Dec 2012, CNNS Workshop, Livermore

COHERENT NEUTRINO-NUCLEAR SCATTERING WITH GERMANIUM

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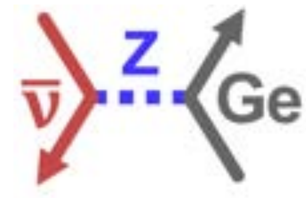
Sandia National Laboratories

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

ULGeN: Ultra-Low noise Germanium Neutrino detection system



- **Project Team:**

Sandia National Laboratories

Belkis Cabrera-Palmer
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Berkeley Lab

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Mark Amman
Paul Luke
Kai Vetter

Daniel Hogan

This project aims at the development, fabrication, and deployment of a kg-scale High Purity Germanium (HPGe) detector with the required ultra-low electronic noise threshold to demonstrate detection of reactor antineutrinos via coherent neutrino-nucleus scattering.

Coherent Neutrino-Nucleus Scattering (CNNS)

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

Coherent effects of a weak neutral current

Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
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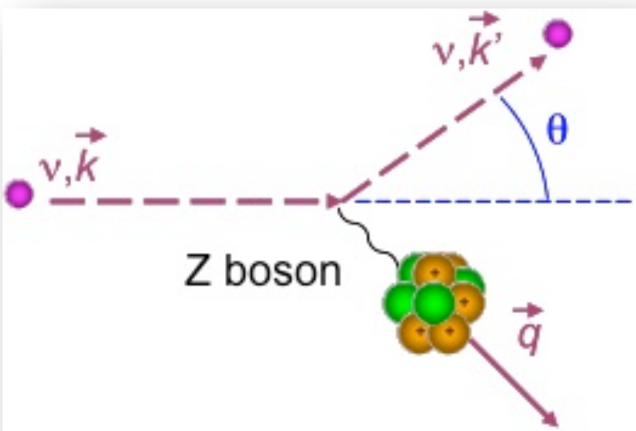
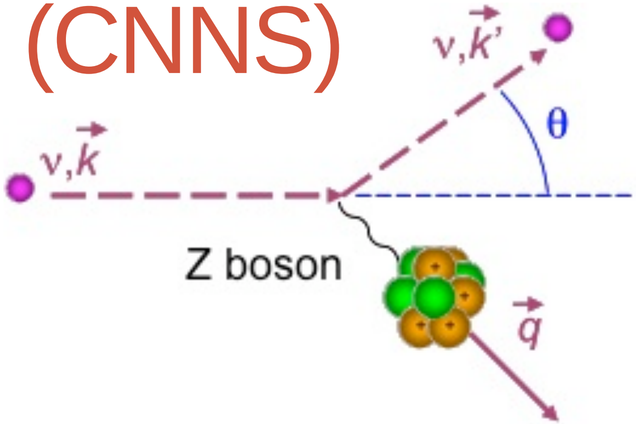
(Received 15 October 1973; revised manuscript received 19 November 1973)



. . . The idea is very simple: If there is a weak neutral current, elastic neutrino-nucleus scattering should exhibit a sharp coherent forward peak characteristic of the size of the target just as electron-nucleus elastic scattering does. . .

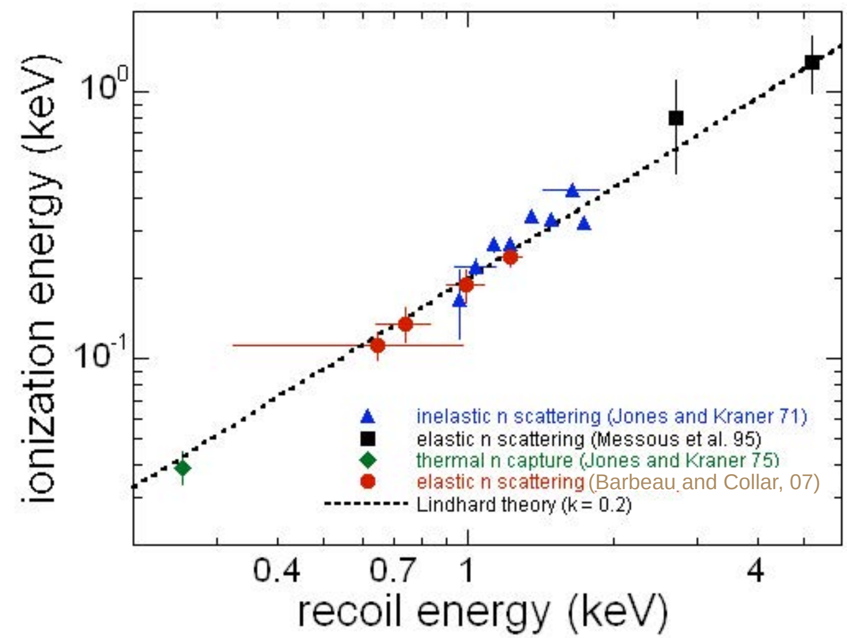
- It has never been observed!

Coherent Neutrino-Nucleus Scattering (CNNS)



- Cross section enhanced by N^2
- Detection of nucleus recoil with transfer momentum ***q*** << 1/(nucleus radius) ~ tens of MeV (condition of coherence)
- Recoil energy $\leq \frac{2}{A}\left[\frac{E_\nu}{1\mathrm{MeV}}\right]^2 \mathrm{keV}$

