 keV at $Q_{\beta\beta} = 2527$ keV

LNGS Underground Facility

- Laboratori Nazionali del Gran Sasso
- Horizontal access through A24 highway tunnel
- Average depth: ~3650 m.w.e. Muon Flux: $(2.58\pm0.3)\times10^{-8}$ per(s cm^2)
- Three experimental halls. Cuoricino/CUORE at Hall A; CUORE R&D work (e.g. CCVR) in Hall C.



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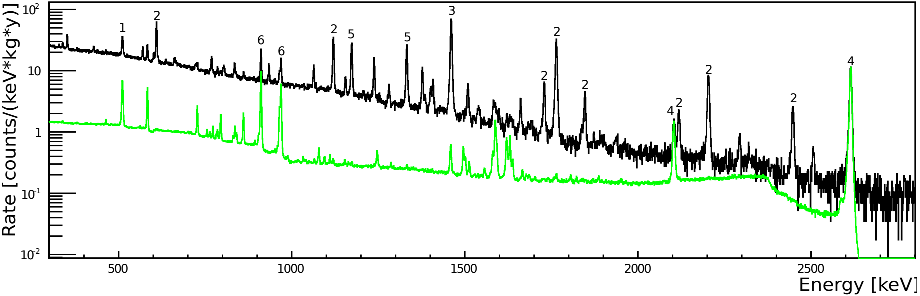
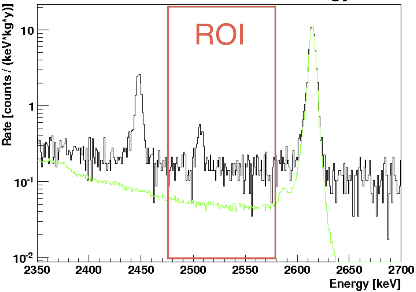


(1) e^+e^-; (2)^{214}Bi; (3)^{40}K; (4)^{208}Tl; (5)^{60}Co; (6)^{228}As; Green: cal; Black: BG

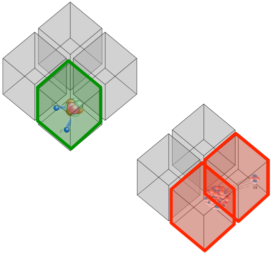
Background in the ROI:

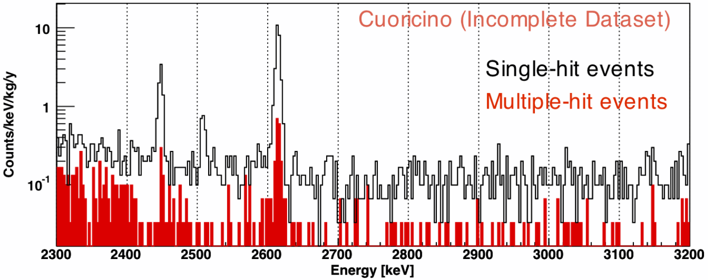
- (40±10)%: from γ peak of ^{208}Tl
- (50±20)%: α from copper
- (10±5)%: α from surface contamination of crystals

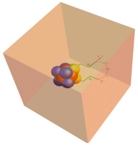
Total BG: 0.17 ± 0.01 cts/(keV kg y)



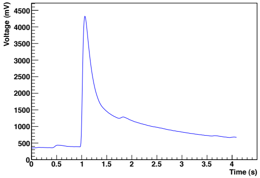
- Anti-coincidence cut (100 ms) window rejects α from crystal surfaces.
- In the ROI, the reduction is about 20%.
- Does not work for α from copper
- The array does self-shield some surfaces from copper







