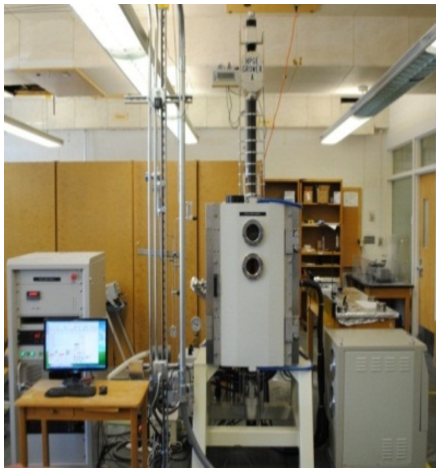
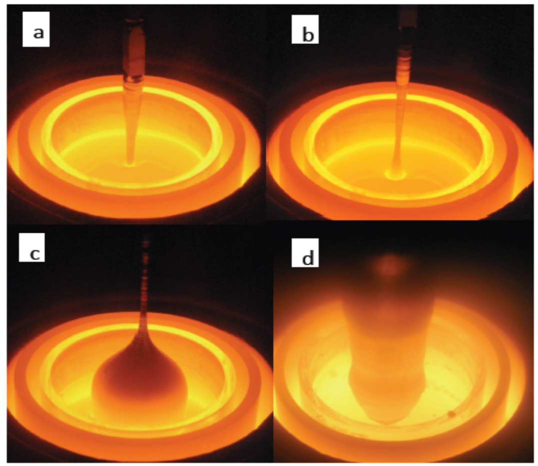
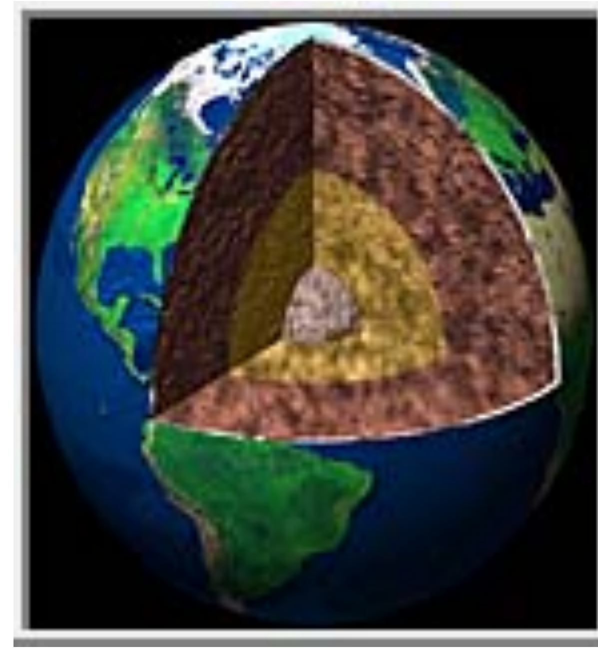
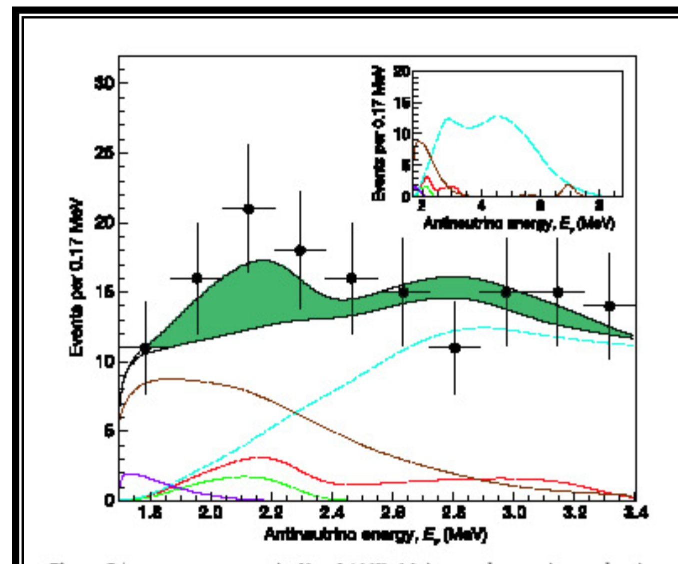
Geo-Neutrinos : a new probe of Earth's interior









- ➢**Geo-neutrinos and their detection**
- ➢**Potential of Growing $CdWO_4$ crystals at USD**
- ➢**Study of $CdWO_4$ detectors at USD**
- ➢**Other Physics with $CdWO_4$ detectors**

What are Geoneutrinos?

the antineutrinos produced by natural radioactivity in the Earth

radioactive decay of uranium, thorium and from potassium-40 produces antineutrinos

$$\bar{\nu}_e$$

assay the entire Earth by looking at its "neutrino glow"

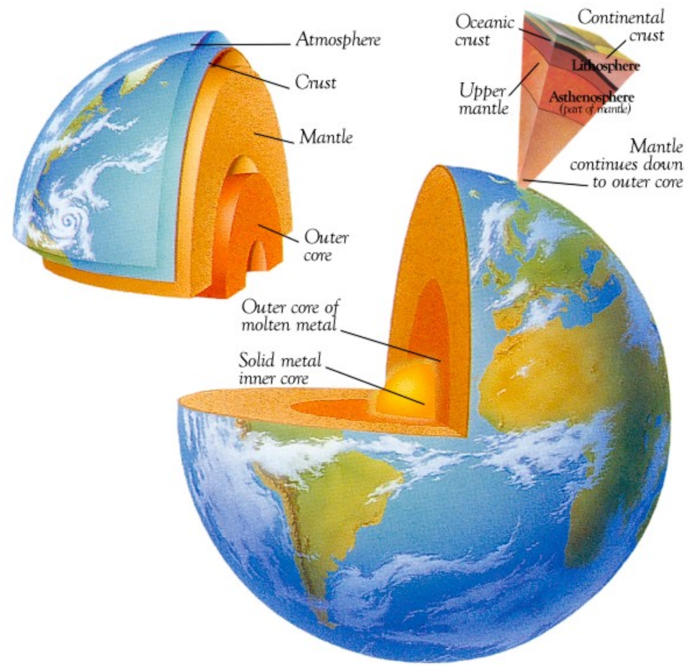


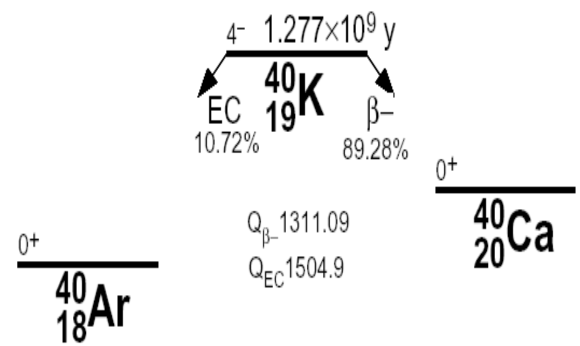
Image by: Colin Rose, Dorling Kindersley

Uranium, Thorium and Potassium

Decay	$T_{1/2}$ $[10^9\ \mathrm{yr}]$	$E_{\max}$ [MeV]	Q [MeV]	$\varepsilon_{\bar{\nu}}$ $[\mathrm{kg}^{-1}\mathrm{s}^{-1}]$	ε_H [W/kg]
$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\ {}^4\mathrm{He} + 6e + 6\bar{\nu}$	4.47	3.26	51.7	7.46×10^7	0.95×10^{-4}
$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\ {}^4\mathrm{He} + 4e + 4\bar{\nu}$	14.0	2.25	42.7	1.62×10^7	0.27×10^{-4}
$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + e + \bar{\nu}$ (89%)	1.28	1.311	1.311	2.32×10^8	0.22×10^{-4}

from G. Fiorentini

- note: ^{40}K also has 10.72% EC branch
  - Q_{EC}=1.505 MeV
  - 10.67% to 1.461 MeV state (E_ν = 44 keV)
  - 0.05% to g.s. (E_ν = 1.5 MeV)
  - thus also emits ν_e



0.0117% isotopic abundance

How to Detect Geoneutrinos

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- inverse beta decay:
  - good cross section
  - threshold 1.8 MeV
  - liquid scintillator has a lot of protons and can easily detect sub-MeV events
  - delayed coincidence signal
    - $\tau = 0.2$ ms, neutron capture on H
    - detect delayed 2.2 MeV γ
    - rejects backgrounds
      - e^+ and n correlated in time and in position in the detector