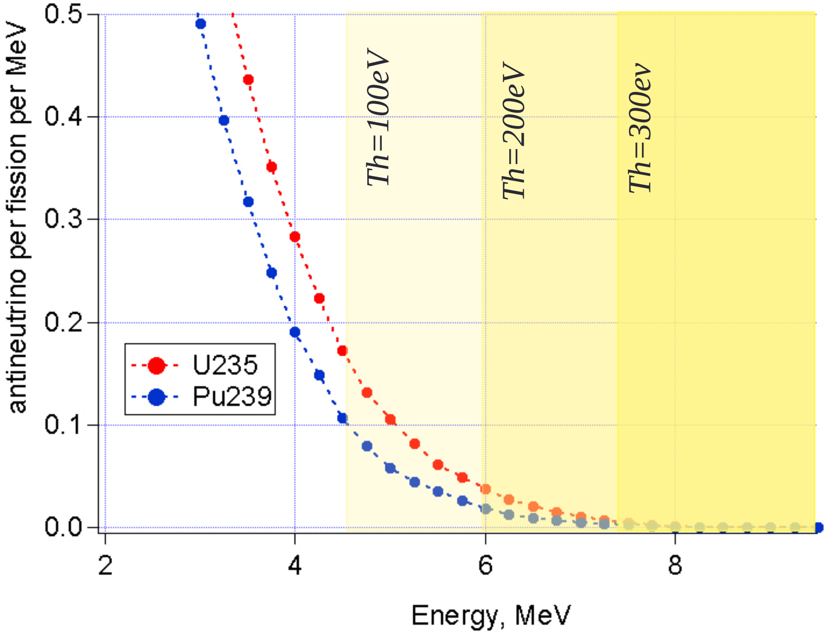
- Reactor antineutrinos produce Ge recoils of <~3keV
- Quenching to ~20% of the recoil energy
- → detection of ionization signal <600eV



Reactor Antineutrino signal vs. HPGe threshold

- Very low event rate largely dependent on energy threshold, target mass and distance to core

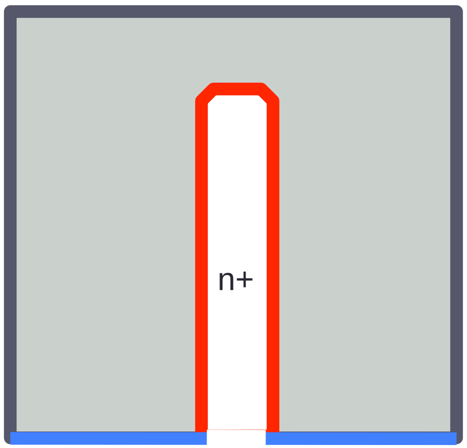
Ge detector Threshold (eV)	CNNS counts / day kg at 25m from core
300	~0.08
200	~0.60
100	~5.01



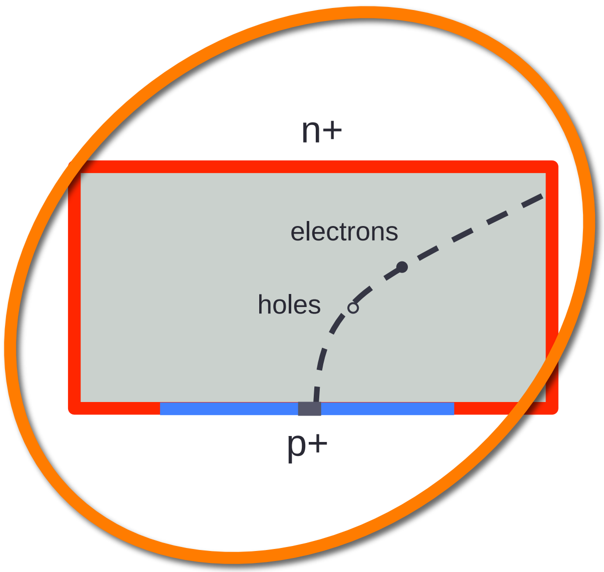
- Detector threshold imposes a kinematic constraint on accessible reactor antineutrino energies $E_\nu^{\min} \sim \sqrt{\frac{A * Threshold(keV)}{2 * QuenchingFactor}}$
- More-energetic antineutrino sources (E_ν~30MeV) admit higher detector threshold

Electronic threshold

Lower electronic threshold with Point-Contact HPGe detectors

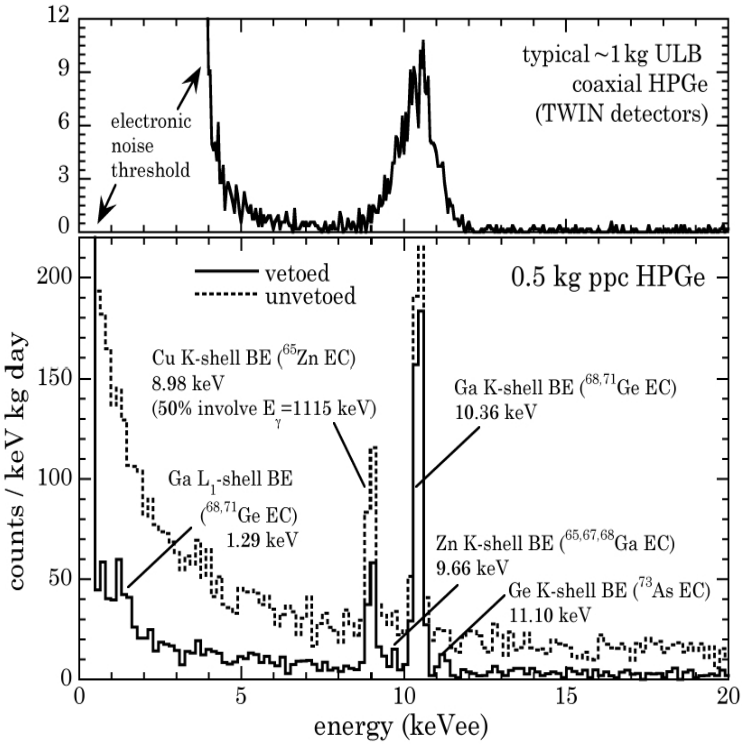


- Coaxial
- Electronic FWHM ~2keV
- ~1kg
- C~20pF



- Point-contact
- BEGe's produced by CANBERRA INC
- Electronic FWHM as low as ~150eV*
- As large as ~0.8kg
- C of order of 1pF