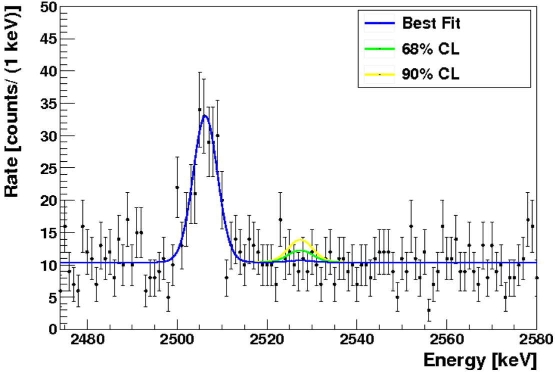
a β may escape



pulse degraded due to noise

Source	Signal efficiency (%)
Energy escape	87.4±1.1 (big crystals) 84.2±1.4 (small crystals)
Pulse-shape cuts	98.5±0.3
Anti-coincidence cut	99.3±0.1
Noise	99.1±0.1
Pile-up with reference pulses	97.7
Total	82.8±1.1 (big crystals) 79.7±1.4 (small crystals)

Cuoricino results



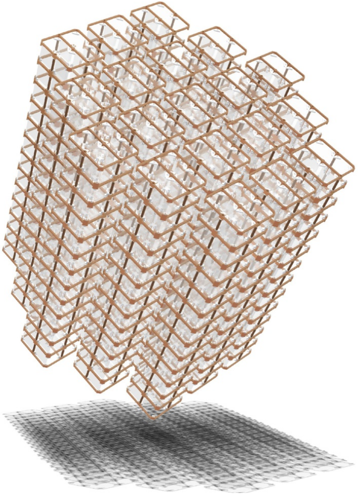
No peak found

$$\Gamma^{0\nu}_{best} = -0.25 \pm 1.44(stat) \pm 0.3(syst)) \times 10^{-25}\, y^{-1}$$

$$\tau^{0\nu}_{1/2} \geqslant 2.8 \times 10^{24}\, y \text{ at 90\% C.L.}$$

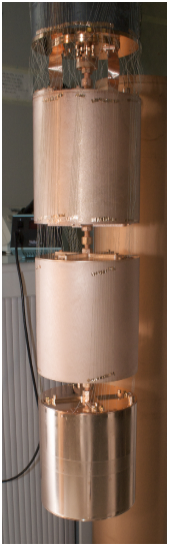
arXiv:1012.3266

CUORE



- Cryogenic Underground Observatory for Rare Events
- 988 TeO_2 crystals, $19 \times 13 \times 4$; 204 kg ^{130}Te

CUORE – Background reduction



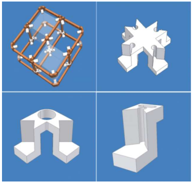
- Three Tower Test (TTT)
  - Bolometric test to compare and validate the copper shielding cleaning procedures.
  - Run in hall A Cuoricino cryostat
  - Comparable γ bg at $Q_{\beta\beta}$, $\times 3$ reduction for α at 3 to 4 MeV when comparing to Cuoricino
  - Baseline cleaning confirmed: plasma cleaning
- Minimize copper frame material facing crystals
- Detector assembly in clean room and anti-radon box
- Target at 0.05 counts/(kg keV y) – CUORE-0 test.

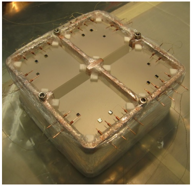
Factoring in:

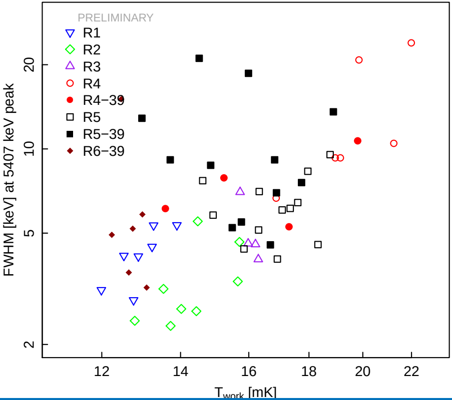
- New radiopure cryostat
- Anti-coincidence and self-shielding
- Target at 0.01 counts/(kg keV y) for CUORE.

