Cosmogenic Activation in CUORE

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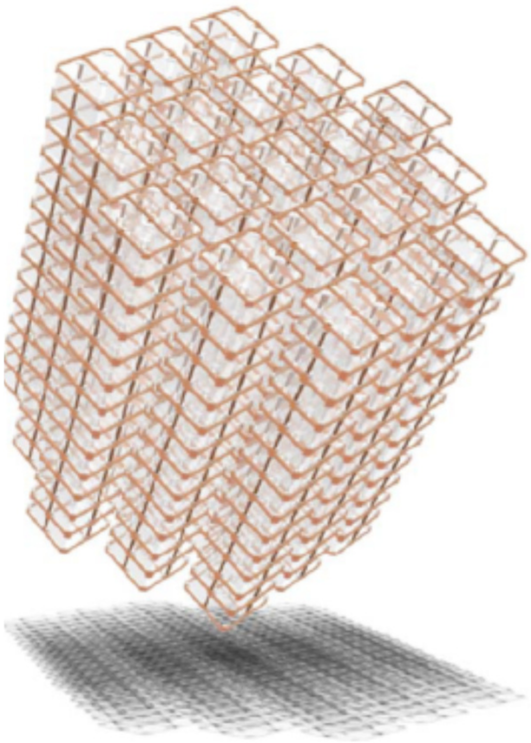
Overview

- **Cryogenic Underground Observatory for Rare Events (CUORE):**
  - Search for **neutrinoless double-beta decay (0νDBD)**
  - Understand nature of ν

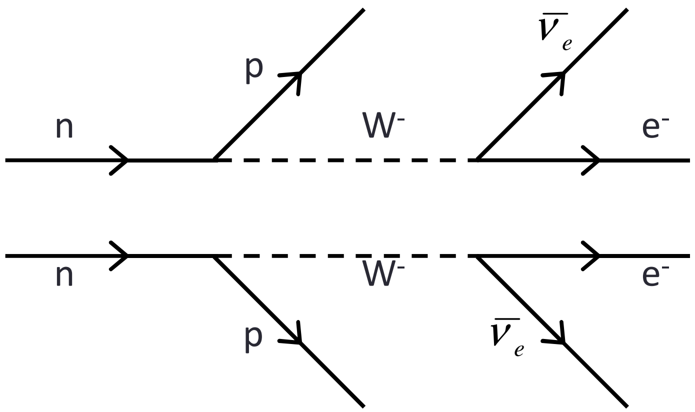
- **Background analysis/characterization important:**
  - Need **low background** to see 0νDBD signature
  - Remove reducible sources of background
  - Minimize irreducible sources of background

- **Background in CUORE from cosmogenic activation highly uncharacterized:**
  - Measure cross-sections for cosmogenic activation of detector materials.
  - Estimate the cosmogenic activation background that will be present in CUORE

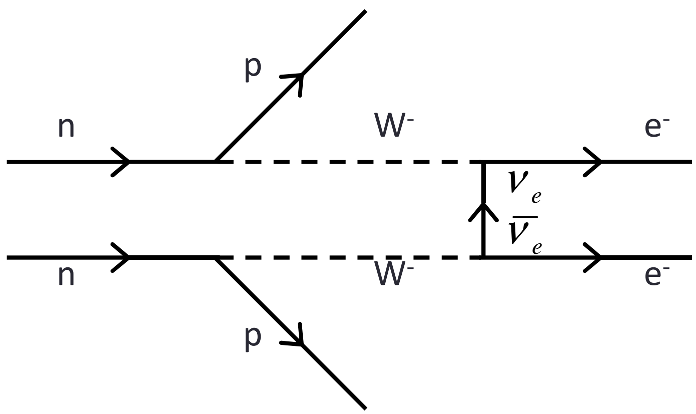


Double-beta Decay

- 2νDBD: $(A,Z) \longrightarrow (A,Z+2) + 2e^{-} + 2\bar{\nu}_e$
  - Observed for several nuclei (e.g., ^{76}Ge, ^{130}Te, ^{136}Xe)

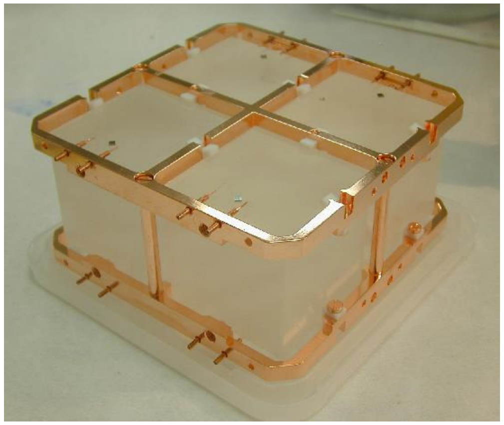


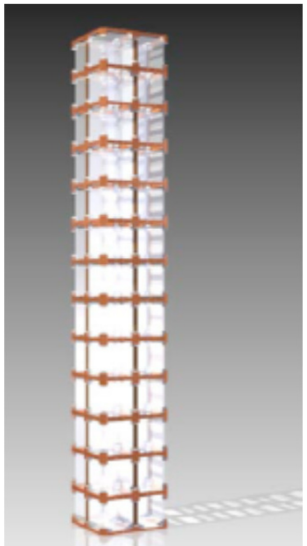
- 0νDBD: $(A,Z) \longrightarrow (A,Z+2) + 2e^{-}$
  - Never observed
  - New physics: nature of ν
    - Dirac ($\bar{\nu} \neq \nu$) or Majorana ($\bar{\nu} = \nu$)?
    - Neutrino mass scale and hierarchy

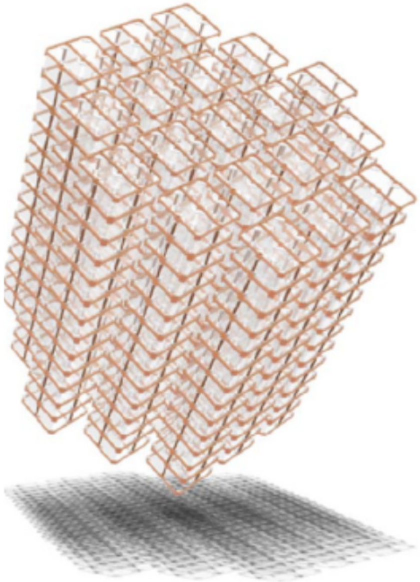


CUORE Detector

- Located underground at the Gran Sasso National Laboratory (LNGS) in Italy
- Will start taking data in 2015
- 988 TeO_2 bolometers at ~10 mK (Natural Te used)
- $^{130}Te \longrightarrow {}^{130}Xe + 2e^-$
  (Q = 2527 keV . Isotopic abundance of ^{130}Te is 34%.)