threshold

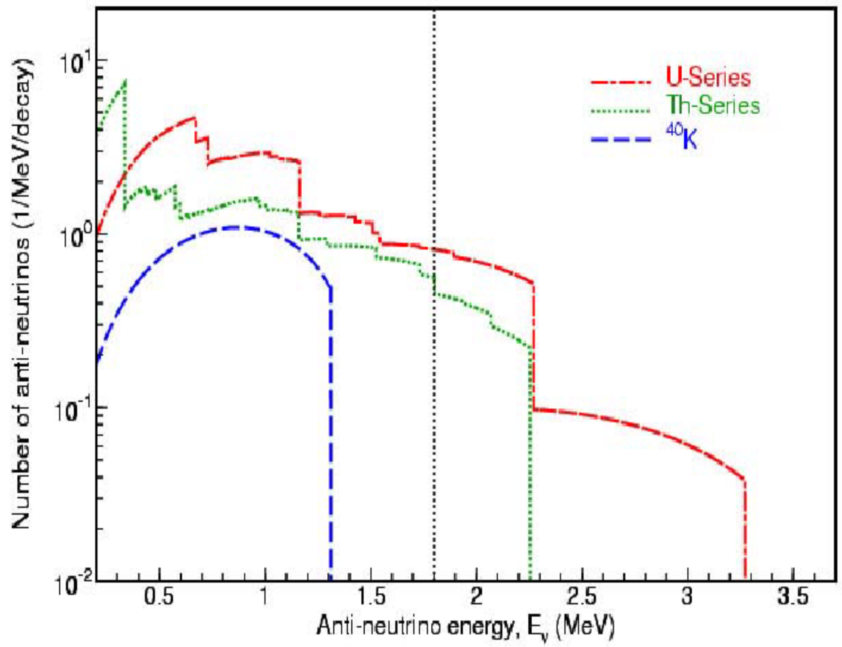


figure from KamLAND Nature paper

Important Questions in Geosciences

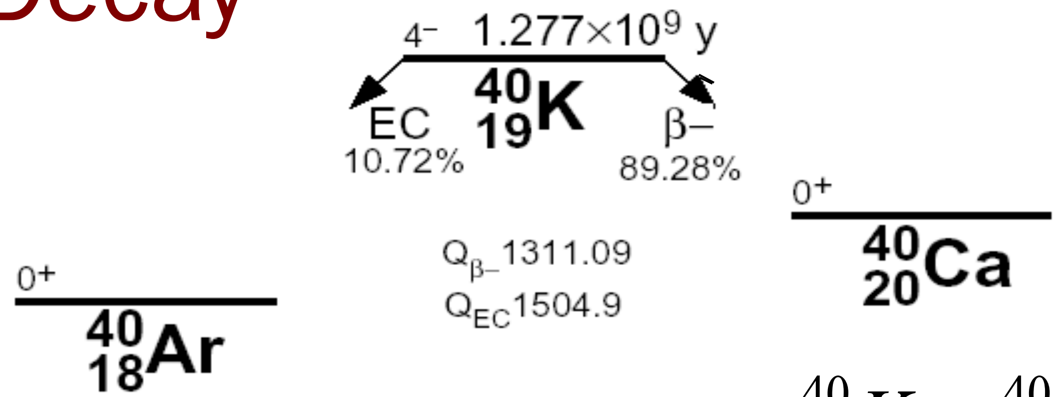
- what is the planetary K/U ratio?
  - can't address until we can detect ^{40}K geoneutrinos
- radiogenic contribution to heat flow?
  - geoneutrinos can measure this
- radiogenic elements in the core?
  - in particular potassium!
- test fundamental models of Earth's chemical origin
- test basic models of the composition of the crust

material in subsequent slides from W.F. McDonough

Important Geoscience Questions

- test fundamental models of Earth's chemical origin
  - are measured fluxes consistent with predictions based upon the BSE?
  - so far yes, KamLAND 2008 measurement central value equals the BSE predicted flux
- test basic ideas of the composition of the crust
  - rock samples used to determine the composition of the crust
    - depth variations not easily sampled
  - are the basic ideas about the continents and how concentrations are enriched compared to the mantle correct?
  - it suggests measurements at a continental site and one that probes the mantle would be very interesting

^{40}K Decay



$$^{40}K \rightarrow {}^{40}Ca + e^{-} + \bar{\nu}_e$$

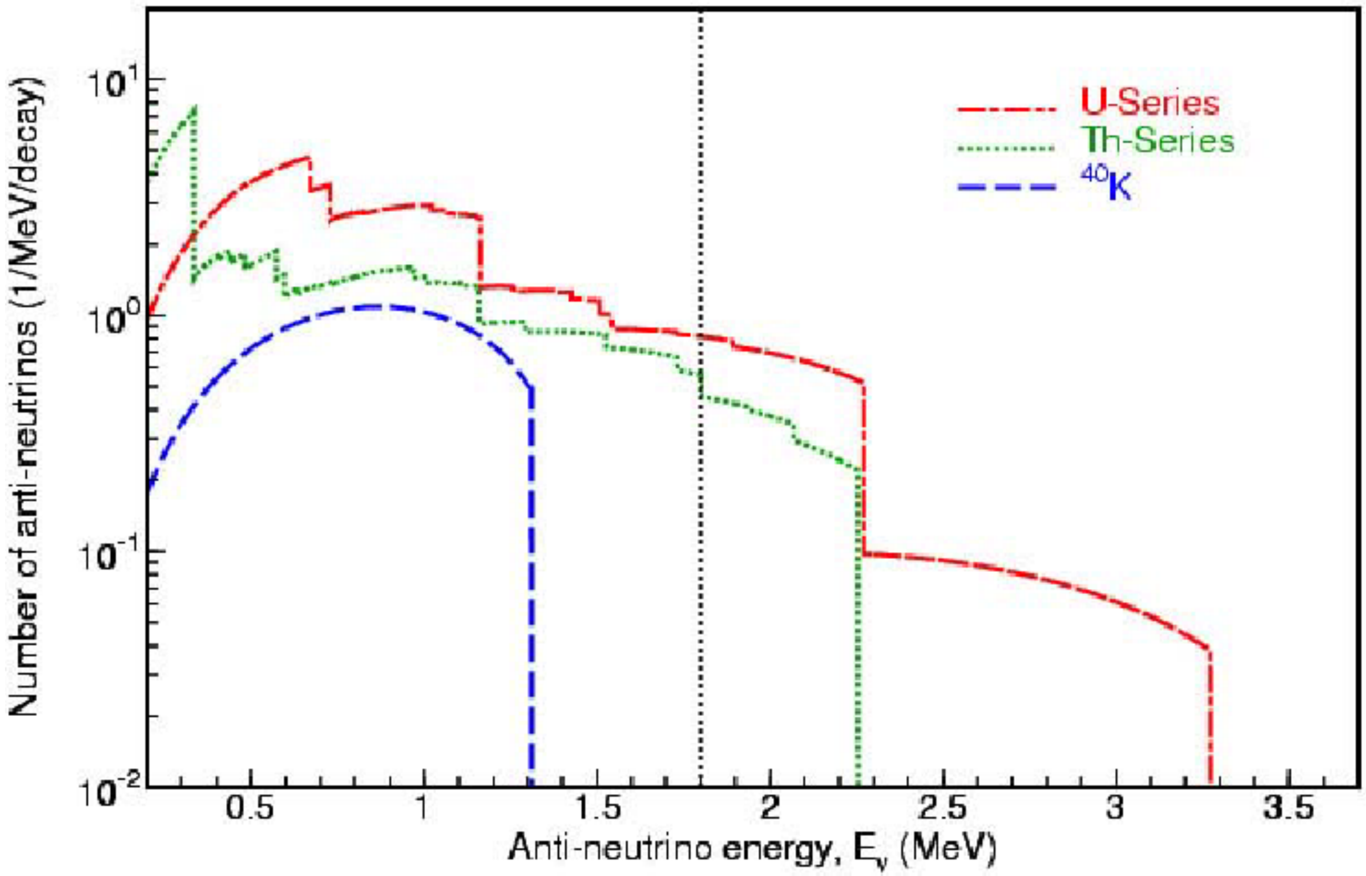
$$^{40}K + e^{-} \rightarrow {}^{40}Ar + \nu_e$$

- 89.28% Q_β=1.311 MeV
- 10.72% Q_{EC}=1.505 MeV
  - 10.67% to 1.461 MeV state (E_ν = 44 keV)
  - 0.05% to g.s. (E_ν = 1.5 MeV)

0.0117% isotopic abundance

^{40}K Spectrum

threshold for $\bar{\nu}_e + p \rightarrow e^+ + n$



[figure from KamLAND Nature paper]

Potassium Geo-neutrino Fluxes

- $(5\text{-}15) \times 10^6\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for the antineutrinos
- $(5\text{-}15) \times 10^5\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for the 44 keV ν_e
- $(2\text{-}6) \times 10^3\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ for the 1.5 MeV ν_e

- compare to 1.44 MeV pep solar neutrinos $1.42 \times 10^8\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$