CUORE – Energy resolution

- CUORE Crystal Validation Runs
- Six done, about one month each run
- Validate the radio-purity and bolometric performance of the crystals.
- CUORE-like copper frame and teflon holders
- Test bed for thermistors, temperature dependence, etc.
- Extremely encouraging results at low temperature. (CUORE: 10 mK)

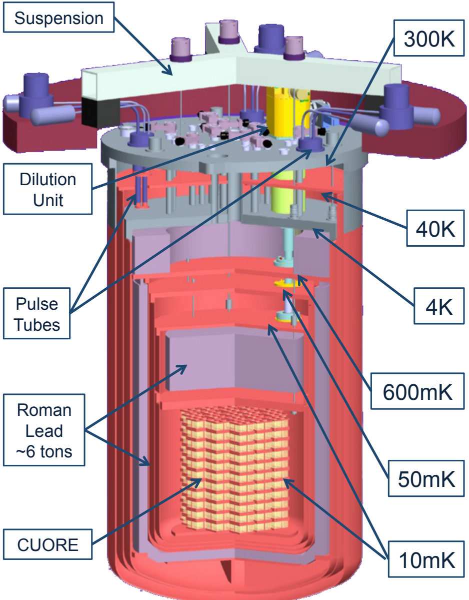


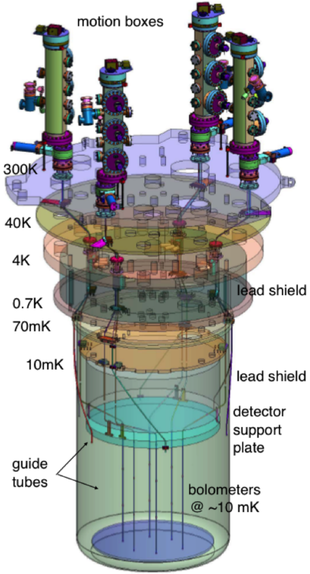




CUORE engineering – Cryostat

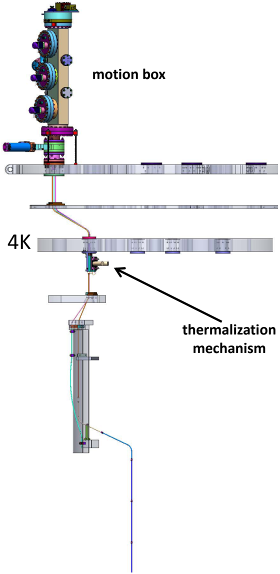
- 10 mK baseline temperature
  - 750 kg of crystal
  - ~20 tons at various T
- Low background
  - Customized cryostat built with radio-pure materials
  - Roman lead from ancient shipwreck, <4mBq/kg ^{210}Pb
- Vibrations
  - Separated suspension for the crystal towers and DR.
- Minimal maintenance and dead time
  - Cryogen free DR





- Even illumination on each crystal
  - 6 strings in between towers
  - 6 strings around
- 4 motion boxes with 3 motors each to lower sources
  - $\sim$800 cycles during CUORE live time
- Adhere to heat load requirements (Critical to duty cycle)
  - Cooling power through contact with guide tubes not sufficient
  - Dedicated thermalization mechanism at 4K
  - Minimize friction

CUORE engineering – Calibration system



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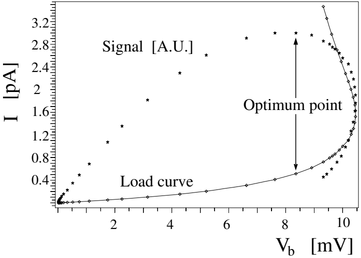
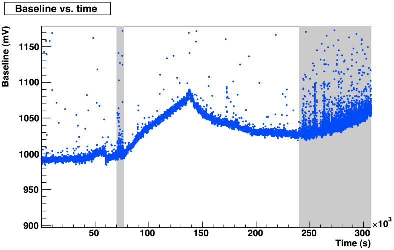
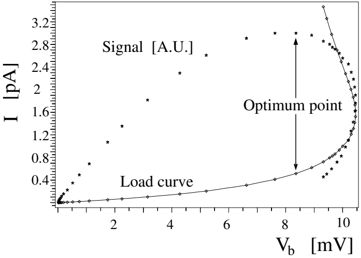
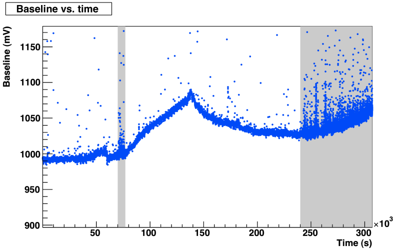
CUORE engineering – Software (example)