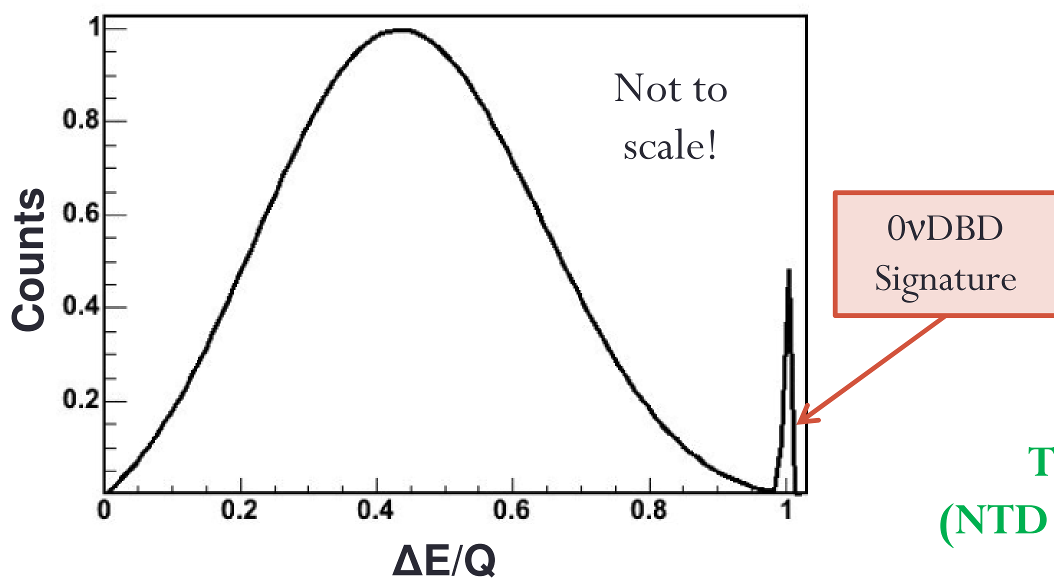


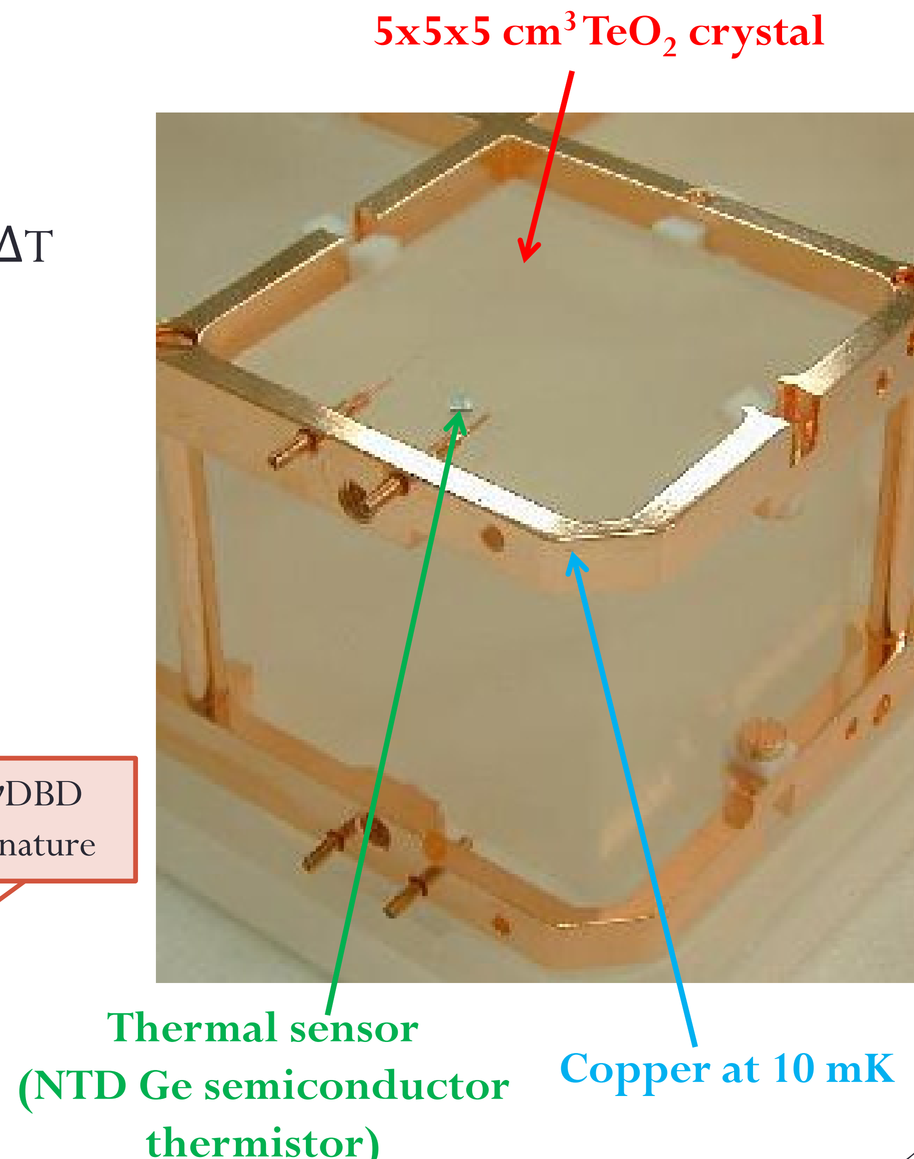




CUORE Detector: Bolometer

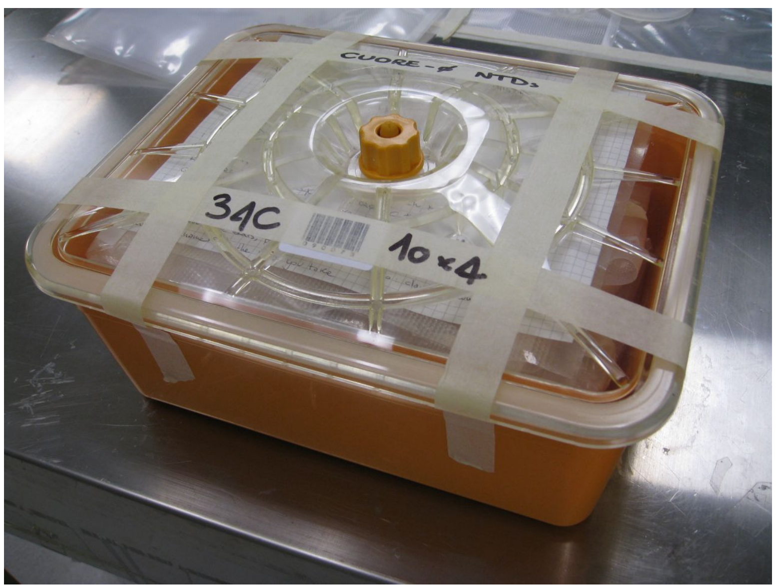
- **Bolometer mechanics:**
  - Interaction in TeO_2
  - Temperature rise (ΔT) measured
  - Interaction energy derived from $E = C\Delta T$ (C = heat capacity)
- **0νDBD: $(A, Z) \rightarrow (A, Z+2) + 2e^-$**
  - Bolometer sees peak at Q-value





Cosmogenic Activation in CUORE

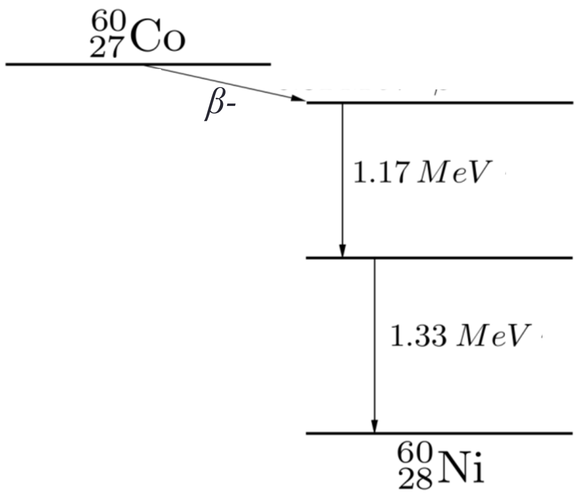
- **Cosmogenic activation: interactions with cosmic rays produce radioisotopes in materials**
  - Problematic for **TeO_2 crystals**
  - Occurs during transportation by boat from crystal production site in China to experiment site in Italy. **Crystals spend ~ 3 months at sea-level.**
  - No shielding is used to protect against cosmic rays

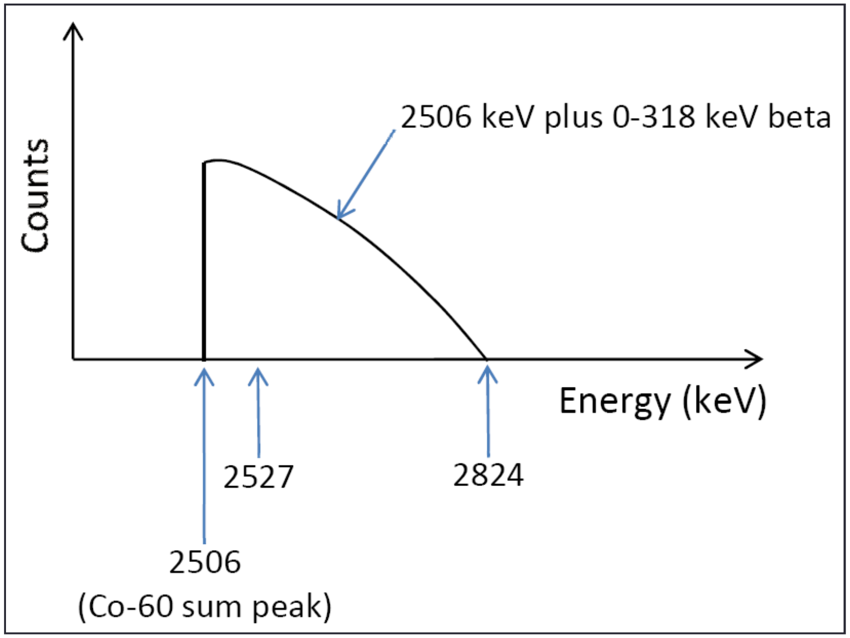


Cosmogenic Activation in CUORE

- Long-lived radioisotopes contribute background to 0νDBD region (around 2527 keV peak).