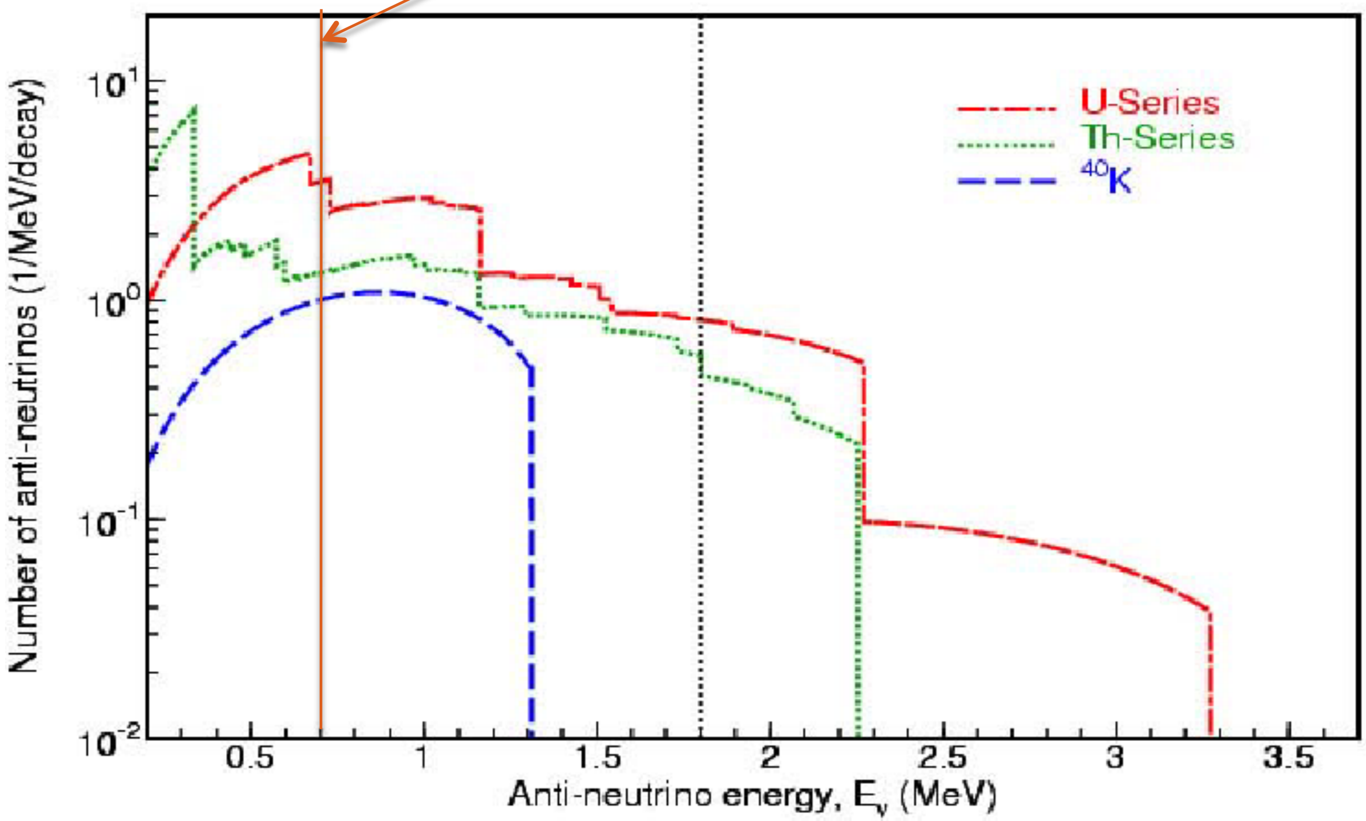
you can probably forget about the ν_e's

^{106}Cd for Potassium Geo-neutrinos

- isotopic abundance 1.25%
- $0^+ \rightarrow 1^+$ allowed transition to the ^{106}Ag g.s.
- Q_β = 194 keV, detectable e^+ (1.02-1.12 MeV)
- followed by a $t_{1/2}$=24 min EC decay (a big one)
  - can consider direct detection of reaction
  - could also consider radiochemical detection of Pd
  - it's a positron decay also! (not a tiny branch)
  - "double-positron" signature potentially distinctive

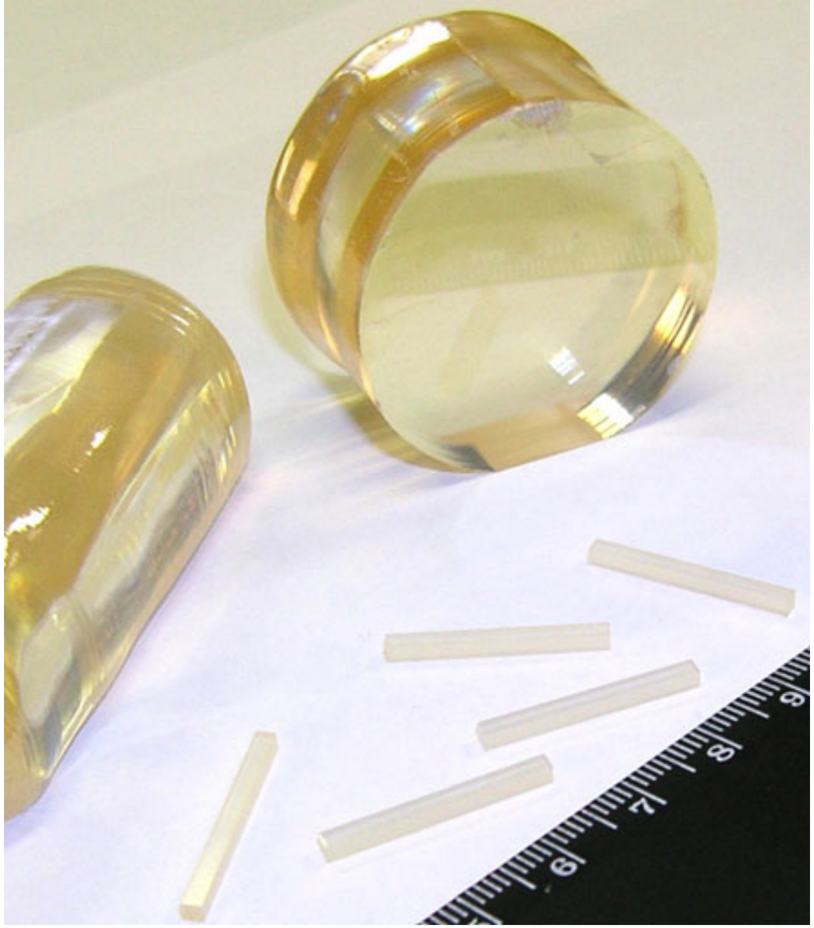
Geo-neutrinos and their detection

Threshold for $\overline{\nu_e} + {}^{106}Cd \rightarrow {}^{106}Ag + e^+$



Cadmium Detectors

- $CdWO_4$ scintillating crystals
- ^{106}Cd enrichment possible (Kiev group has enriched ^{116}Cd for double beta decay search)



In the next three slides, I will show the potential of growing $CdWO_4$ crystals at USD

Detector-Grade Germanium Crystal growth

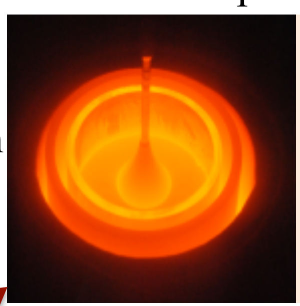
Refinement

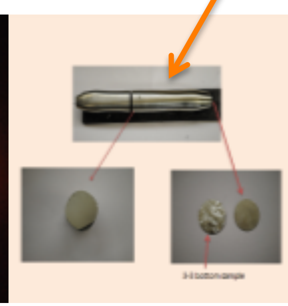
The removal of impurities contained in the starting materials has been done with a well-established zone refinement process.

Mobility: >25,000 cm^2/Vs
Resistivity: >1000 Ω cm
Impurity: < $2.5x10^{11}/cm^3$
Measured at 77 K

Fabrication challenges have included understanding growth mechanisms and microscopic control of growth to achieve high quality crystals.

Axial crystalline structure



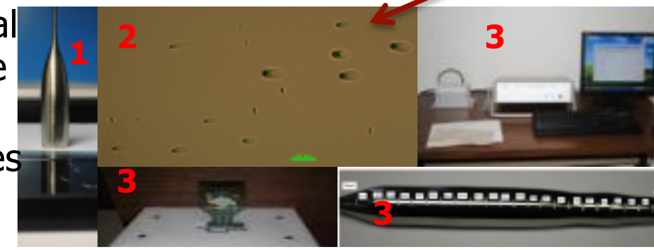


Dash-nicking C[illegible]l of c[illegible]ion

Characterization

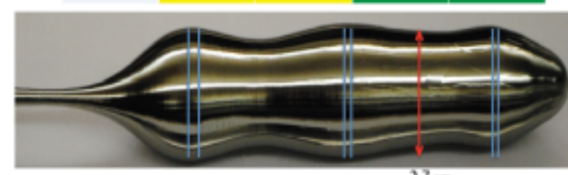
1. Determine the crystal orientation; 2. measure the dislocation density; 3. identify the impurities and their sources;

Dislocation density of $3.3x10^3/cm^2$



Resistivity Measurements

	Resistivity (Ω•cm)		Carrier Concentration (cm^{-3})	
Temperature	~300 K	77 K	~300 K	77 K
Slice #1	56.6	27,450	$5.3x10^{13}$	$5.7x10^9$
Slice #2	47.9	22,760	$-5.7 x10^{13}$	$6.9x10^9$
Slice #3	54.4	32,260	$-5.4x10^{13}$	$4.8x10^9$



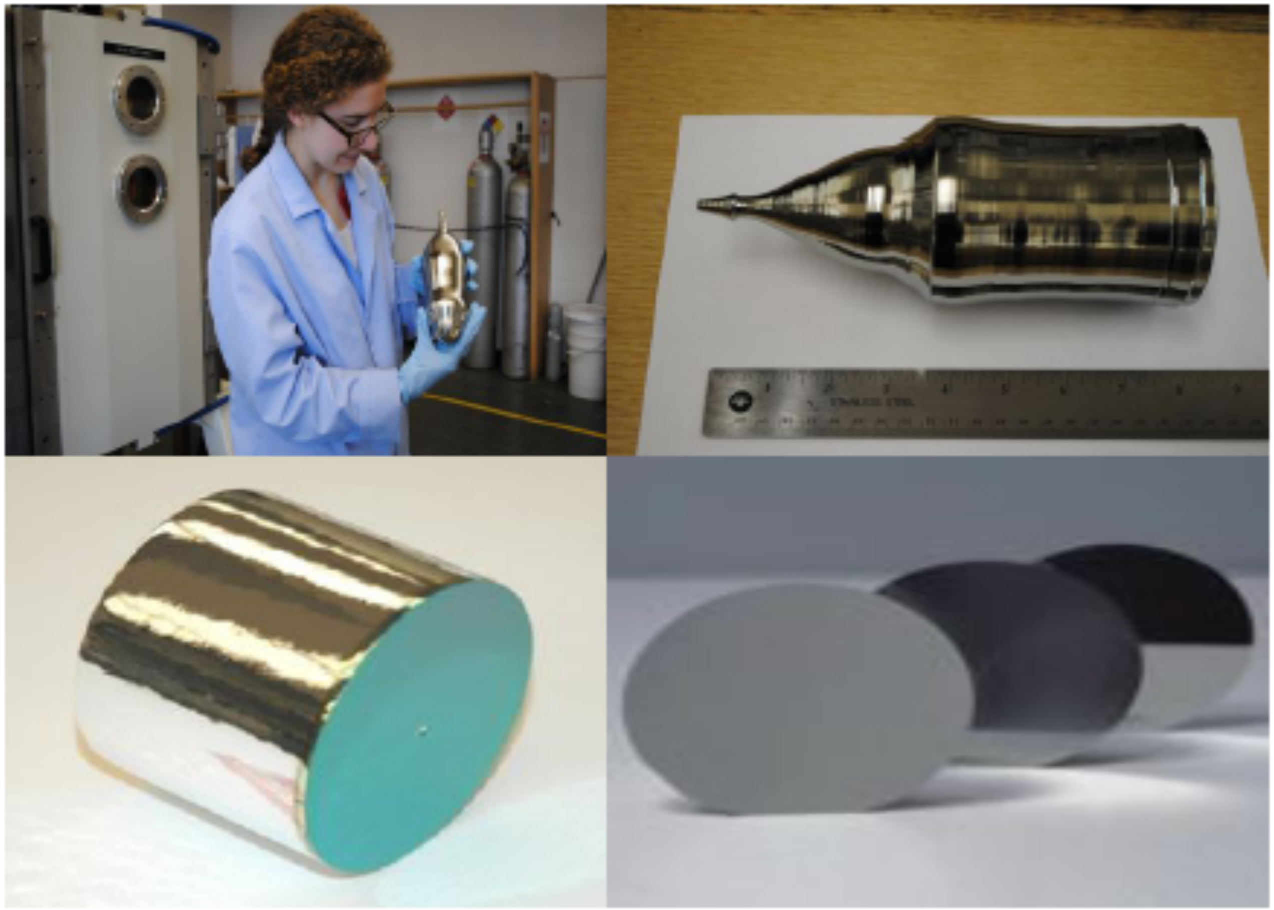
#1 1.16 mm #2 1.08 mm #3 1.64 mm

Success of detector-grade crystal growth with the reduction of spontaneous contamination by working quickly with standardized procedures in a clean small working area filled with hydrogen gas.