- Decrease capacitance to lower noise threshold and improve resolution

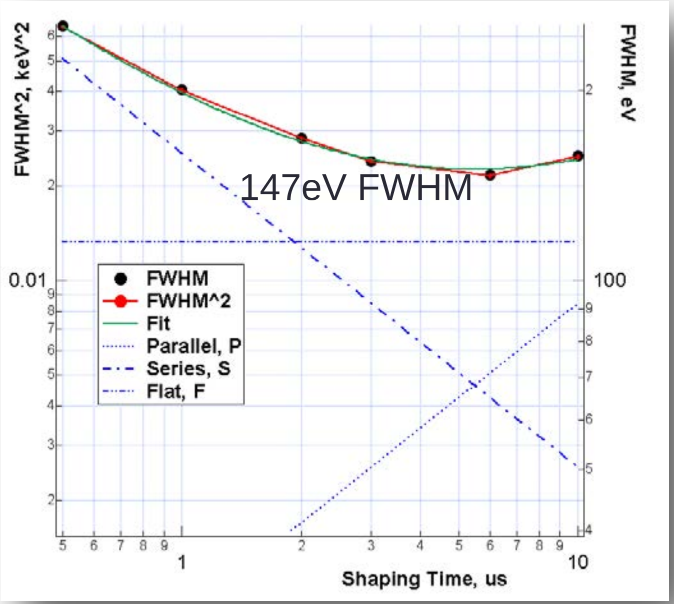


Aalseth *et al.* PRL 101, 251301 (2008)

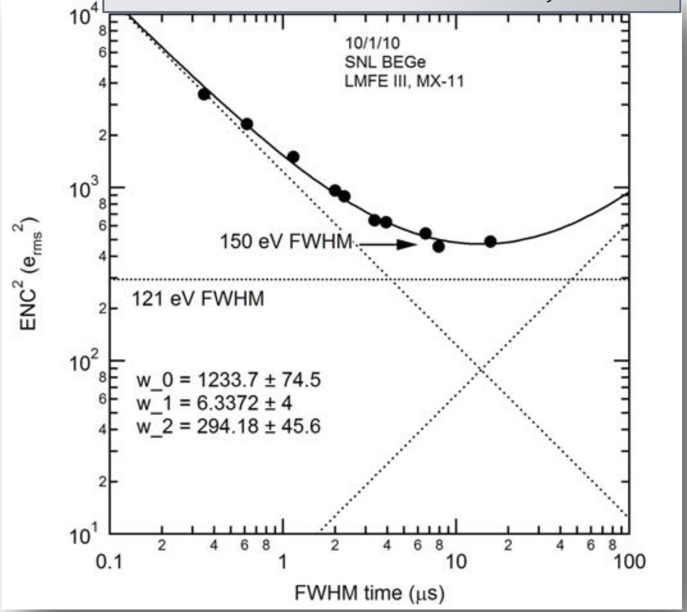
We started with a BEGe…

- Mass ~ 0.82kg,
- Point-contact diameter ~ 5mm,
- Capacitance ~1.5pF
- From CANBERRA: 147eV FWHM

- Expected threshold 350-450eV: still too high for CNNS detection
- **SPICE analysis:** Negligible contribution from preamp and High Voltage circuits
- ➔noise mainly from detector element and Front-End (FE) electronics
- **Detector element tested in LBNL Front-End:** all noise components are identical in two very different FE assemblies
- ➔noise mainly from the detector element
- ➔**path to lower noise: decrease capacitance again by reducing the point contact size (See Paul Barton's talk)**



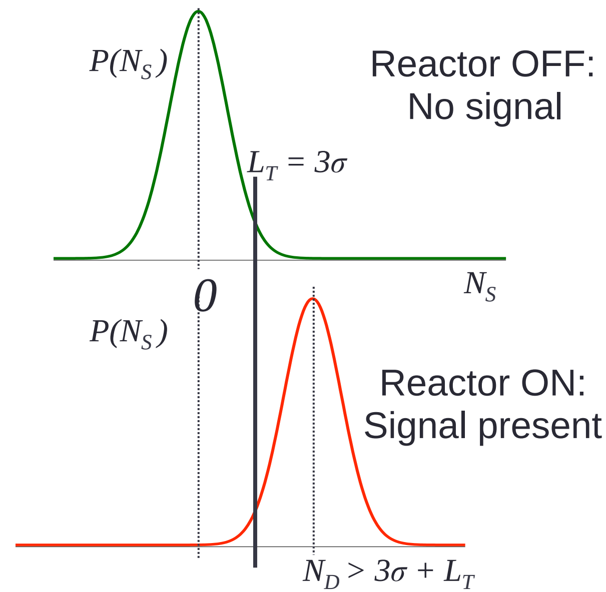
BEGe detector element tested in LBNL FE by Paul Luke



Background

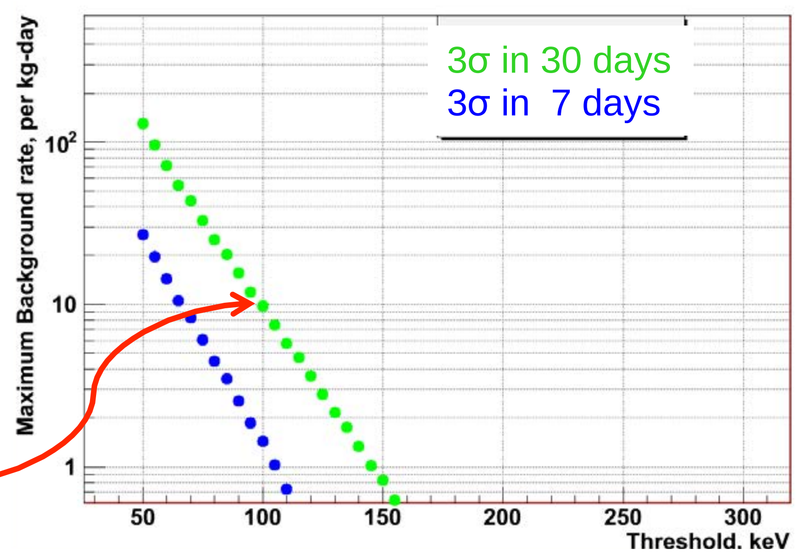
Threshold vs. Background

The background rate and measurement time (e.g., 7days or 30days), set the required electronic threshold to achieve a 3σ-confidence level measurement of reactor status ON vs. OFF



- The plots show an estimation of the maximum background rate (per kg of Ge, per day) integrated from threshold to 1keV, that would allow a *3σ observation of reactor ON/OFF transition, versus energy threshold.*

- A 100eV threshold admits no more than 10 bckg counts/kg-day in the region < 1keV