Example: Beta decay of Co-60 ($t_{1/2}$ = 5.27 y)



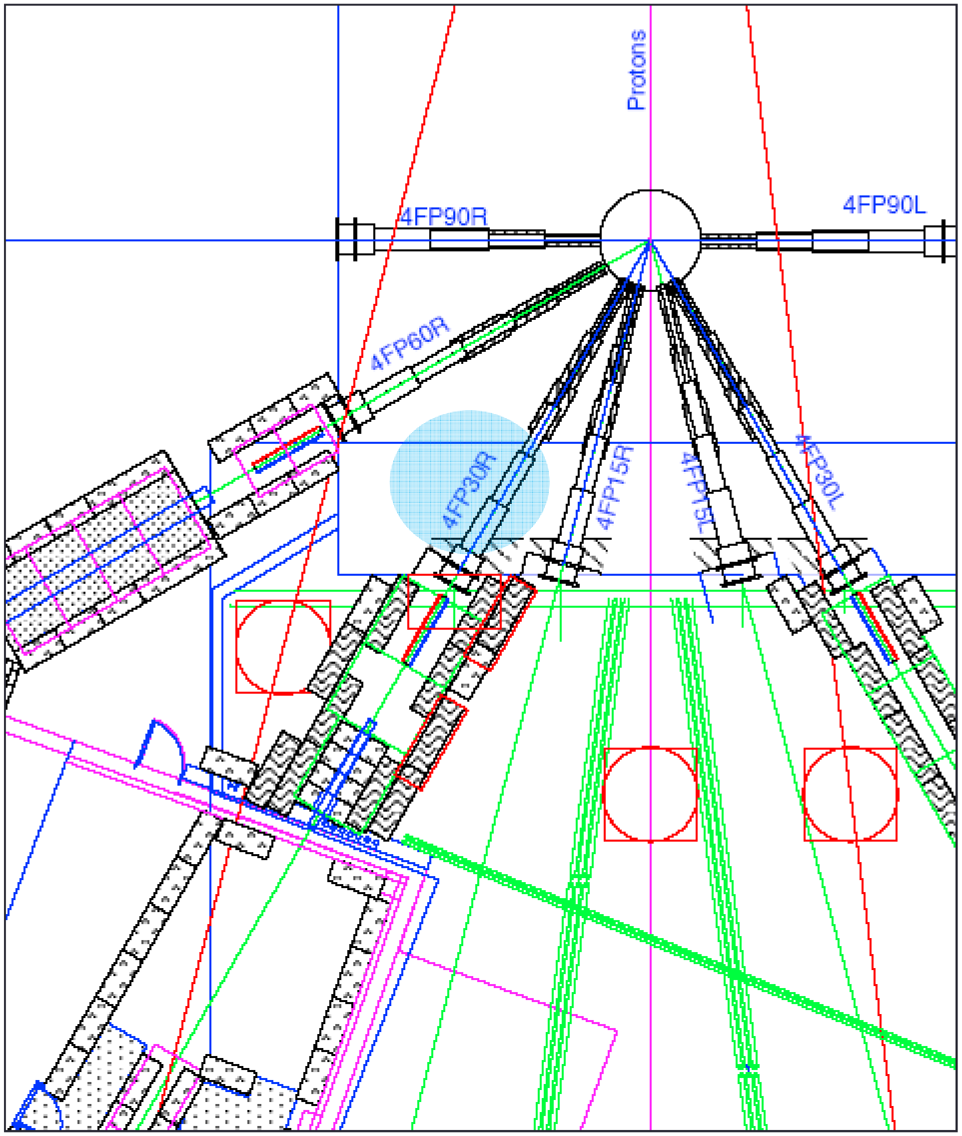


- Good estimation of this background needed
  - Difficult to obtain ⟶ **lack cross-section data**

Cosmogenic Activation Background Analysis

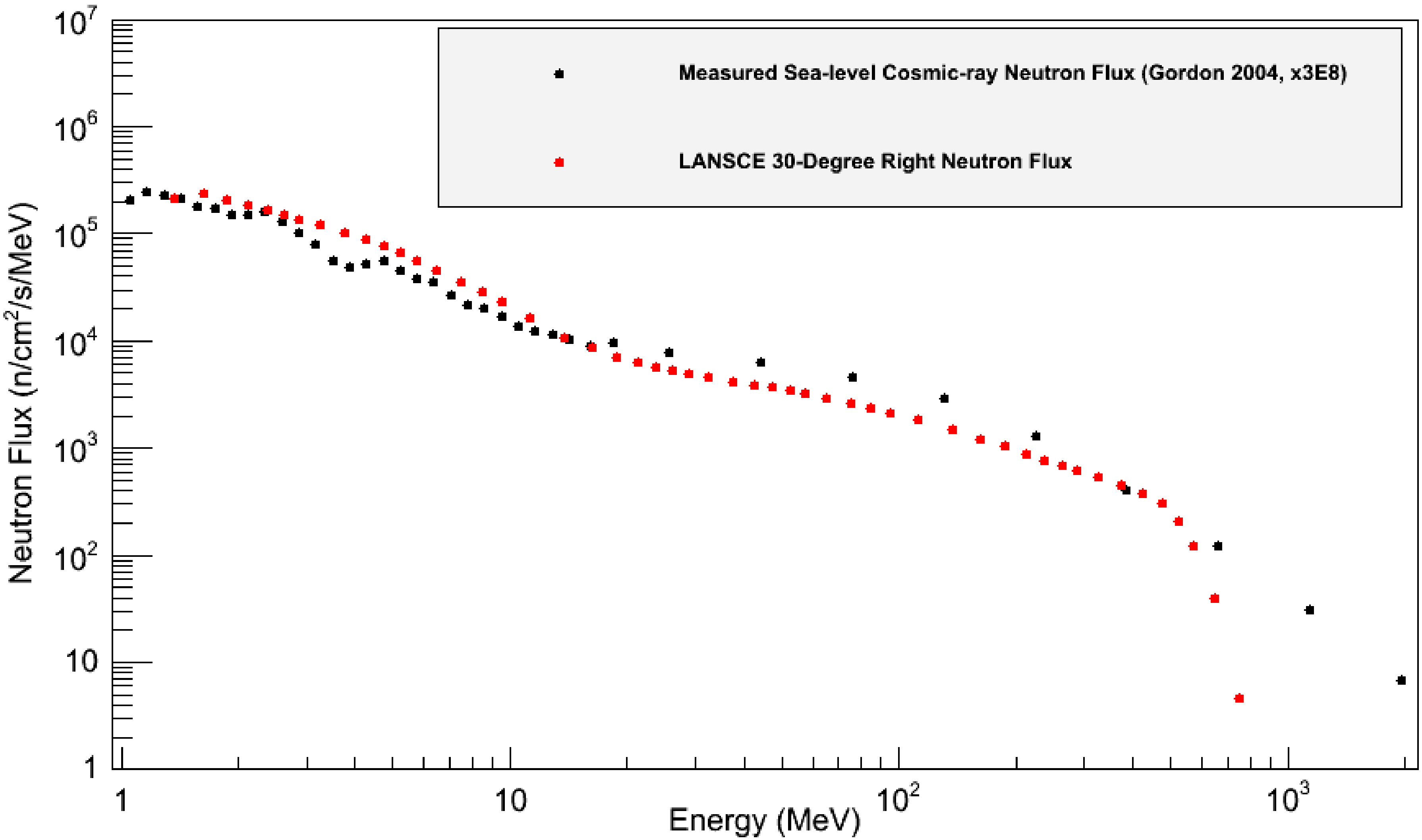
- **Cross-section measurements have been performed for neutron activation of radioisotopes in TeO_2.**
  - Why neutrons?
    - Cosmogenic activation at sea-level mostly due to interactions with cosmic ray hadrons, of which **neutrons make up 97%.**
  - **Neutron energy range of interest? → 18-800 MeV**
    - Activation cross-sections exist for neutron (and proton) energies outside this range.
- **Use data from measurements to:**
  - Identify isotopes produced in TeO_2
  - Identify isotopes that can contribute background to $0\nu\beta\beta$ region
  - Estimate total cosmogenic background present in $0\nu\beta\beta$ region in CUORE.