Potential Impact 1. Breeding ultra-high sensitivity detectors for underground experiments. 2. Single-crystalline high-purity germanium crystals — are ideal for high sensitivity optoelectronic sensors and imaging system. 3. High-purity single crystals for electronic devices including transistors, diodes, fuel cells, sensors, etc. 4. High efficiency solar cells and solar panels.

References:
1. D.-M. Mei et al., "Underground High-Purity Germanium Crystal Growth", submitted to the Journal of Crystal growth.
2. G. Yang, et al., Radial and axial impurity distribution in high-purity germanium crystals, Journal of Growth (2012), doi:10.1016/j.jcrysgro.2011.12.042.
3. G.-J. Wang et al., Development of large size high-purity germanium crystal growth, Accepted for publication by the Journal of Crystal Growth.

High-Purity Germanium Crystal Growth

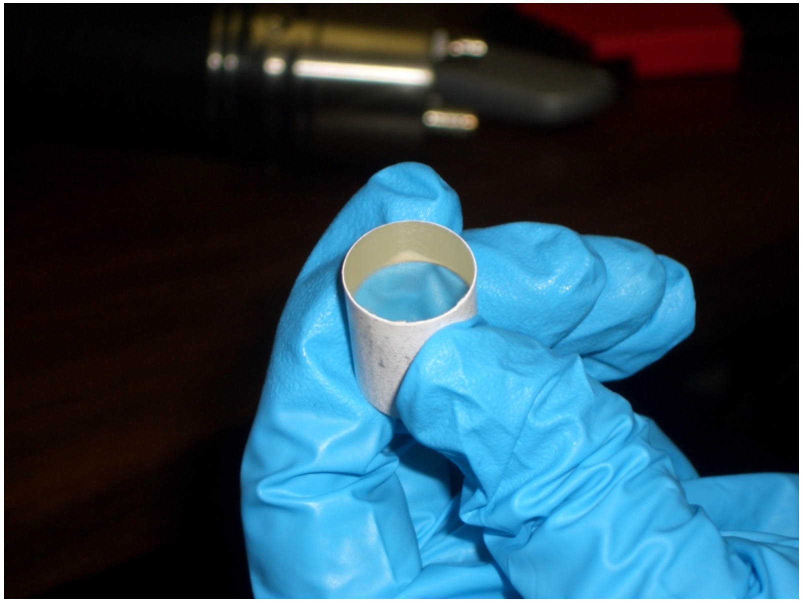


Large size crystals with a diameter of ~10 cm

Study of $CdWO_4$ at USD

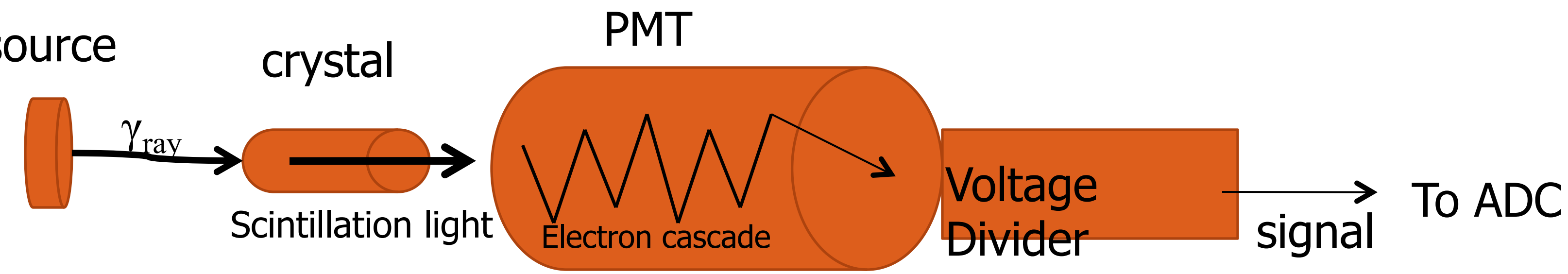
$CdWO_4$ and CsI crystals

	$CdWO_4$	CsI(Tl)
Density (g/cm^3)	7.9	4.51
Melting point (K)	1598	894
Thermal expansion coefficient (C^{-1})	10.2×10^{-6}	0.54×10^{-6}
Hygroscopic	No	Slightly
Wavelength of emission max. (nm)	475	550
Lower wavelength cutoff (nm)	330	320
Refractive index @ emission max (nm)	2.2-2.3	1.79
Primary decay time	14 (μs)	1000 (ns)
Light yield (photons/ keV-γ)	12-15	54



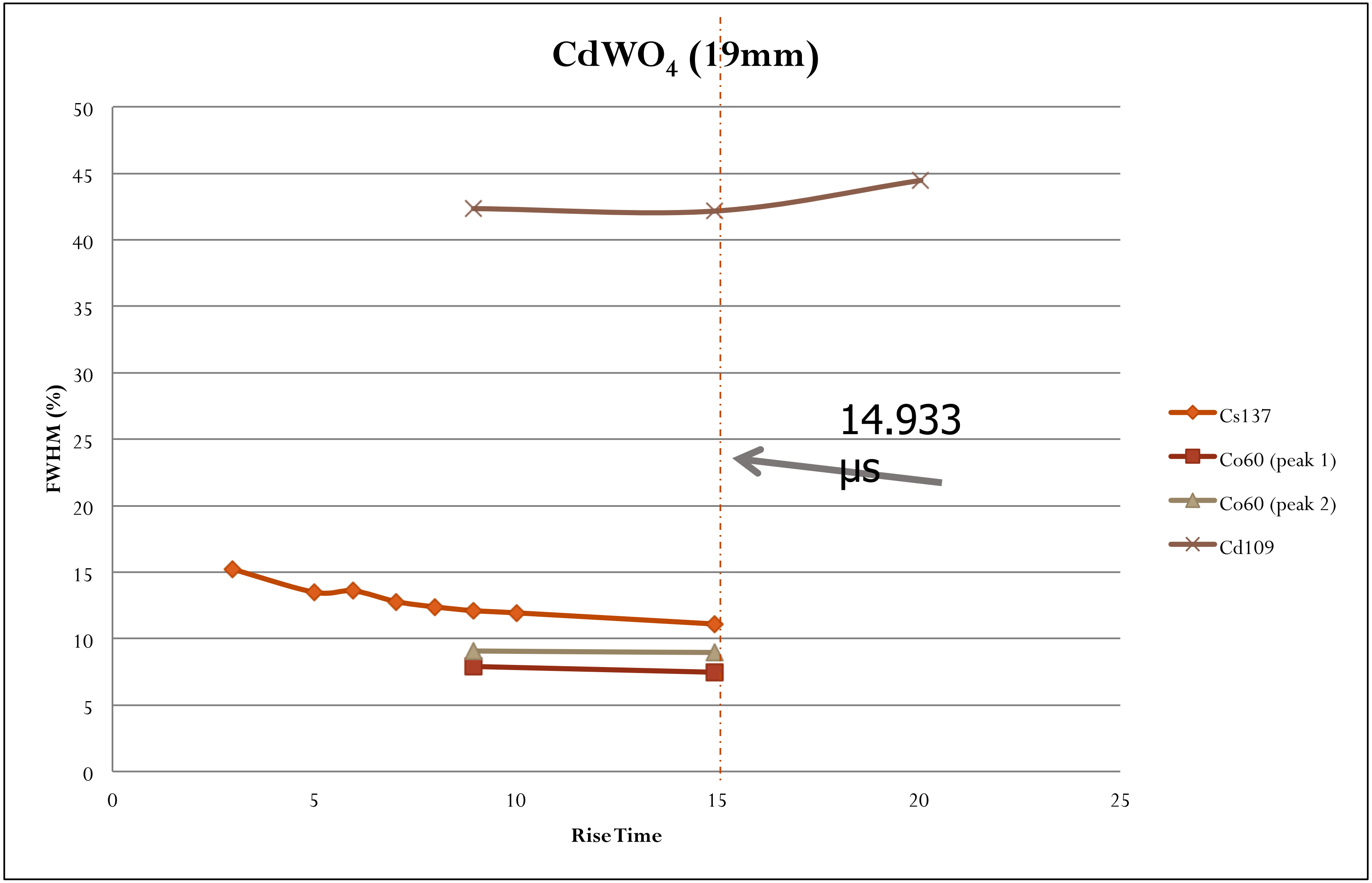
Study of $CdWO_4$ at USD

- Source emits γ_{ray}
- Enters crystal where its is absorbed and reemitted as scintillation light
- Light enters PMT where it ejects an electron via the photoelectric effect, and induces a cascade of electrons
- The resulting signal is read out to the computer from an Analog-To-Digital Converter