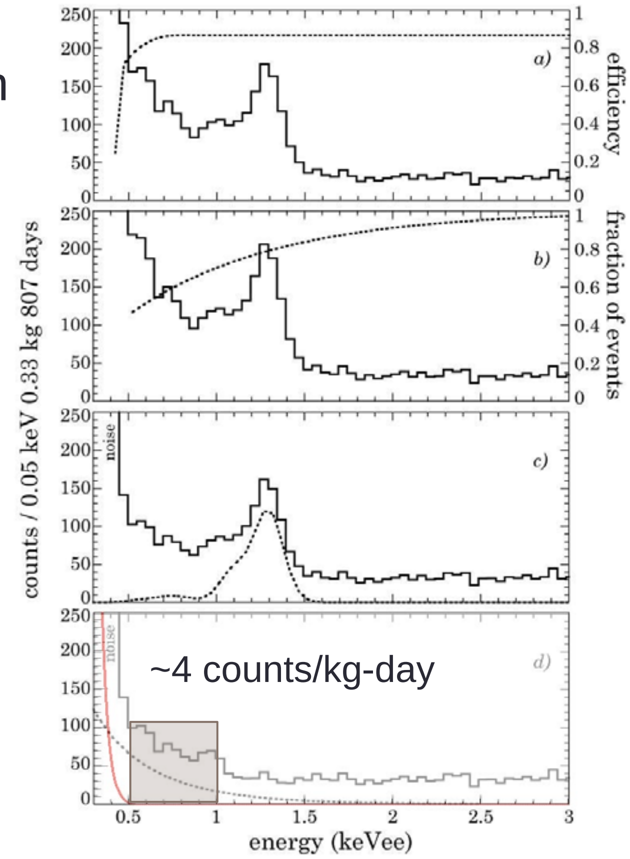
Background signals < 1keV

<table>
<tr><th>Primary particle</th><th>Process</th><th>Background signal</th></tr>
<tr><td>Cosmic secondary n and μ-induced n</td><td>Scattering off Ge nucleus</td><td>Ge-nucleus recoils</td></tr>
<tr><td>Cosmic secondary n and μ-induced n</td><td>Nuclei activation: ^{71}Ge, ^{68}Ga, ^{65}Zn, …</td><td rowspan="3">Partial energy depositions from X-rays and Auger e-, internal to germanium</td></tr>
<tr><td>Cosmic primary p at sea level</td><td>Nuclei activation: ^{73}As, ^{68}Ge, …</td></tr>
<tr><td>Thermal n</td><td>Nuclei activation: ^{71}Ge</td></tr>
<tr><td>γ</td><td>Natural radioactivity from detector materials</td><td>Forward-peaked Compton scattering</td></tr>
<tr><td>Solar and Geo ν</td><td rowspan="2">Scattering off Ge nucleus</td><td rowspan="2">Ge-nucleus recoils</td></tr>
<tr><td>WIMP ?</td></tr>
</table>

Measured backgrounds from other experiments: underground mine

CoGeNT 2012 data: CANBERRA BEGe , 330 g of fiducial volume, 163eV FWHM, deployed in Soudan mine at 2,100m.w.e.

- Threshold 0.5keVee
- Near-threshold counts: **~8keV^{-1}kg^{-1} d^{-1}**
- Irreducible counts (after all cuts) in region 0.5-1keVee: **~4 kg^{-1} d^{-1}**



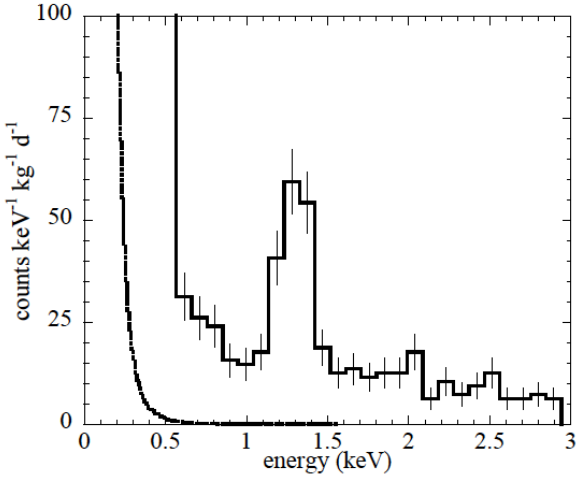
Aalseth *et al*. arXiv:1208.5737

- Confirmed that decays from cosmogenic activation internal to Ge populate the region <3keV. (Use cosmogenic peaks for calibration.)
- Partial energy deposition events (from nuclei decays) are significant near threshold but can be efficiently rejected by “risetime” cuts.
- Natural radioactivity from materials near the detector is estimated to be negligible.

Measured backgrounds from other experiments: SONGS Tendon Gallery

SONGS 2009 data: same CANBERA BEGe, deployed in SONGS reactor at 25m.w.e.

- Near-threshold counts: **~22 keV^{-1} kg^{-1} d^{-1}**
- Counts in 0.5-1keVee range: **~11 kg^{-1} d^{-1}**
- “Risetime Cuts” not applied here because the raw preamplifier traces were not recorded, but x2-3 reduction expected.
- No evidence of significant increase in neutron background at this overburden with proper shielding.