Neutron Beam at LANSCE

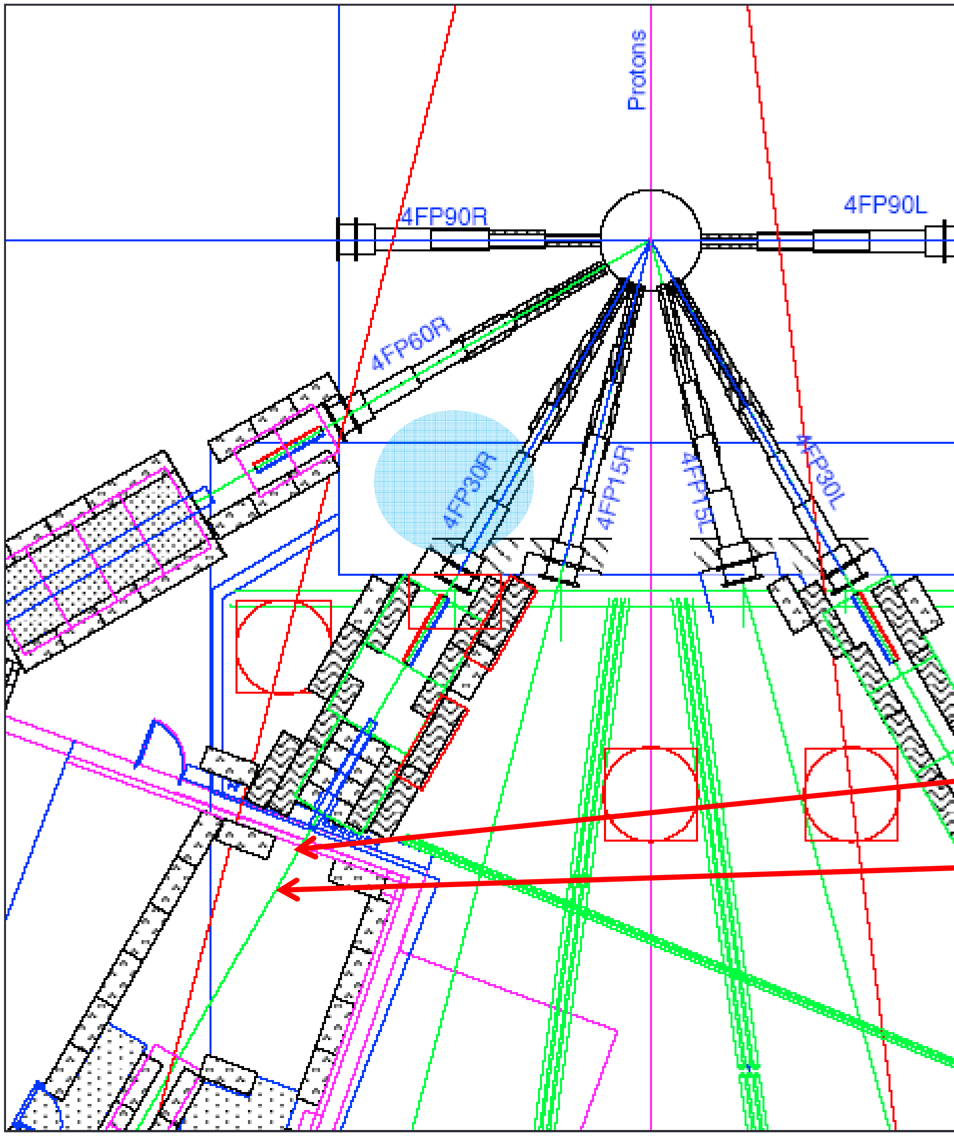


- At LANSCE (Los Alamos Neutron Science Center), **neutrons with energies 0-800 MeV** are produced by spallation of 800 MeV protons on tungsten.
- Flux-shape of neutrons along **30^0-right flight path** very similar to that of cosmic ray neutrons at sea level.

LANSCE Neutron Flux Compared with Sea-level Cosmic-ray Neutron Flux

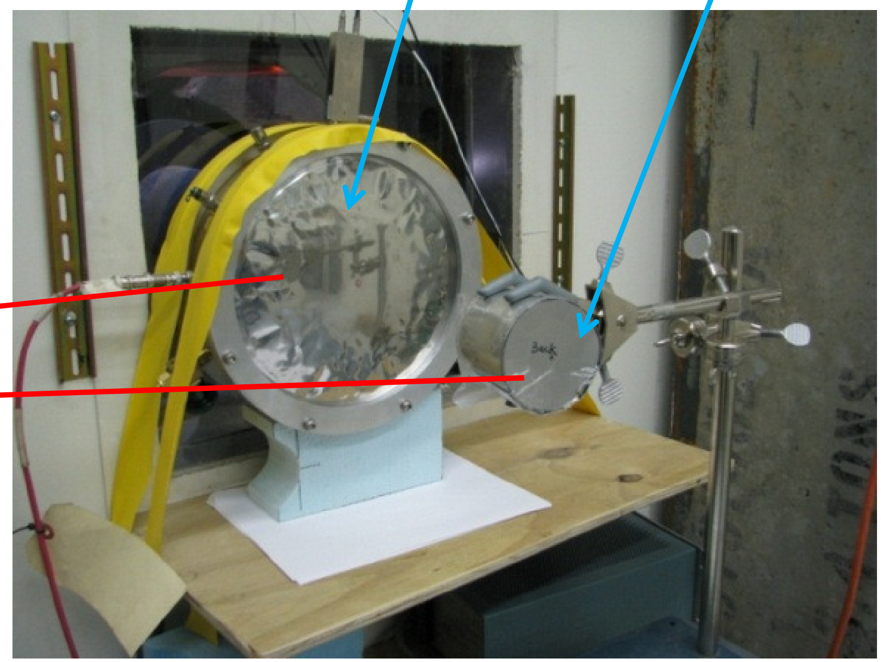


Obtaining the Neutron Spectrum at LANSCE



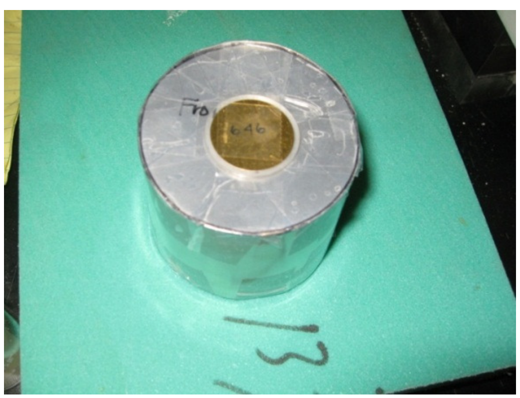
U-238 fission ionization chamber (located upstream of target) and **time-of-flight** used to obtain **neutron spectrum from 1.25 MeV to 800 MeV**

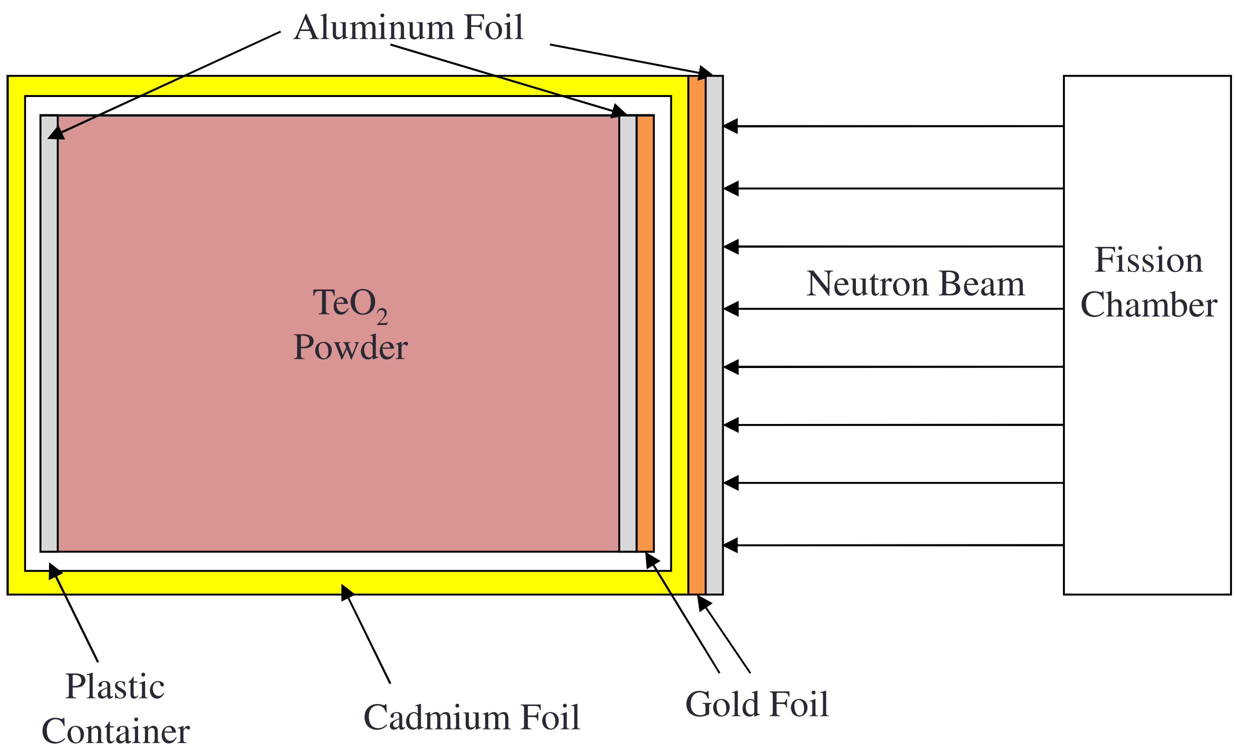
Target



Cross-section Measurement at LANSCE

- **Experiment dates:** February 25-27, 2012
- **Target:** 272 g TeO_2 powder
  - Aluminum foils track neutron attenuation
  - Cadmium foil removes thermal neutrons
  - Gold foils provide information on neutrons with energies < 1.25 MeV
- **Irradiation time:** 42 hours
- **Neutron flux:** 1.4E6 n/cm^2/s
- **Source-target distance:** 14.14 m
- **Beam spot diameter at target:** 8.4 cm
- **Target diameter:** 6.4 cm