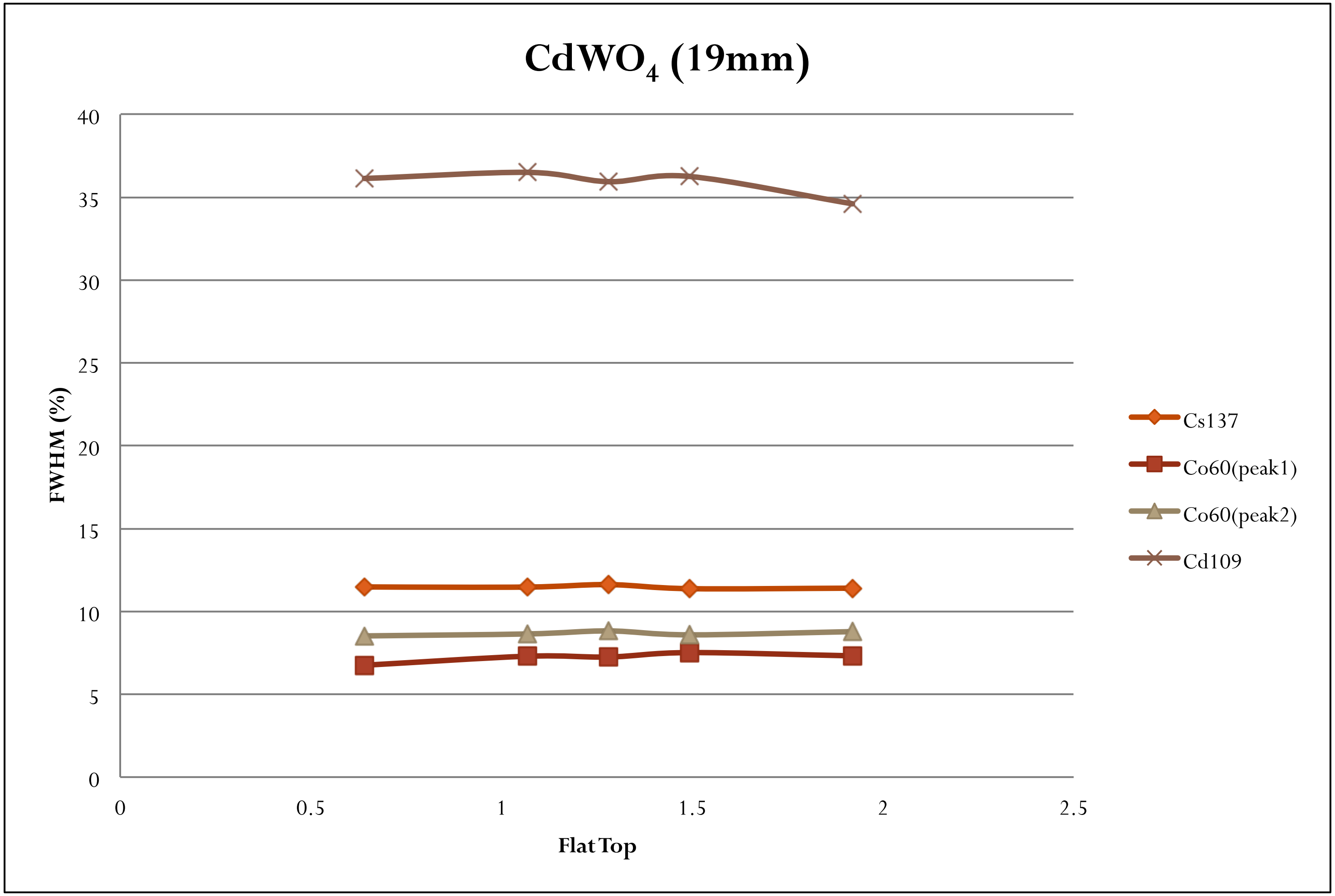
γ_{ray} α Scintillation light α Signal Energy

Rise time calibration of $CdWO_4$ crystal



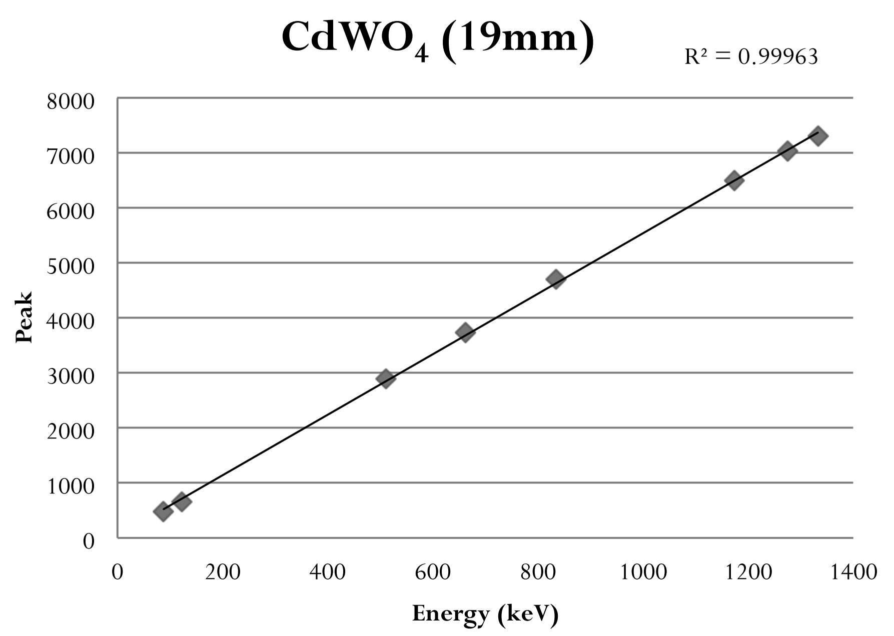
Rise Time: 14.933 µs

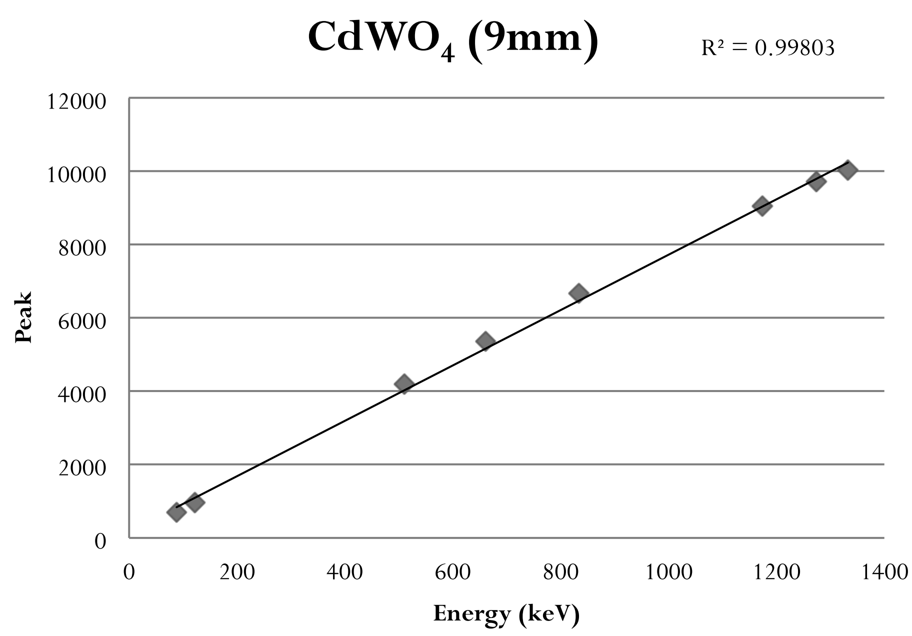
Flat top calibration of $CdWO_4$ crystal