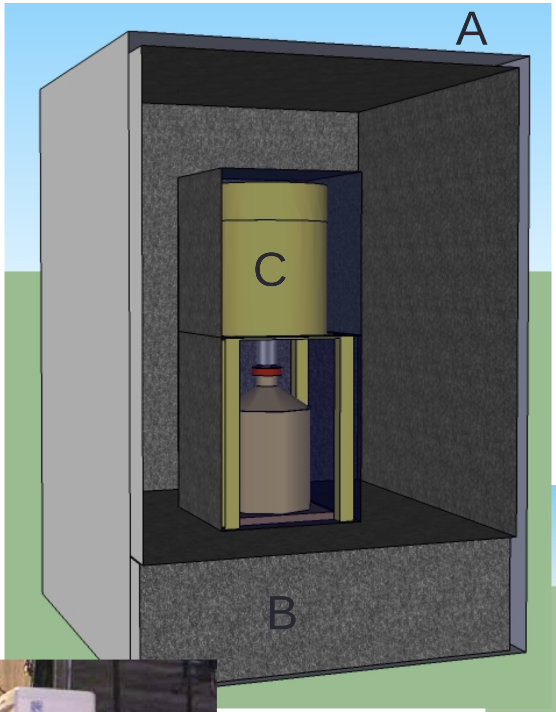
Courtesy of
P. Barbeau and J. Collar

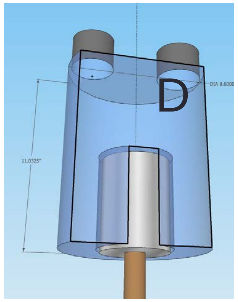
Proposed shielding

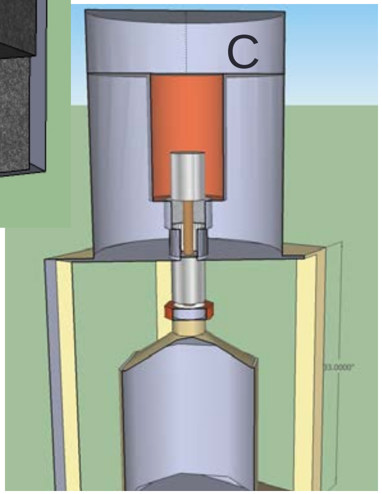
A. 2” external muon veto
B. 20” HDPE neutron moderator with internal 2” borated Poly as thermal neutron absorber
C. Ultra-low background Canberra Lead shield
D. Anticoincidence veto for fast neutrons and gammas

And also:

- 30 m.w.e overburden
- Radioclean detector and shield materials
- Purging Radon with nitrogen gas
- Lithium-diffused n+ contact covering most Ge surface electrode (*in p-type a ~1mm-Li layer suppresses betas and alphas from surrounding materials*)
- Time to cool down of Ge activation from exposure to surface cosmic rays



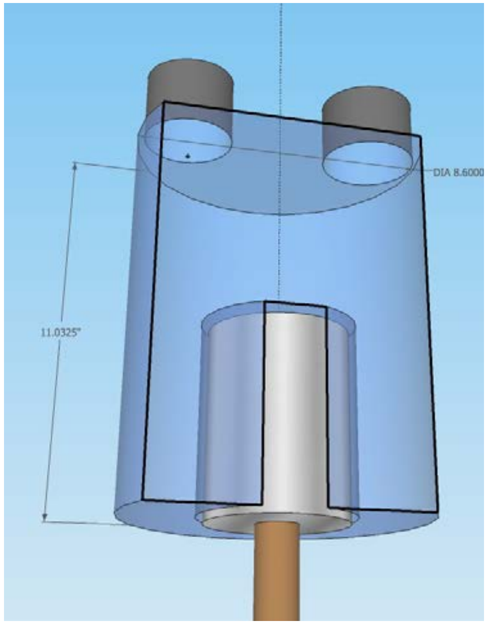


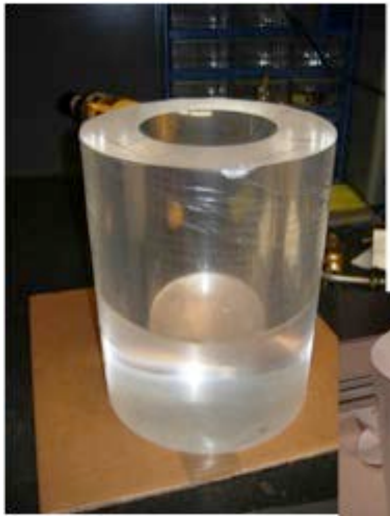


- Working on background simulations to validate shielding design

Anticoincidence veto

- Neutrons penetrating the external shield, if un-vetoed, could create a ubiquitous background in the near-threshold energy region.
- Built and characterized an anticoincidence internal veto, made of plastic organic scintillator (PS) in order to increase sensitivity to neutrons in the vicinity of the HPGe detector..
- Inside Lead shield: Cylinder with internal well made of EJ200 PS, surrounded by GORE® Diffuse Reflector, plus 4 low-bkgd Hamamatsu PMTs, signal and HV cables
- Other experiments use inorganic scintillators like NaI(Tl) and CsI(Tl), which have high sensitivity for gammas but not for neutrons. CoGeNT at Soudan did not use AntiCompton veto.