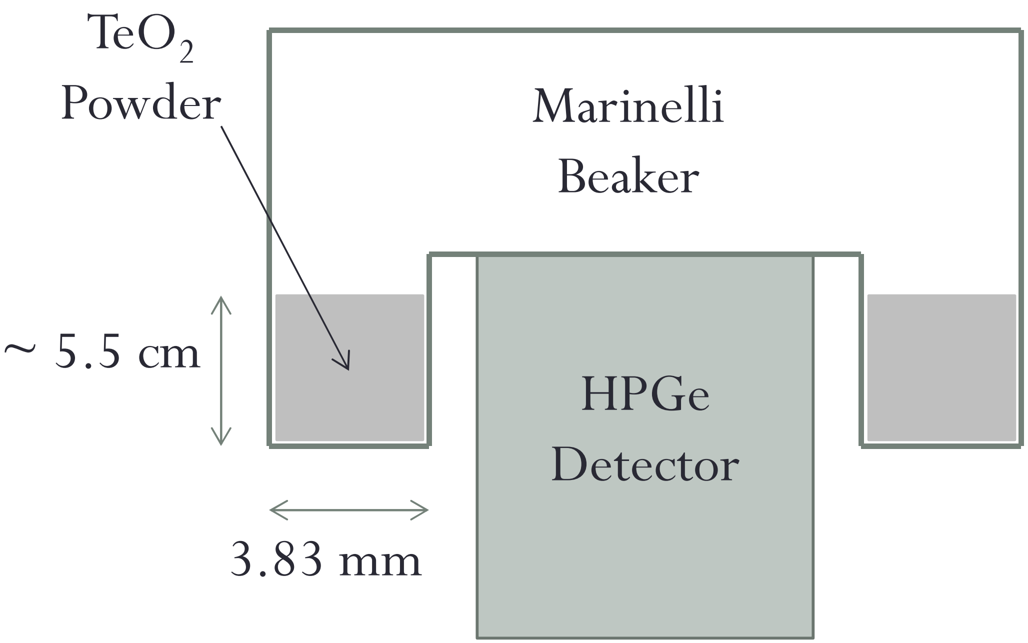




Counting TeO_2 Powder

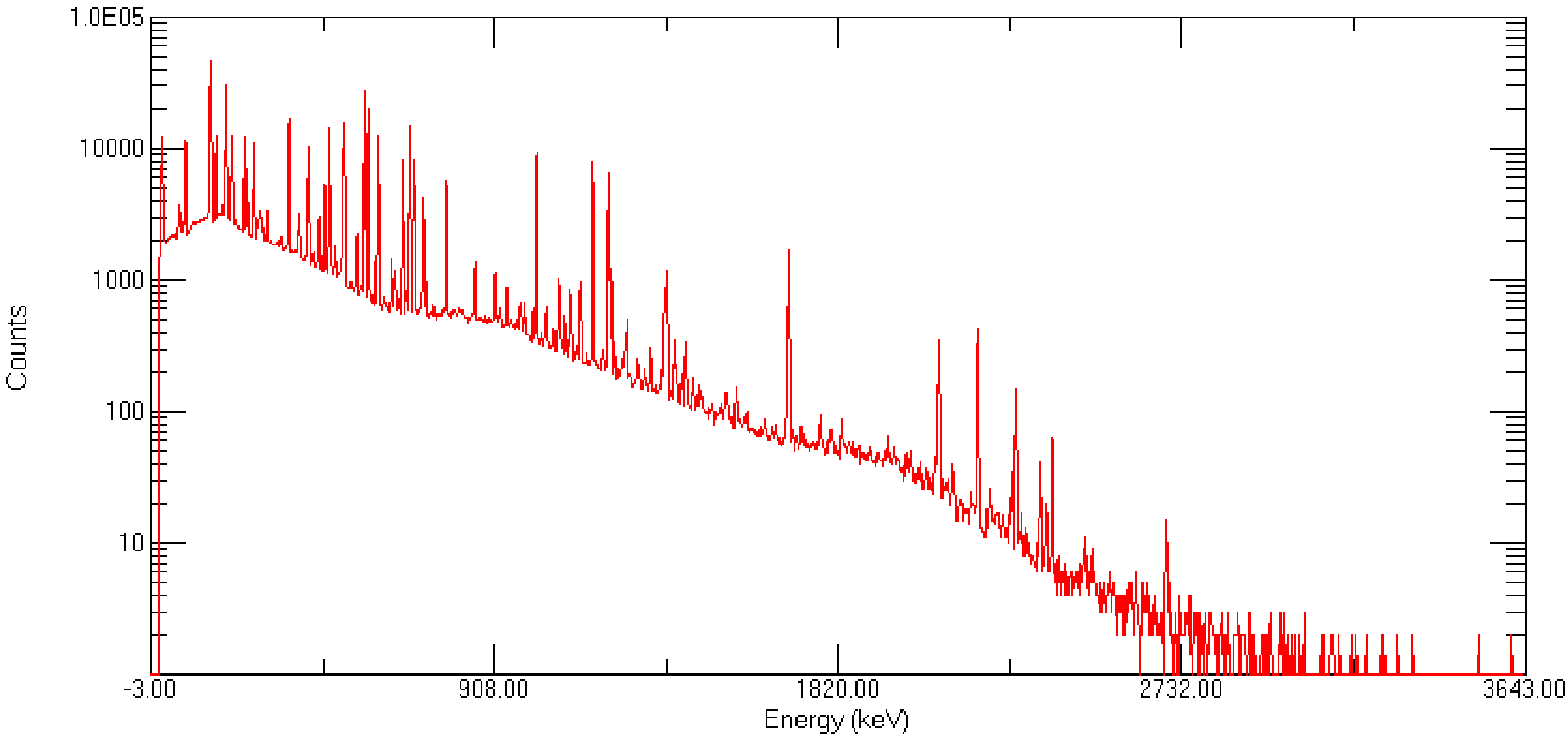
- TeO_2 powder thoroughly mixed and placed in Marinelli beaker for counting with HPGe detector
- Purpose of Marinelli beaker:
  1) Maximize surface area of detector exposed to TeO_2 powder
  2) Minimize self-attenuation through TeO_2

(Photo taken from: http://www.ga-maassociates.com)



TeO_2 Powder Spectrum

1-hour long spectrum collected 7 days after irradiation



Radionuclides Present in TeO_2	Half-life
Te-118	6.00 d
Te-119m	4.7 d
Te-121	19.17 d
Te-121m	164.2 d
Te-123m	119.2 d
Te-125m	57.4 d
Te-127 (Te-127m and Sb-127 parents)	9.35 h
Te-127m	106.1 d
Te-129 (Te-129m parent)	69.6 m
Te-129m	33.6 d
Te-131 (Te-131m parent)	25 m
Te-131m	33.25 h
Xe-131m (Te-131m parent)	11.84 d
Sb-118 (Te-118 parent)	3.6 m
Sb-119 (Te-119m parent)	38.19 h
Sb-120m	5.76 d
Sb-122	2.7238 d
Sb-124	60.2 d
Sb-125	2.75856 y

Radionuclides Present in TeO_2	Half-life
Sb-126	12.35 d
Sb-127	3.85 d
Sn-113	115.09 d
Sn-117m	14 d
Sn-123	129.2 d
Sn-125	9.64 d
Rh-100	20.8 h
Rh-101m	4.34 d
In-111	2.8047 d
In-114m	49.51 d
I-126	12.93 d
I-131 (Te-131m parent)	8.0252 d
Cd-115	53.46 h
Ag-105	41.29 d
Ag-106m	8.28 d
Ag-110 (Ag-110m parent)	24.6 s
Ag-110m	249.76 d
Ag-111	7.45 d
Be-7	53.24 d

Isotopes that Contribute to 0vDBD Region

Isotope	Half-life	Mode of Decay	Q-value of Decay (keV)
Te-119m	4.7 d	Electron capture / Beta plus	2554
Sb-118 (Te-118 parent)	3.6 m	Electron capture / Beta plus	3657
Sb-120m	5.76 d	Electron capture / Beta plus	$2681+E_{ex}$
Sb-124	60.2 d	Beta minus	2904
Sb-126	12.35 d	Beta minus	3673
Rh-100	20.8 h	Electron capture / Beta plus	3635
Ag-106m	8.28 d	Electron capture / Beta plus	3055
Ag-110 (Ag-110m parent)	24.6 s	Beta minus	2892
Ag-110m	249.8 d	Beta minus	3010

- Last shipment of TeO_2 crystals will arrive at LNGS around March 2013.
- CUORE will begin taking data in early 2015.
- **Ag-110m** will be main contributor to background in $0\nu\beta\beta$ region because of its long half-life (249.8 days).