Flat Top: 1.28 μs

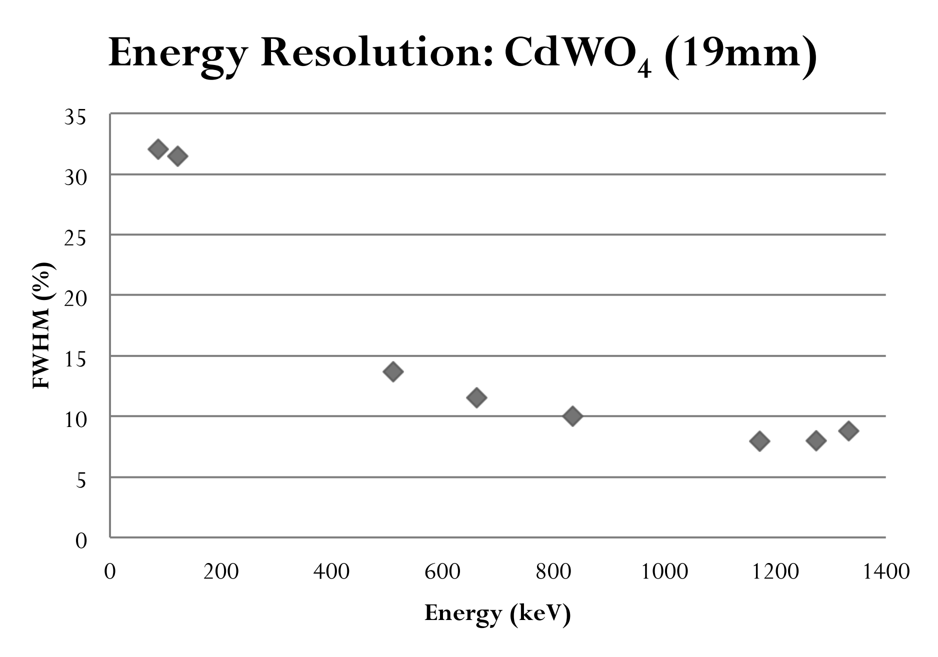
Peak v. Energy for $CdWO_4$ crystal

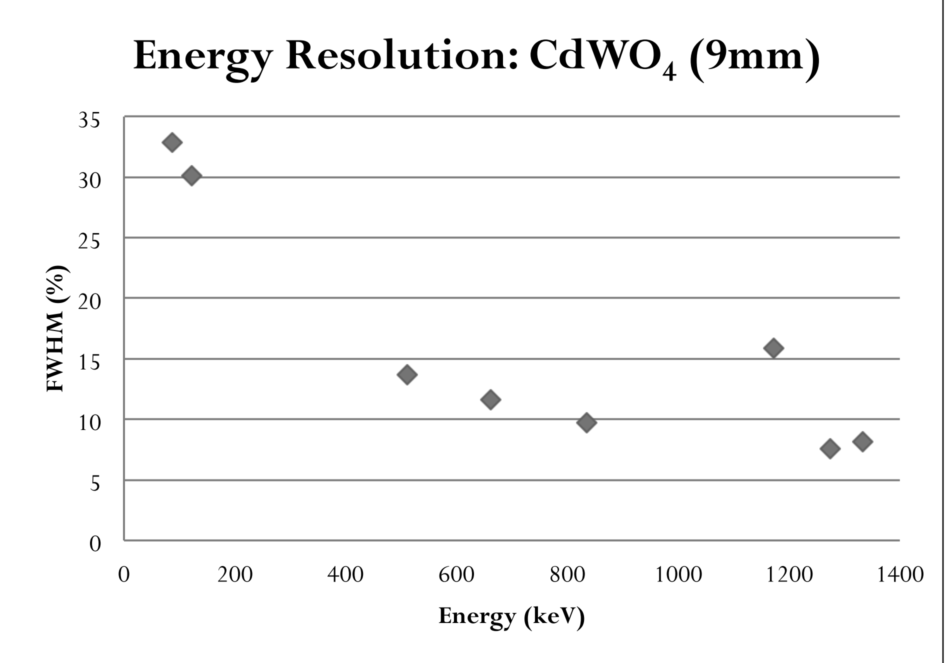




- **Peak v. Energy data inconclusive for 5mm $CdWO_4$ crystal**

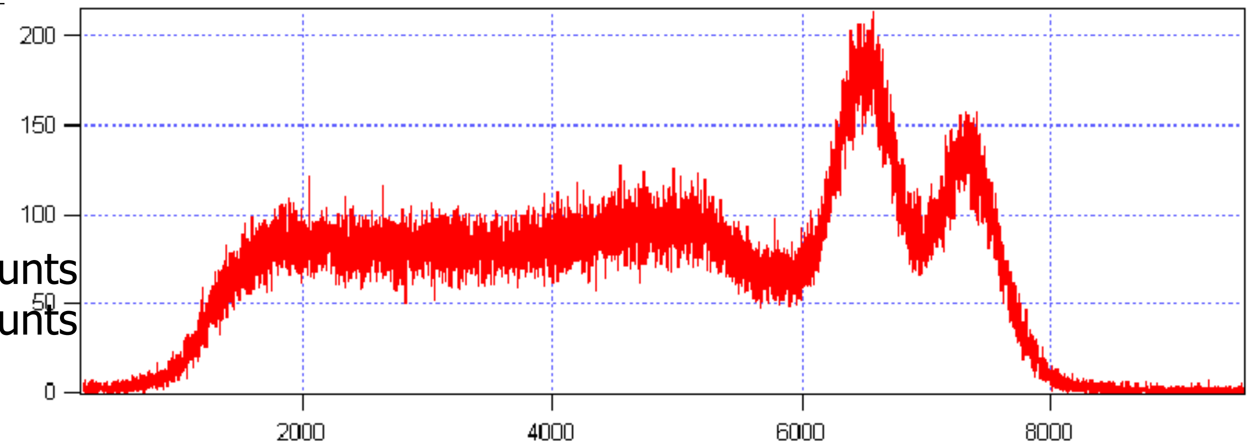
$CdWO_4$ Energy Resolution



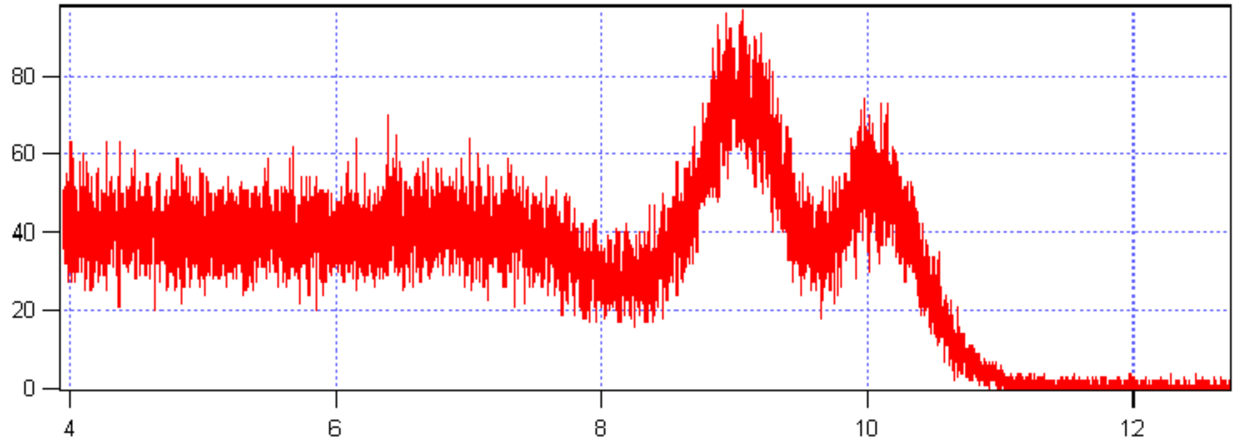


- **Energy Resolution data inconclusive for 5mm $CdWO_4$ crystal**

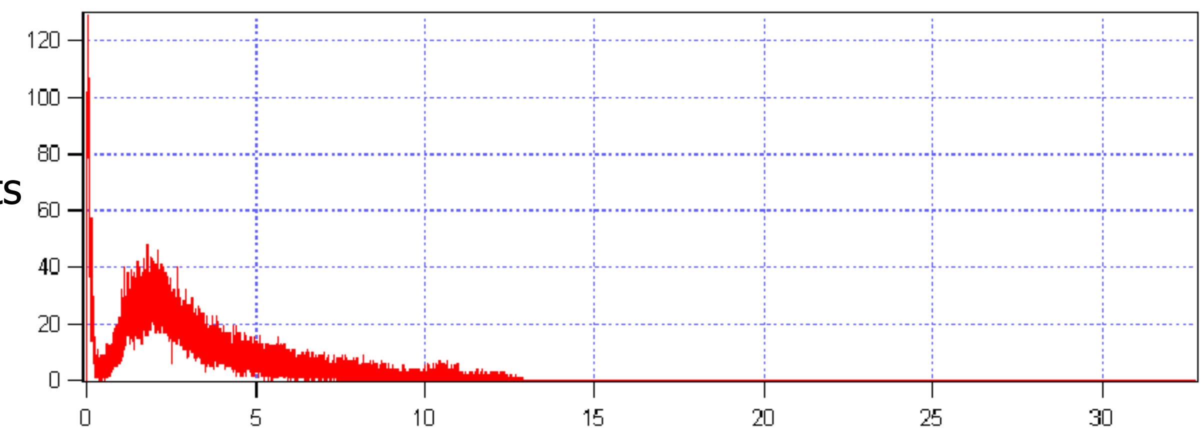
- 19mm
    - 1173.2 keV Peak: ~200 counts
    - 1332.5 keV Peak: ~150 counts



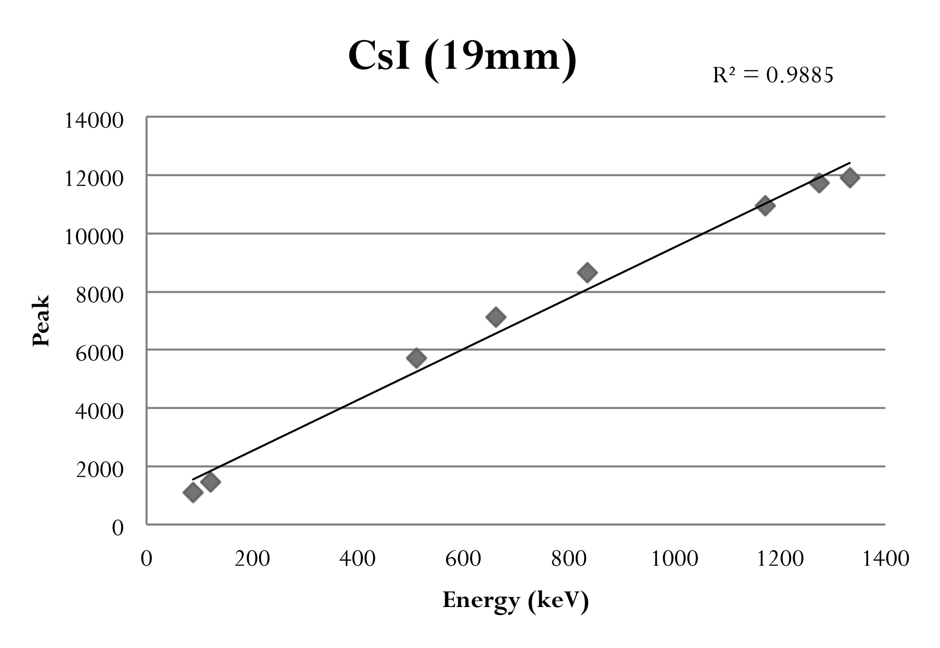
- 9mm
    - 1173.2 keV Peak: ~100 counts
    - 1332.5 keV Peak: ~70 counts