CUORE engineering – Software (example)

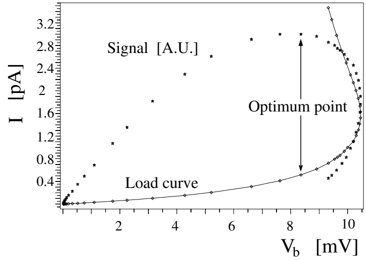


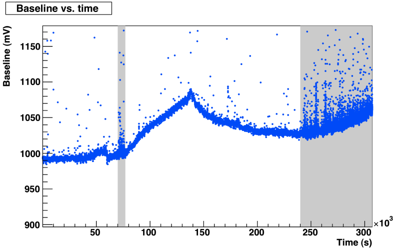


X1000

X1000

CUORE engineering – Software (example)





X1000

X1000

- Automated working point finder
- WP info stored in DB
- Multiple WP's possible

- CUORE Online/Offline Run Check
- Better way to visualize
- Automated noisy period finder

Future

Half life sensitivity $\propto \eta \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$

Isotopic abundance	Detecting efficiency	Detector mass	Background rate	Energy resolution	Measuring time
$\times 1$	$\times 1$	$\times 19$	$\times 1/17$	$\times 1/1.6$	$\times 2.5$

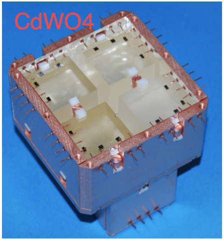
When comparing CUORE to Cuoricino.

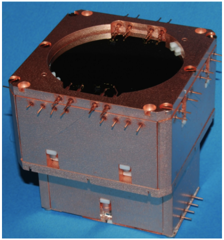
- Overall, $\sim$40$\times$ more sensitivity. $\tau^{0\nu}_{1/2} \sim 10^{26}$ y
- Expect to see CUORE data taking in 2013.

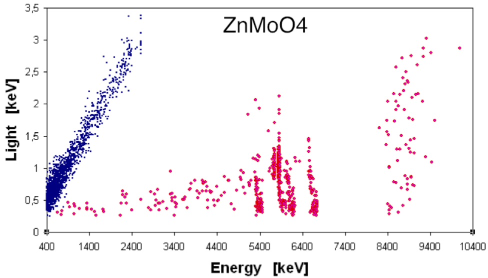
Bolometer R&D – New DR at 75 LeConte

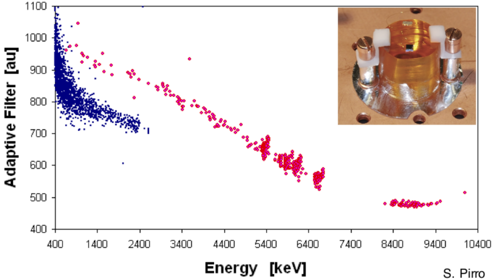
- TRITON400 from Oxford Instruments
- Cryogen free dilution refrigerator
- 10 mK base temperature.
- Cooling power of 400 μW at 100 mK.
- Fast cooling down in $<$24h
- 240 mm x 240 mm sample space
- Ultra-low vibration
- Semi-portable: underground lab

Scintillating Bolometer



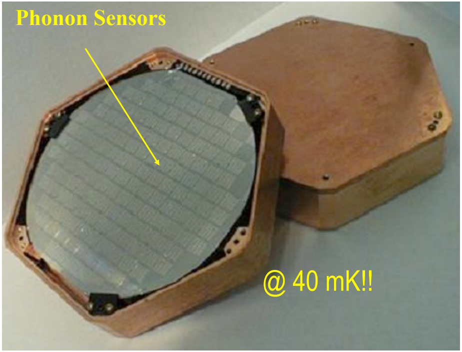






S. Pirro

Even Ionization, like CDMS



CDMS II ZIP detector