Flux-averaged Cross-sections

- **Flux-averaged cross-sections obtained from peaks in the gamma spectra:**

$$\bar{\sigma}_i = \frac{\int_{1.25\text{ MeV}}^{800\text{ MeV}} \sigma_i(E)\varphi(E)\,dE}{\int_{1.25\text{ MeV}}^{800\text{ MeV}} \varphi(E)\,dE} = \frac{c_i R_i}{N \int_{1.25\text{ MeV}}^{800\text{ MeV}} \varphi(E)\,dE}$$

$c_i \equiv$ Correction factor needed if threshold energy for reaction is < 1.25 MeV. Equals 1 if threshold is > 1.25 MeV

$R_i \equiv$ Production rate for nuclide "i"

$N \equiv$ Number of target nuclei

$\varphi(E) \equiv$ Differential neutron flux $\left[\text{n/MeV/cm}^2\text{/s}\right]$

$\bar{\sigma}_i(E) \equiv$ Cross-section at E $[\text{mb}]$

$$R_i = \frac{\lambda_i C_\gamma}{\varepsilon_\gamma B_\gamma \left[\exp(-\lambda_i t_{start}) - \exp(-\lambda_i t_{end})\right]\left[1 - \exp(-\lambda_i t_{irrad})\right]}$$

$\lambda_i \equiv$ Decay constant of nuclide "i"

$C_\gamma \equiv$ Number of counts at energy of interest

$\varepsilon_\gamma \equiv$ Absolute peak efficiency of γ with energy of interest

$B_\gamma \equiv$ Branching ratio

$t_{start} \equiv$ Start time of counting relative to the end of irradiation

$t_{end} \equiv$ End time of counting relative to the end of irradiation

$t_{irrad} \equiv$ Irradiation time

Efficiency Measurement for TeO_2 Powder

- **"Natural source method"**
  1) Create source of known activity that has same density and geometry as sample of interest.
  2) Use source to determine the absolute peak efficiencies at multiple gamma-energies.

- **Natural source mixture:**

Compound	Mass (g)	Activity (Bq)
TeO_2 powder	228	0
Lu_2O_3 powder	6	278
La_2O_3 powder	23	17
K_2SO_4 powder	14	194
Total	271	489

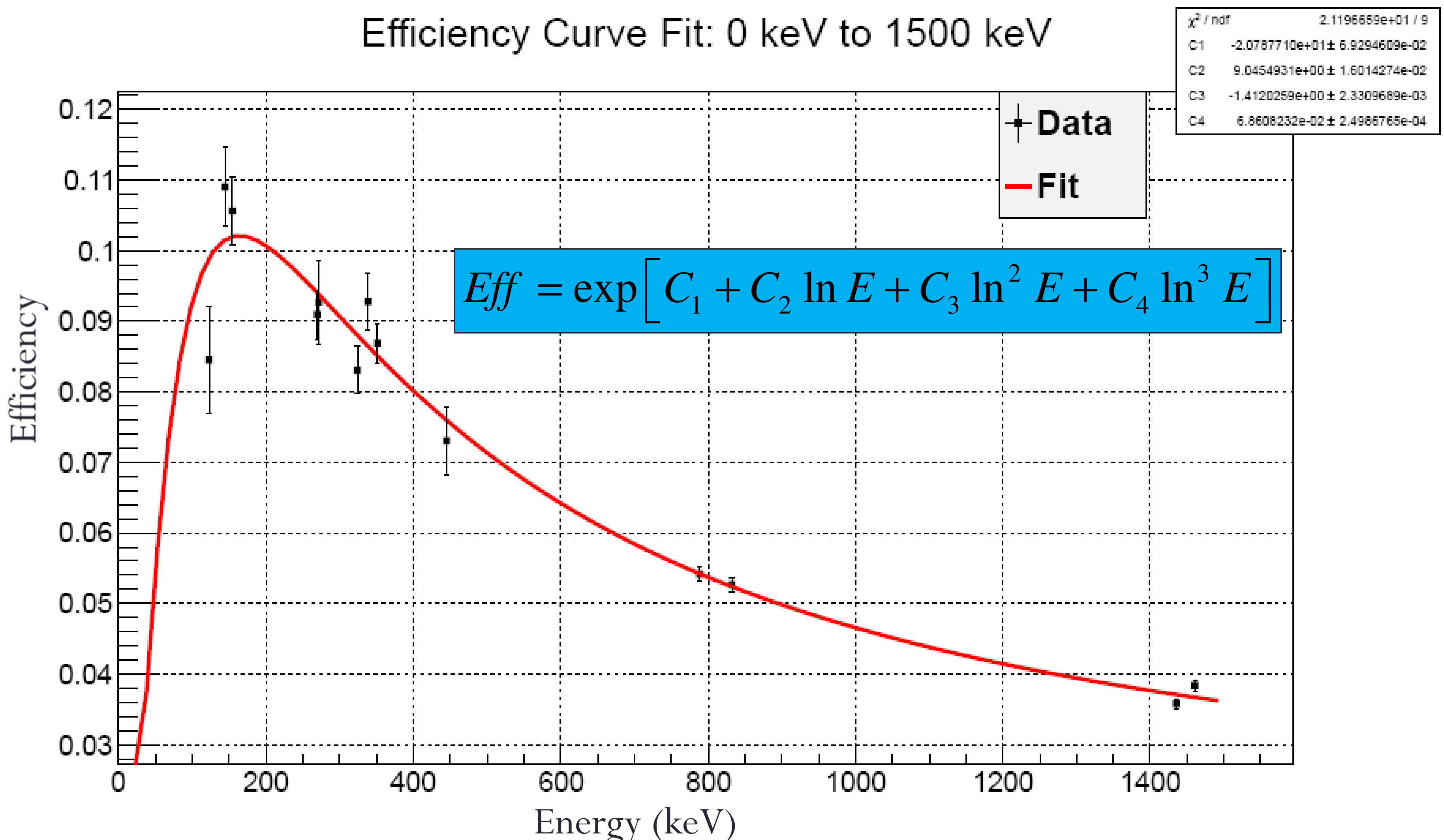
All elements have their natural composition. No enrichment performed.

- La_2O_3 was contaminated with Ac-227. Ac-227 daughters also used to calibrate efficiency.

Gammas emitted from natural source:

Isotope	Gamma (keV) [nudat]	Intensity (%) [nudat]
Lu-176	88	14.5
Lu-176	202	78
Lu-176	307	93.6
La-138	789	34.4
La-138	1436	65.6
K-40	1461	10.66
Pb-211	832	3.52
Bi-211	351	13.02
Rn-219	271	10.8
Ra-223	122	1.209
Ra-223	144	3.27
Ra-223	154	5.7
Ra-223	269	13.9
Ra-223	324	3.99
Ra-223	338	2.84
Ra-223	445	1.29

Absolute Peak Efficiency Curve for TeO_2 Powder



Neutron Attenuation Through TeO_2 Powder During Irradiation

- Aluminum foils used to track attenuation through TeO_2 powder sample during irradiation.
- Use the reaction **Al-27(n,X)Na-22** to look at attenuation (Half-life of Na-22 = 950 days).

$$\bar{\sigma} = \frac{\int_{1.25\text{ MeV}}^{800\text{ MeV}} \sigma(E)\varphi(E)\,dE}{\int_{1.25\text{ MeV}}^{800\text{ MeV}} \varphi(E)\,dE} = \frac{R}{N\int_{1.25\text{ MeV}}^{800\text{ MeV}} \varphi(E)\,dE}$$

$$f = \int_{1.25\text{ MeV}}^{800\text{ MeV}} \sigma(E)\varphi(E)\,dE$$

Aluminum Foil Location	f (s^{-1})	Flux-averaged Cross-section (mb)
In front of Cd	$(7.0 \pm 0.3)\text{x}10^{-21}$	5.0 ± 0.5
Behind Cd, in front of TeO_2 powder	$(6.9 \pm 0.3)\text{x}10^{-21}$	4.9 ± 0.5
Behind TeO_2 powder	$(6.9 \pm 0.3)\text{x}10^{-21}$	4.9 ± 0.5

- All three f values are within error.
- Reaction threshold for Al-27(n,X)Na-22 is 23 MeV.
- Suggests there is no attenuation for neutrons with energy > 23 MeV.
- What about energies < 23 MeV? Consider looking at the Cd. Consider performing a simulation.