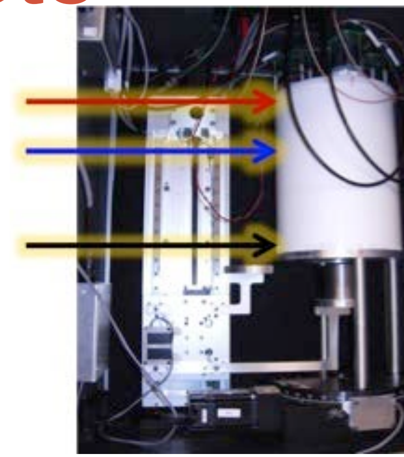




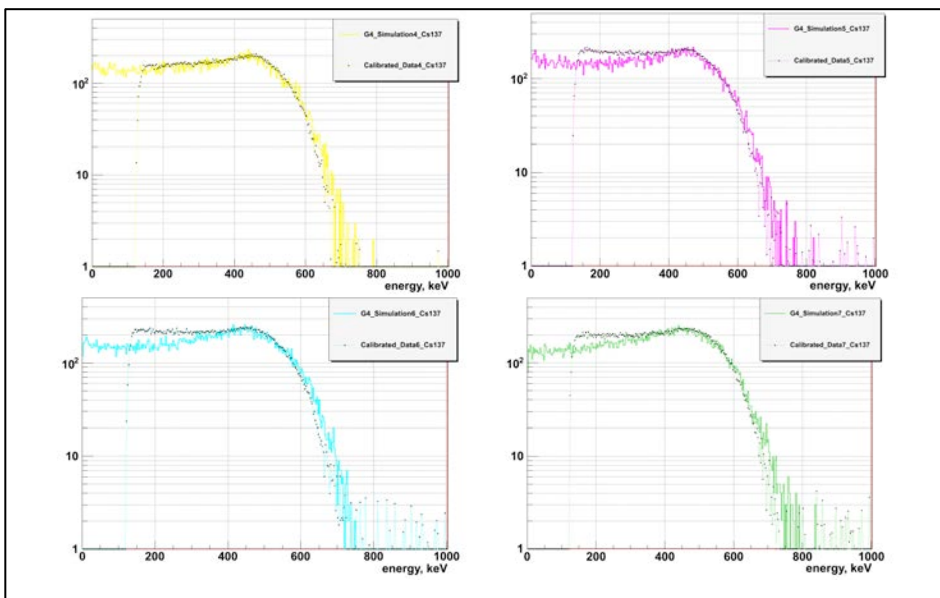

Testing PS Anticoincidence veto

- G4 simulations of particle interaction, scintillation, and optical propagation, compared to measurement of vertical scan with ^{137}Cs and ^{133}Ba
- Results: good spatial uniformity in light collection efficiency

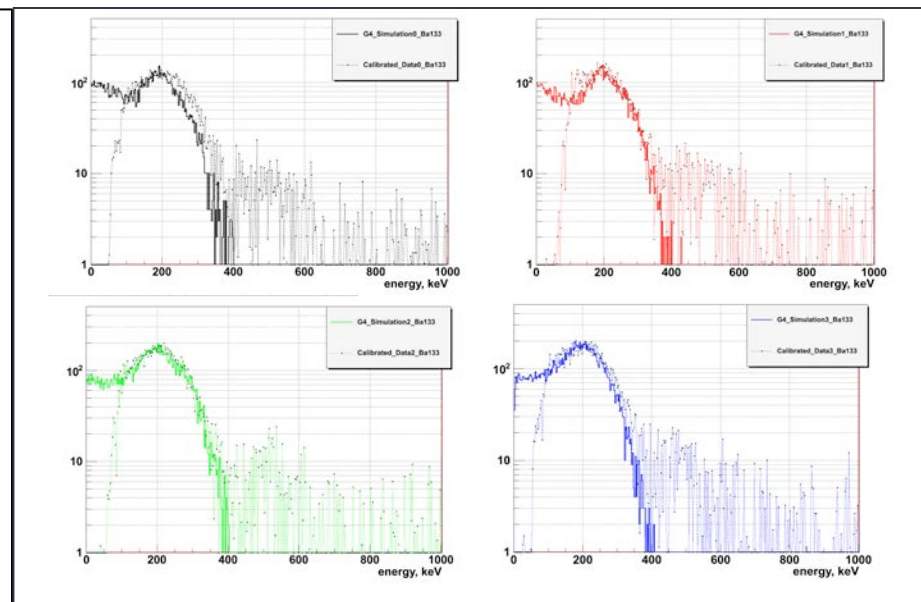
Vertical scan with Cs137 and Ba133



^{137}Cs source at 25.4mm (yellow), 101.6mm (pink), 177.8mm (blue), and 254.0mm(green). Black dots are data.

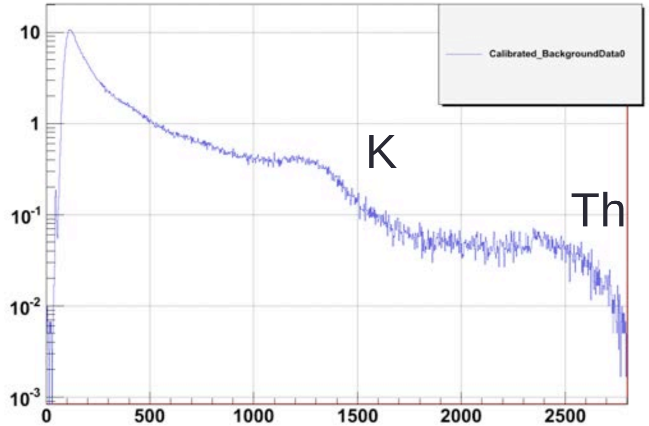


^{133}Ba source at 25.4mm (black), 101.6mm (red), 177.8mm (green), and 254.0mm(blue). Black dots are data.



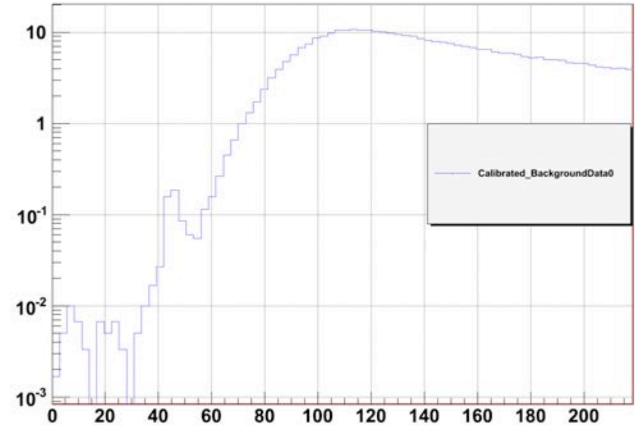
Testing PS Anticoincidence veto

- Well defined K and Th Compton edges: good energy resolution thanks to high reflectivity of the GORE® Diffuse Reflector
- Results: hardware threshold at ~100keVee
- Threshold for neutrons ~ 1MeV



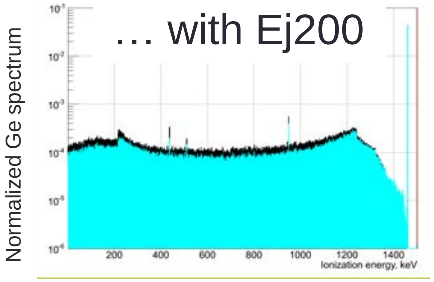
Energy Histogram of ambient background, showing the K and Th Compton edges.