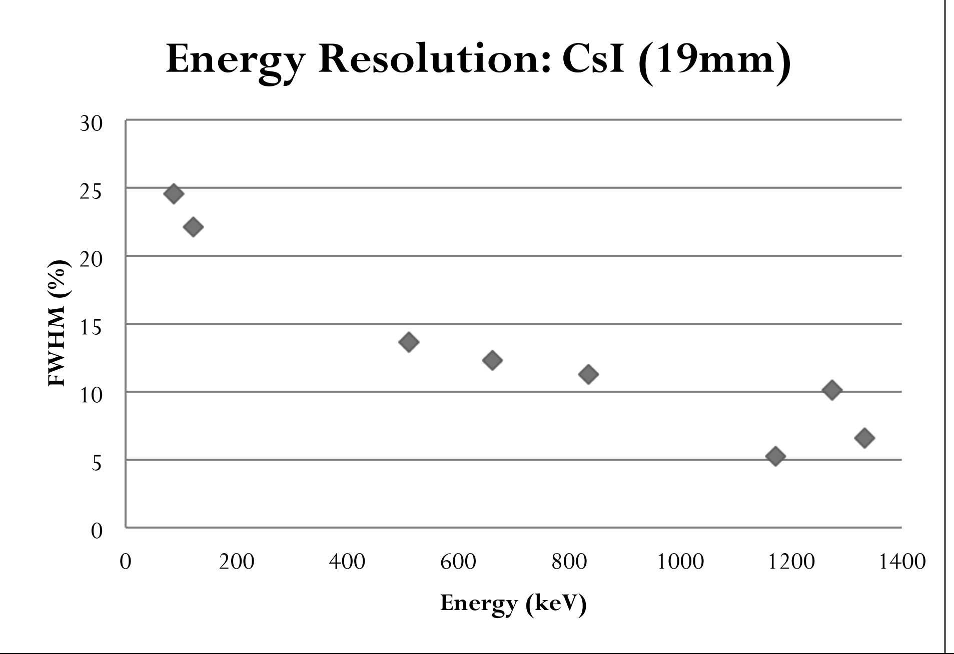


- 5mm
    - 1173.2 keV Peak: ~10 counts
    - 1332.5 keV Peak: ~5 counts

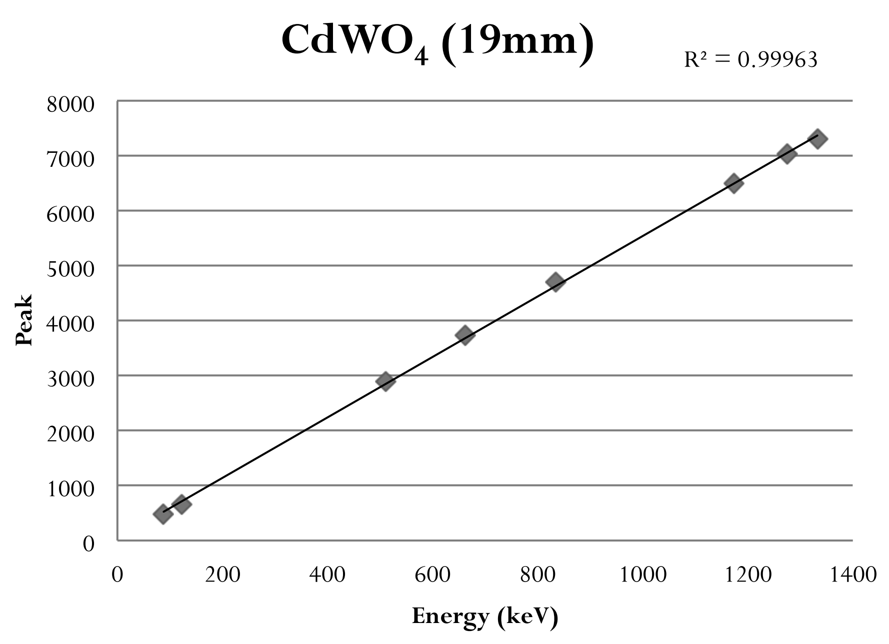


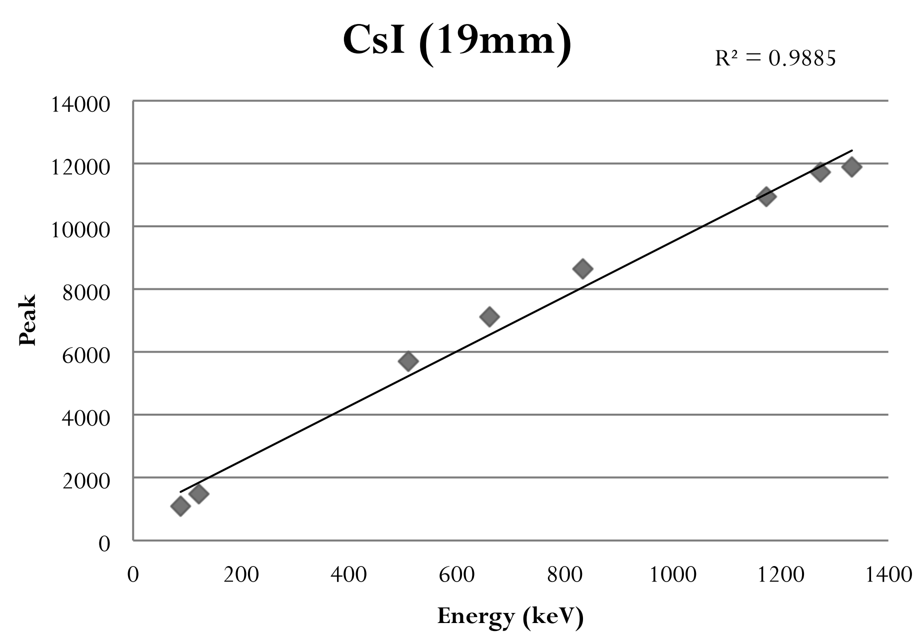
Peak v. Energy and Energy Resolution for CsI (19mm) crystal





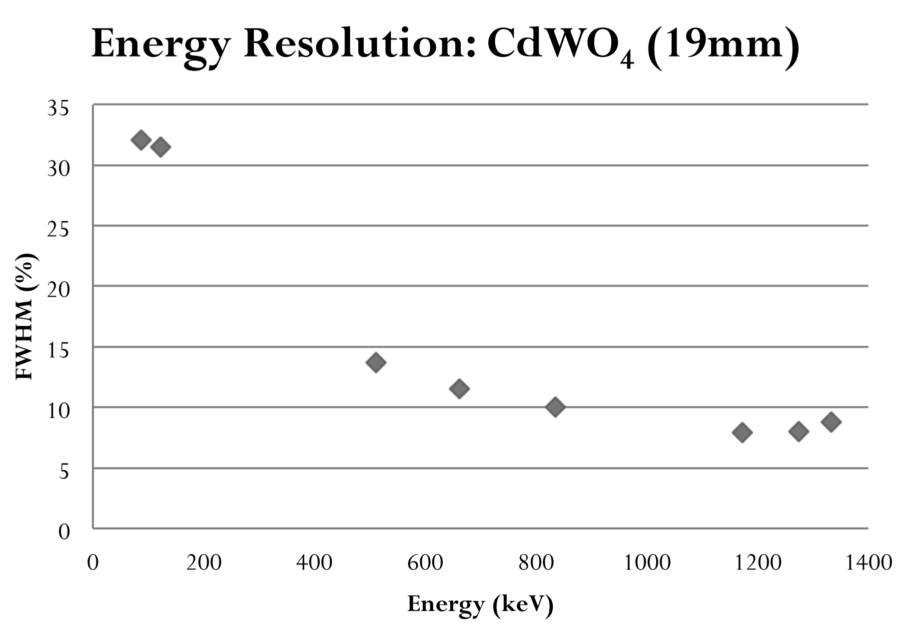
Comparing Peak v. Energy

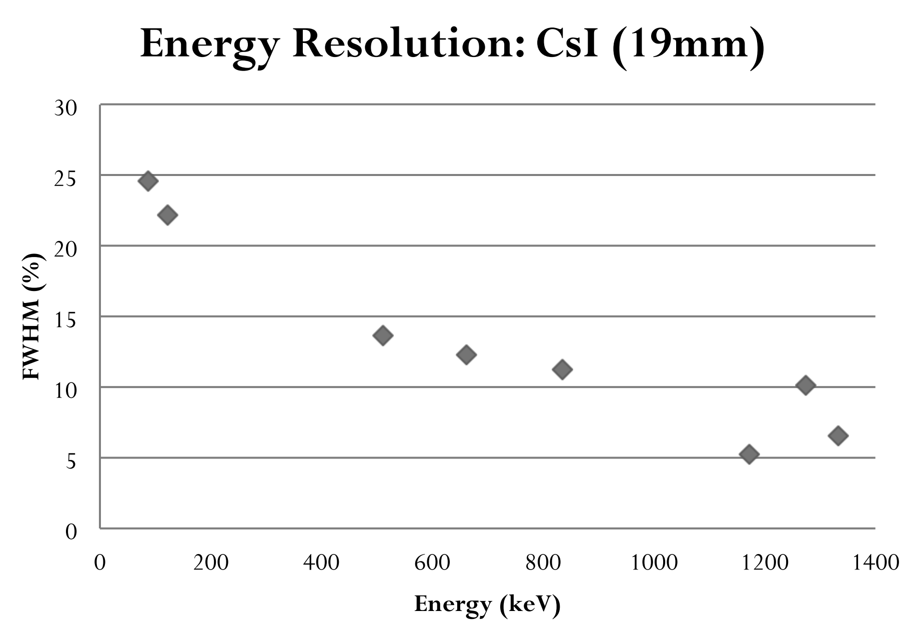




$CdWO_4$ is more linear than CsI, showing that this crystal is more predictable.