Looking at Low-energy Neutrons with Gold

- Gold foils used to look at neutrons in spectrum with energy < 1.25 MeV. Flux-averaged cross-sections (**uncorrected for neutrons < 1.25 MeV**) are shown below:

$$\bar{\sigma} = \frac{R}{N \int_{1.25\text{ MeV}}^{800\text{ MeV}} \varphi(E)\,dE} = \frac{\int_{0\text{ MeV}}^{800\text{ MeV}} \sigma(E)\varphi(E)\,dE}{\int_{1.25\text{ MeV}}^{800\text{ MeV}} \varphi(E)\,dE}$$

Gold Foil Location	Reaction	Reaction Threshold (MeV)	Uncorrected Flux-averaged Cross-section (mb)
In front of Cd	Au-197(n,g)Au-198	0	335 ± 35
Behind Cd, in front of TeO_2 powder	Au-197(n,g)Au-198	0	422 ± 44

- Theoretical flux-averaged cross-section is: (Obtained using cross-sections from EXFOR)

$$\bar{\sigma} = \frac{\int_{1.25\text{ MeV}}^{800\text{ MeV}} \sigma(E)\varphi(E)\,dE}{\int_{1.25\text{ MeV}}^{800\text{ MeV}} \varphi(E)\,dE} \approx 14\text{ mb}$$

- These results suggest that the neutron flux < 1.25 MeV is substantial.
- A correction must be made to the cross-section if the reaction threshold is < 1.25 MeV

Flux-averaged Cross-sections

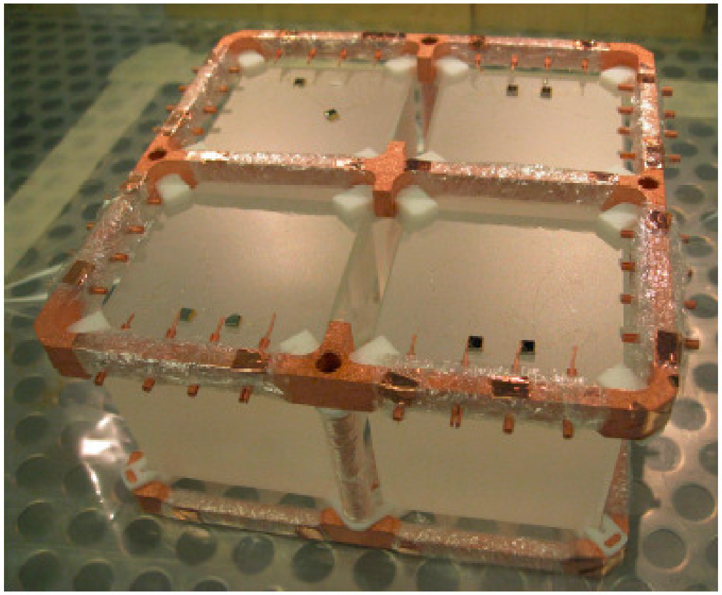
- Summing effects caused by the radioisotopes themselves currently being analyzed. Correction factors will be obtained with GEANT.
- Flux-averaged cross-sections for some isotopes:

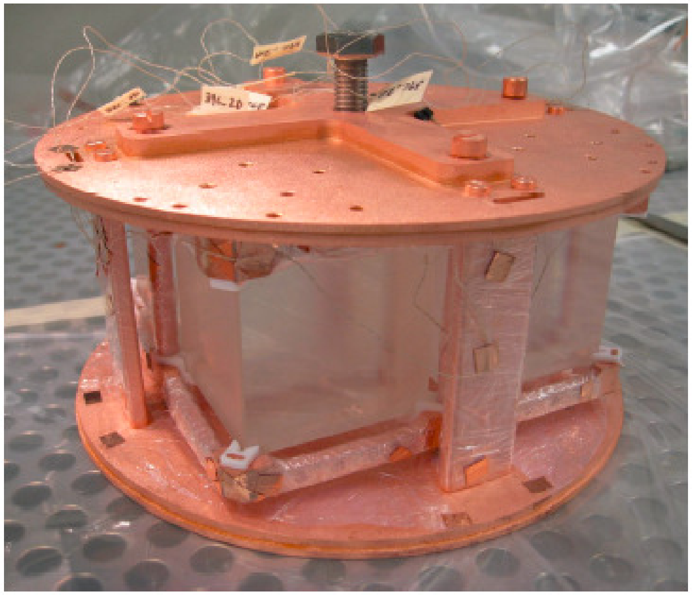
Isotope	Half-life (d)	Flux-averaged Cross-section(mb)
Sb-122	2.7	13 ± 2
Sn-113	115.1	2.7 ± 0.4
In-114m	49.5	2.1 ± 0.3
Be-7	53.2	1.4 ± 0.2
Ag-110m (Preliminary value. Summing correction needs to be added)	249.8	0.18 ± 0.03

- **Will use final cross-sections in a simulation of the entire CUORE detector** to estimate the cosmogenic activation background in the $0\nu\beta\beta$ region.
- **Need to perform benchmarking simulations first.**

CCVR

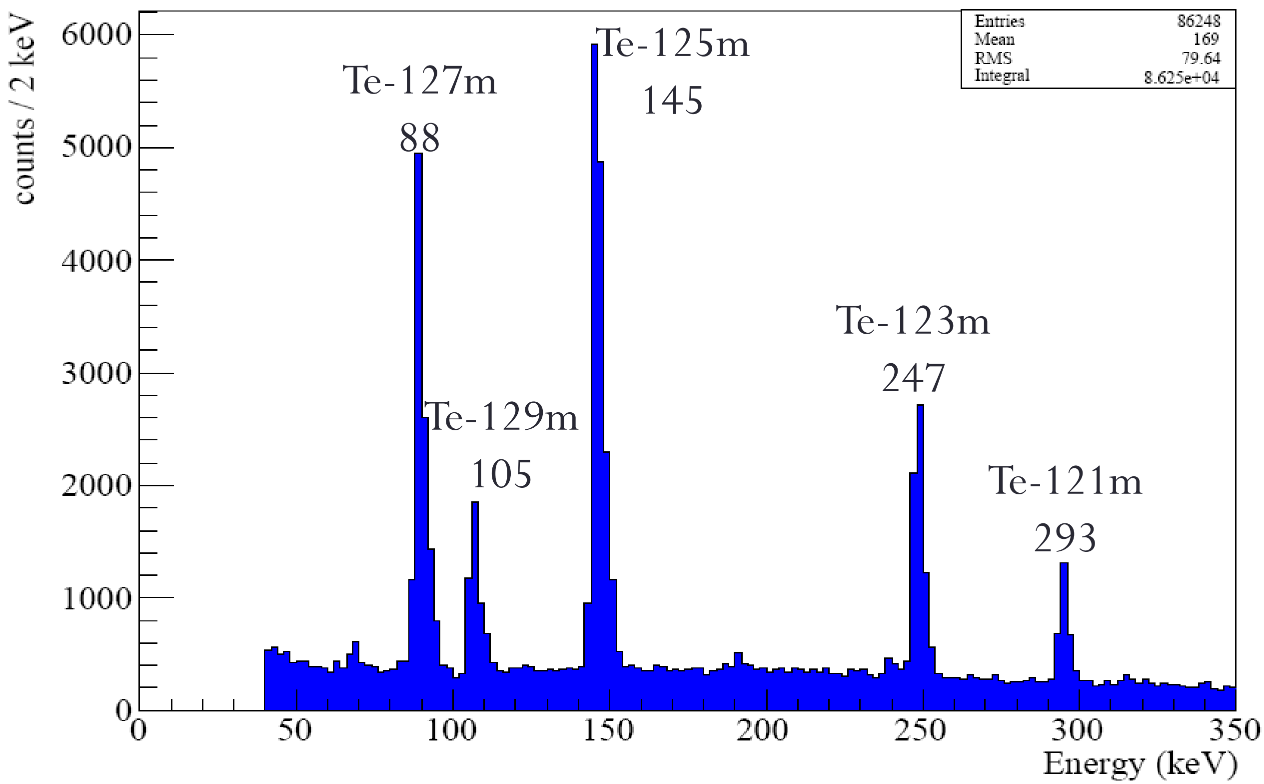
- CCVR = CUORE Crystal Validation Run
- Performed at LNGS
- 4 crystals selected randomly from among latest shipment of crystals
- Crystals assembled into a module with 2 NTDs per crystal
- 3-4 week bolometric test performed to make sure radioactive contamination levels of crystals are low enough.