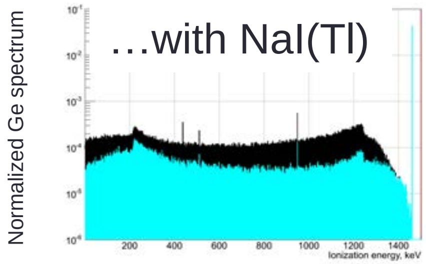
keV



Anti-Compton efficiency: Ej200 vs NaI(Tl)

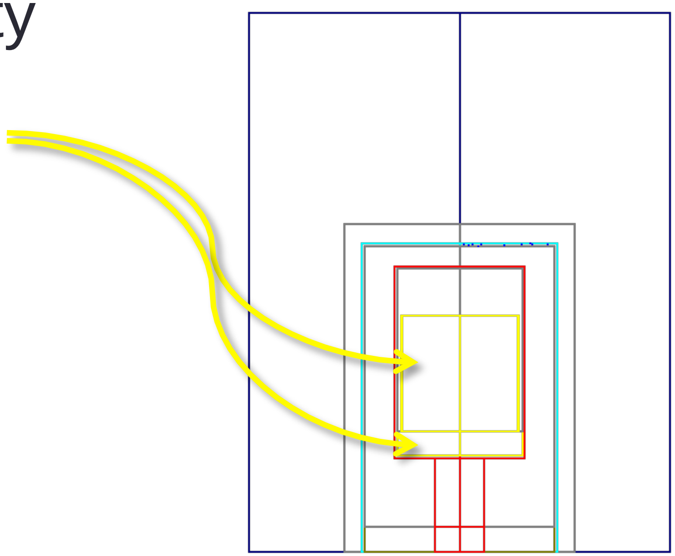
- G4 simulation of K40 radioactivity from Teflon lining and isolation





Black: all Ge counts

Blue: Ge counts with AC suppression

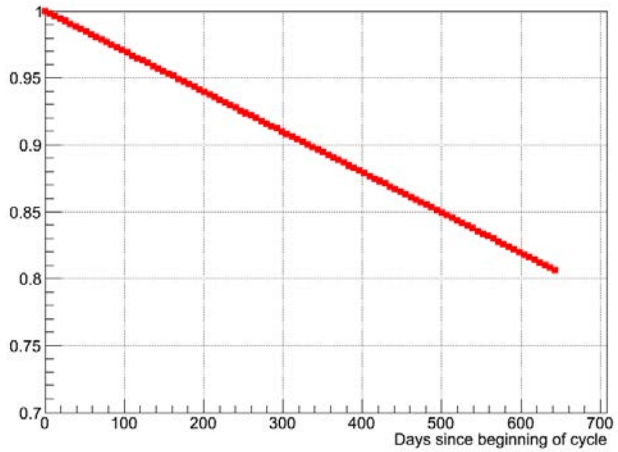


	AC efficiency Full range	AC efficiency 0.1-3 keV
Ej200	0.20	0.31
NaI(Tl)	0.55	0.73

- Anti-Compton rejection efficiency degraded by ~½ with Ej200 compared to Na(I)
- Care in choosing low radioactivity materials, including the materials for Front-End and the veto itself

Why a Germanium detector for Reactor monitoring?

Change in CNNS signal rate from reactor anti-ν vs. fuel cycle



- About 20% variation in total C(anti)NNS events during NPP fuel cycle: higher sensitivity to fuel composition than inverse beta (10% variation)
- Cryogenic germanium detectors are already well known and are frequently used at nuclear reactor facilities around the world.
- Little or no safety concerns from the facility operators.
- In addition, the ability to shrink the active detector from 1 ton of scintillator material to something on the order of 10 kg of germanium might allow for much more flexibility in finding locations suitable for detector installation.

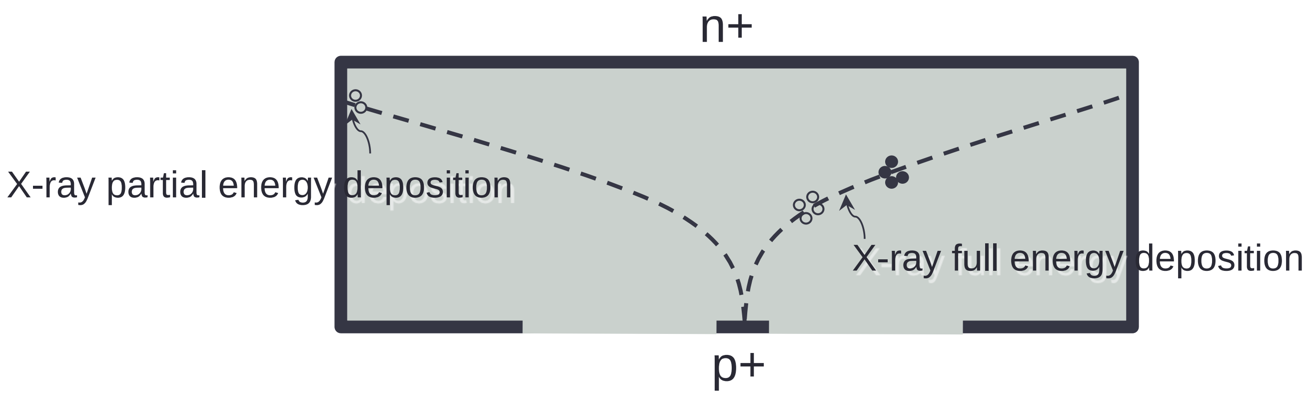
Summary

- Electronic noise threshold is the main barrier for reactor monitoring with PPC HPGe detectors. Our initial tests indicated that a path to lower noise is smaller capacitance (next talk)
- Measured background (CoGeNT2012, SONGS2009) “allow” possible observation of CNNS (reactor ON/OFF) with 100eV electronic threshold and proper shielding.
- ULGeN (LBNL-SNL-UCB) currently working on the development and towards the deployment of new 1-kg detector PPC HPGe