Comparing Energy Resolution

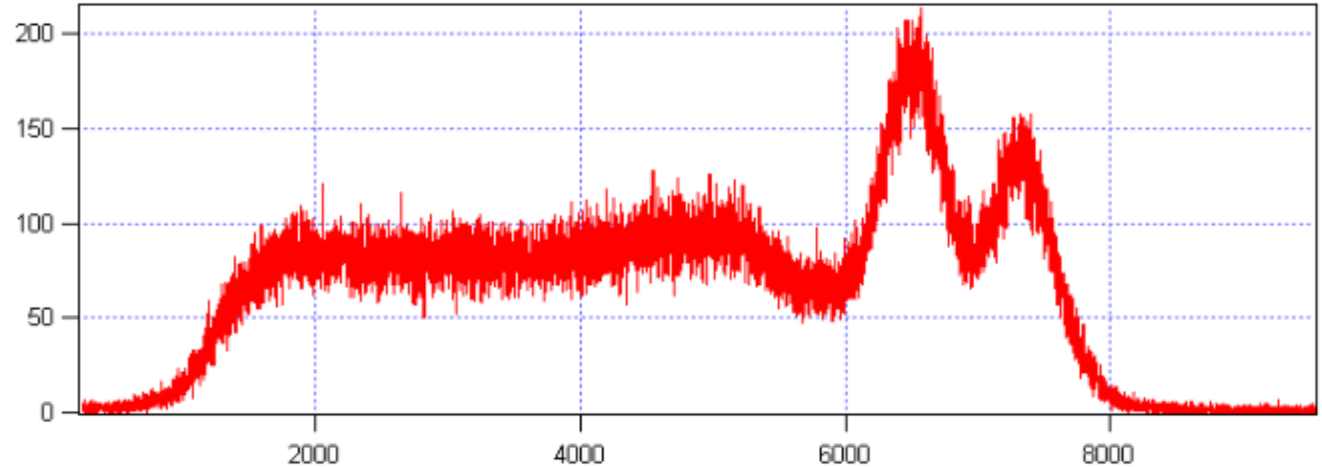




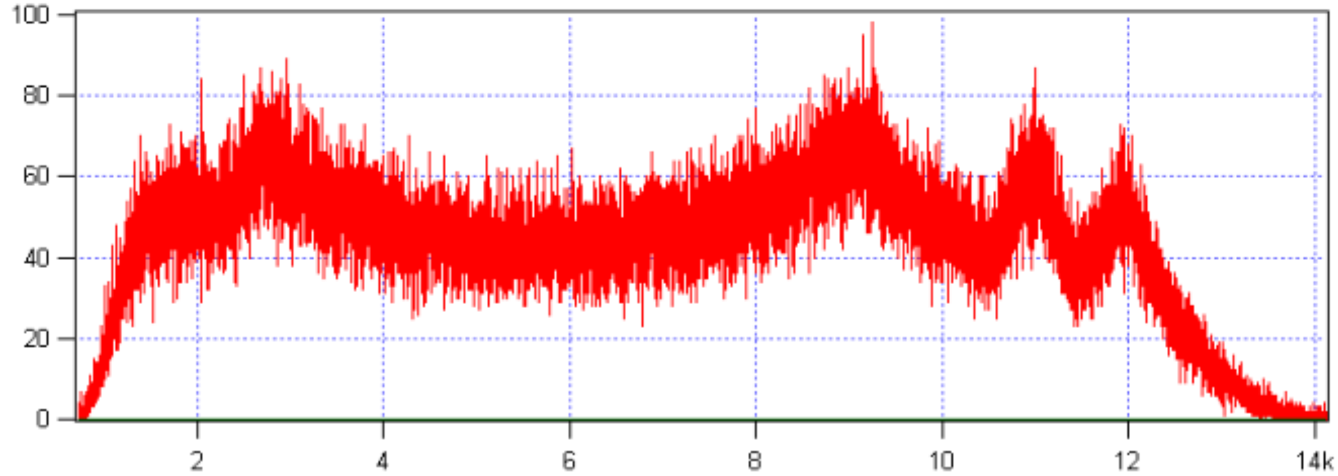
CdWO$_4$ has a greater energy resolution for sources with higher energies and CsI with lower energies as seen through their exponential shape.

High Energy Results of Co60

$CdWO_4$

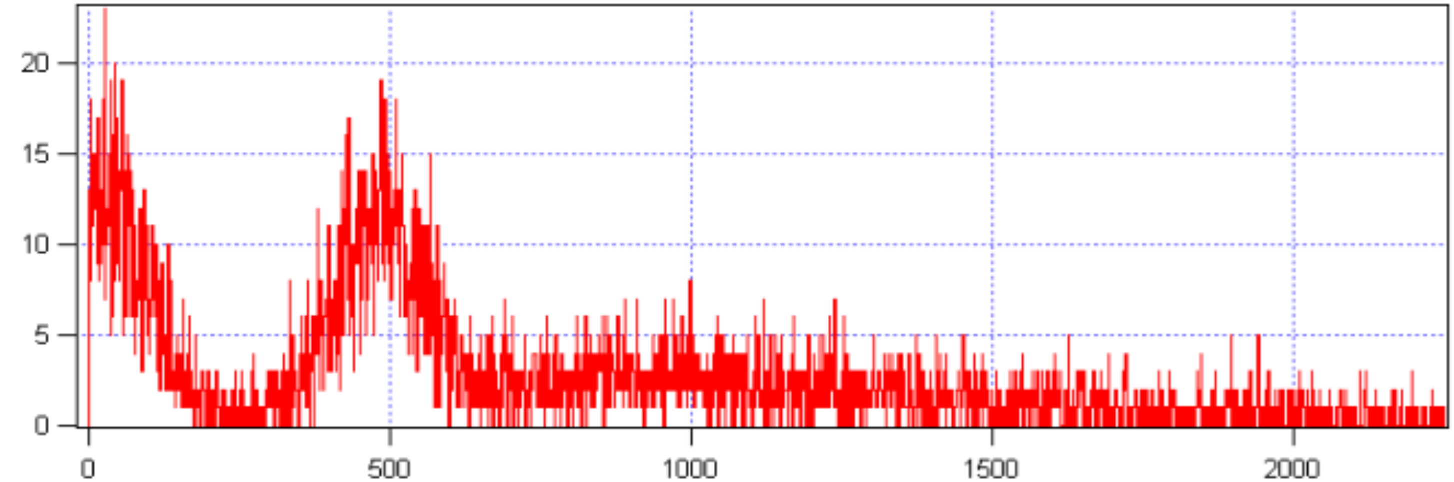


CsI

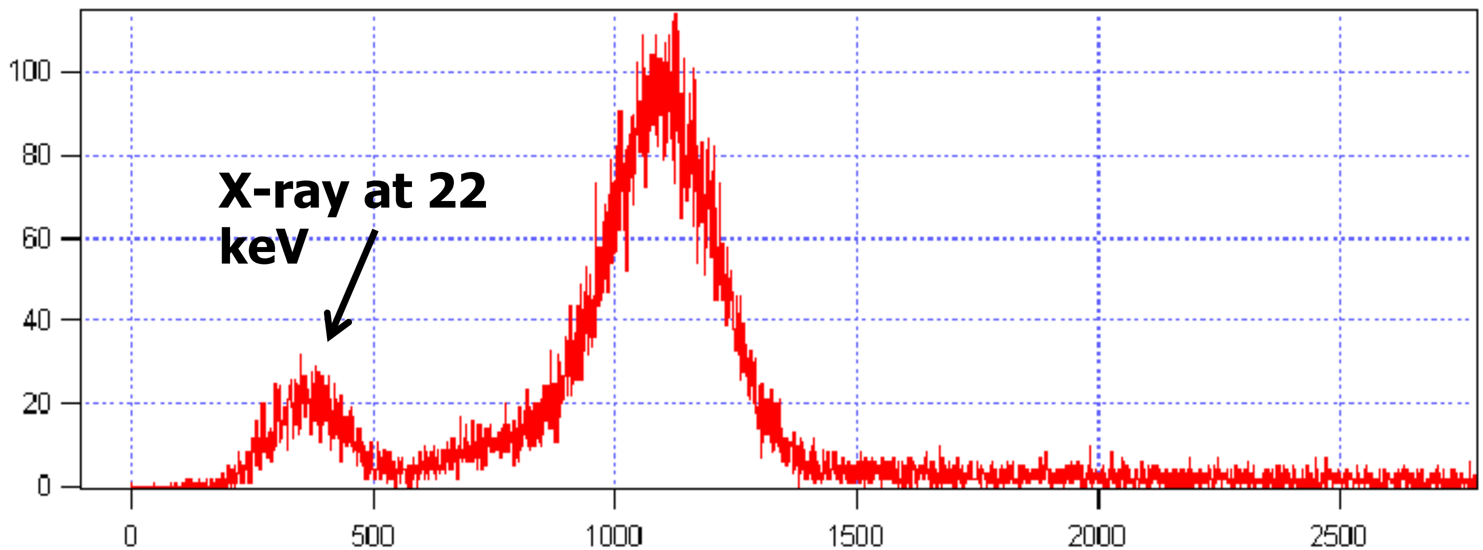


Low Energy Results of Cd109

$CdWO_4$



CsI



Backgrounds from Double Beta?

- actual double beta decay of ^{106}Cd produces both positrons at once
- antineutrino capture produces two positrons separated by $t_{1/2}$=24 min
- how about accidental coincidences (24 min window)
  - ^{113}Cd (12.2% isotopic abundance) β decay (Q = 320 keV)
    - 14.2 kHz (for 1 ton of ^{113}Cd)
  - ^{116}Cd (7.5% isotopic abundance) ββ decay (Q = 2.8 MeV)
    - 3.7 decays per second (for 1 ton of ^{116}Cd)

high isotopic purity of ^{106}Cd is needed unless you have positron identification

Geo-neutrino Signal Rates ^{106}Cd

- Geo-neutrinos from ^{40}K is $\sim 10^6/cm^2/s$
- Inverse beta-decay cross section $\sim 10^{-44}$ cm^2
- Enrich ^{106}Cd to 50%
- Detection efficiency of ~50%

in the few to ~ten events per year per kiloton

Smaller volume but expensive project ~$500M-$1B

Summary

- ^{40}K geo-neutrino detection using ^{106}Cd
- ^{106}Cd could be made into scintillating crystals or semiconductor detectors
- distinctive "double-positron" signature
- USD can potentially grow crystals and make detectors