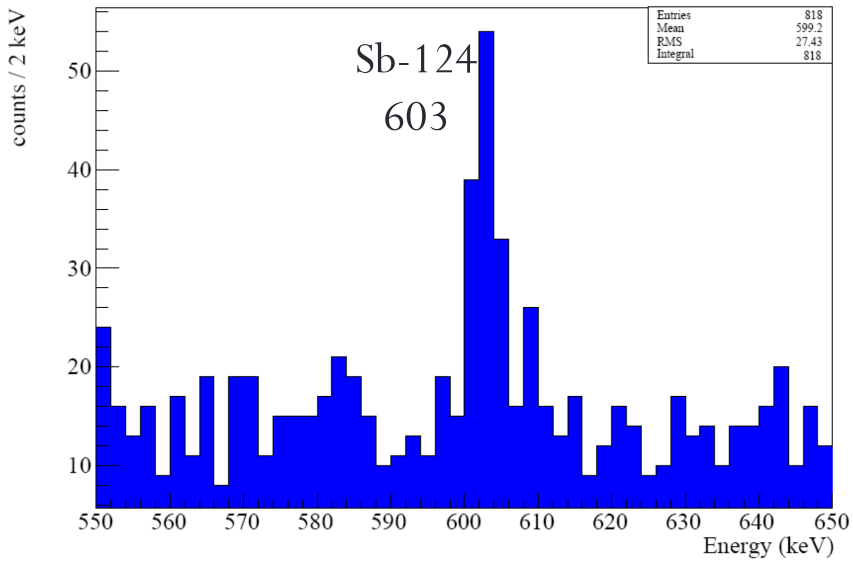


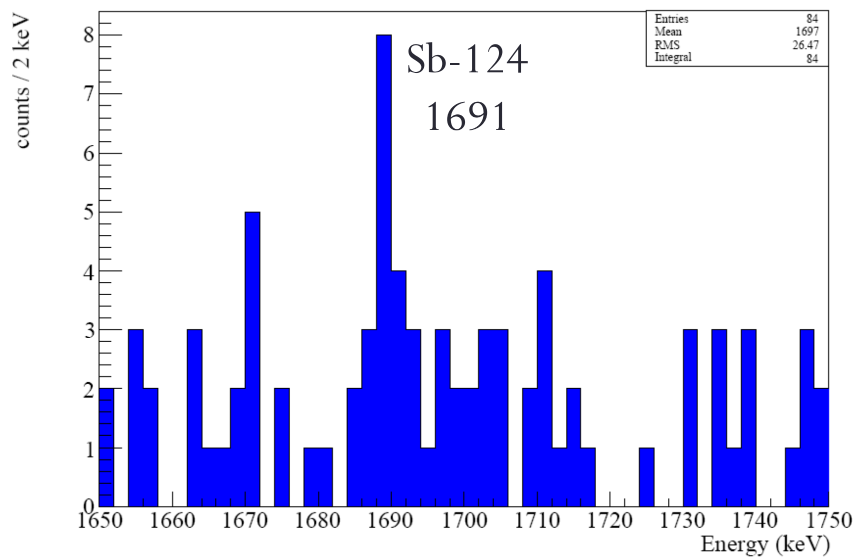
CCVR1: Cosmogenic Activation

- CCVR1: First CCVR run
- Crystals were flown instead of transported by boat
- Higher levels of radioactivity present due to cosmogenic activation. Metastable Te isotopes, Sb-124, and Sb-126 observed.
- **Perform benchmarking simulation of this run**

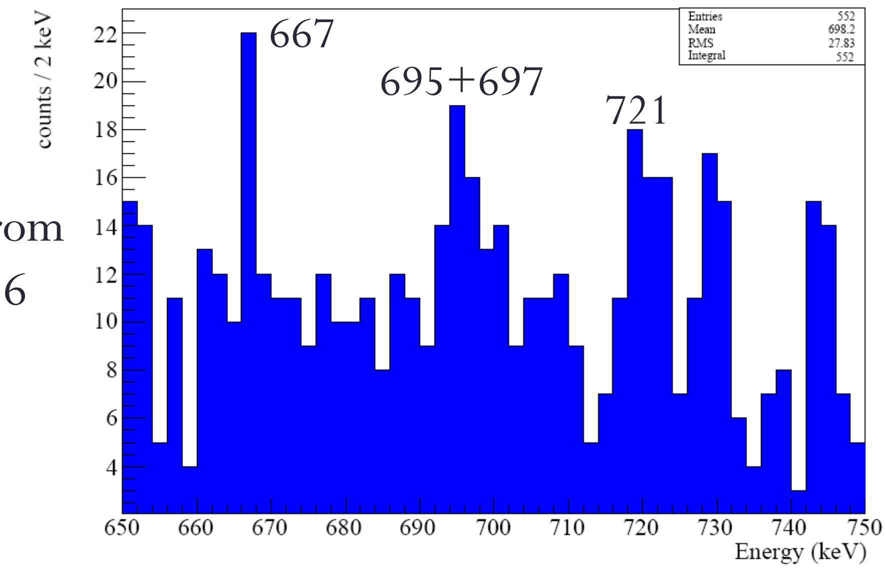


CCVR1: Cosmogenic Activation



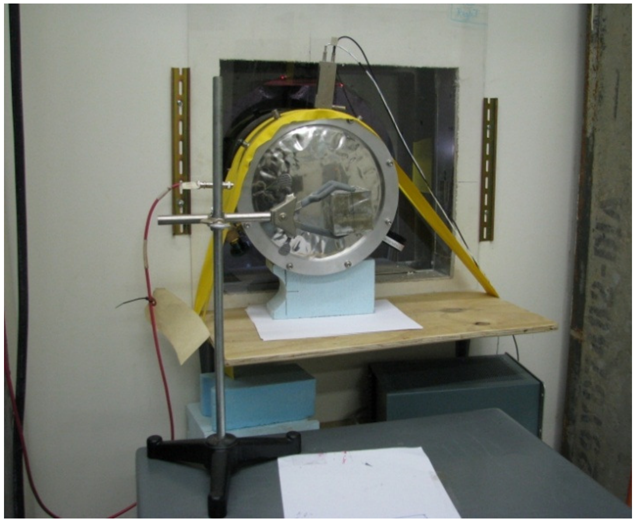


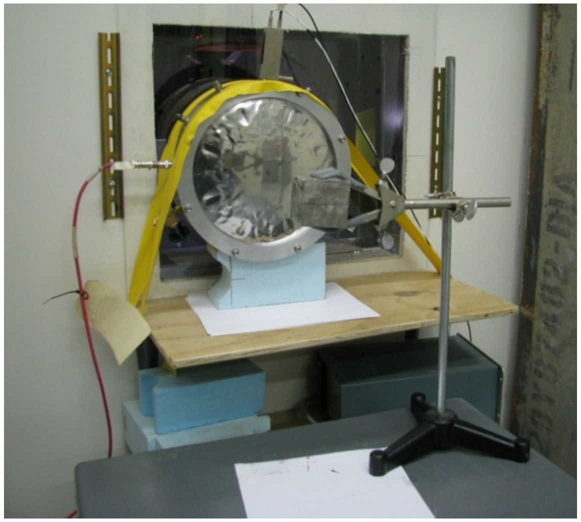
Peaks from
Sb-126



Irradiation of 5x5x5 cm^3 TeO_2 Crystal

- CUORE-sized (5x5x5 cm^3) crystal irradiated at LANSCE on February 25, 2012 for ~ 3 minutes
- Plan to operate crystal as a bolometer at LNGS
- Compare measured results with simulation. **This will also be used to benchmark the simulation of the entire CUORE detector.**





Conclusions

- **Cross-section measurements** have been performed for neutron interactions with TeO_2.
- These cross-sections will be used in a **simulation of the entire CUORE detector** to estimate the cosmogenic activation background that will be present in the $0\nu\beta\beta$ region.
- **Ag-110m** will dominate this background.
- **Benchmarking simulations** will be performed using the CCVR1 measurement and the planned bolometric measurement of a recently-irradiated TeO_2 crystal.

Thank you for listening.

Special thanks to:

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Stephen A. Wender (Los Alamos National Laboratory)

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