Backup slides

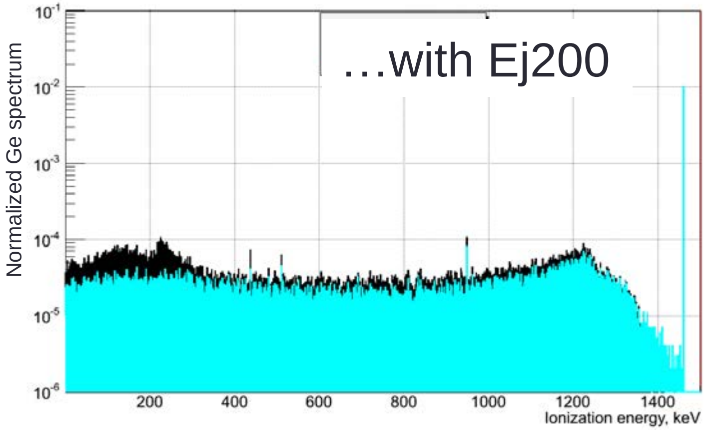
How “Risetime” cuts work

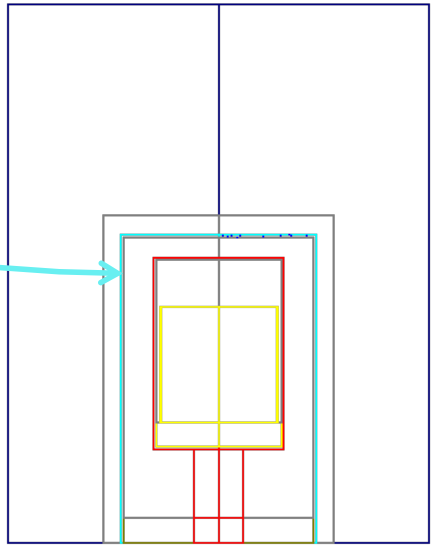
- Events near the dead region will only deposit part of the energy
- But also, the induced charge in the electrodes will rise slowly because near the dead layer the electric field is weak



AntiCompton efficiency: Ej200 vs NaI(Tl)

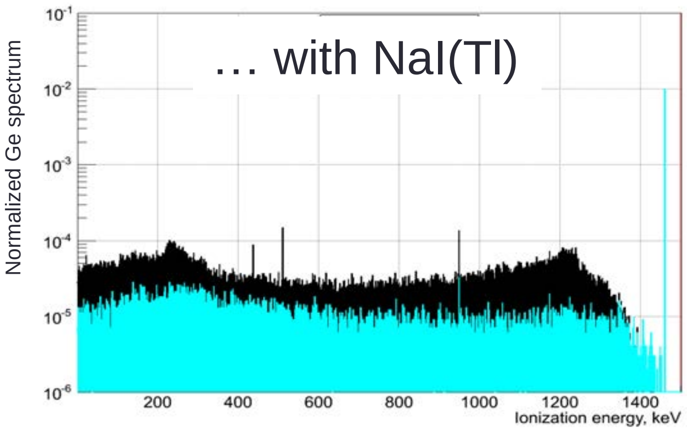
- G4 simulation of K40 radioactivity from Aluminum Cap





Black: all Ge counts

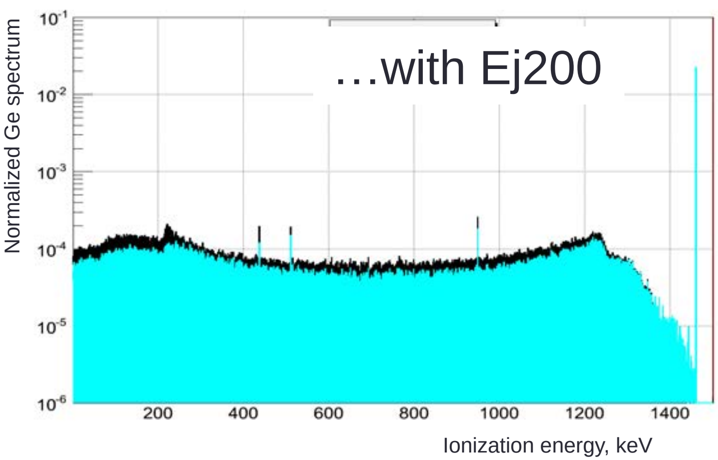
Blue: Ge counts with AC suppression

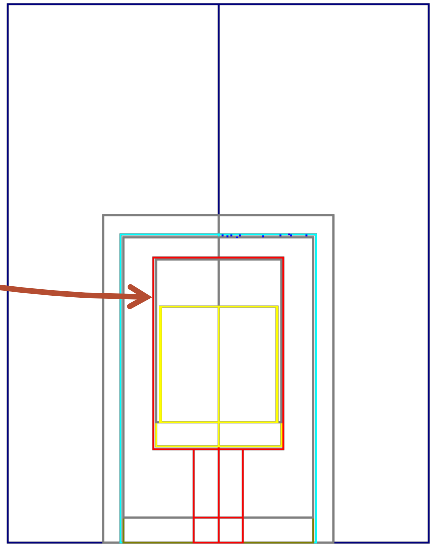


	AC efficiency Full range	AC efficiency 0.1-3 keV
Ej200	0.28	0.49
NaI(Tl)	0.60	0.75

AntiCompton efficiency: Ej200 vs NaI(Tl)

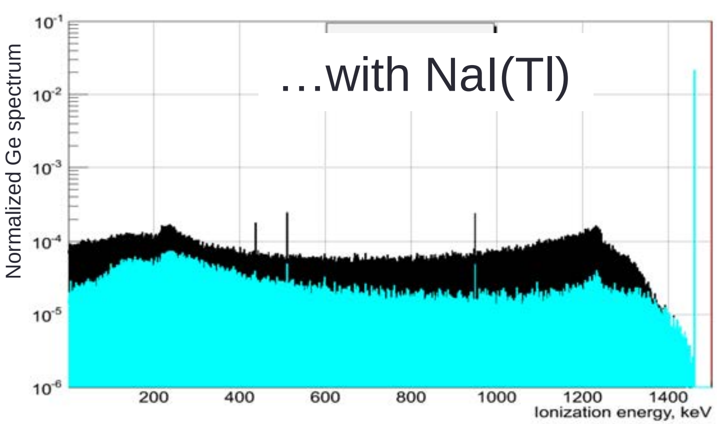
- G4 simulation of K40 radioactivity from **Copper Can**





Black: all Ge counts

Blue: Ge counts with AC suppression



	AC efficiency Full range	AC efficiency 0.1-3 keV
Ej200	0.21	0.33
NaI(Tl)	0.55	0.79