Remote Detection of Fissile Material: Cherenkov Counters for Gamma Detection

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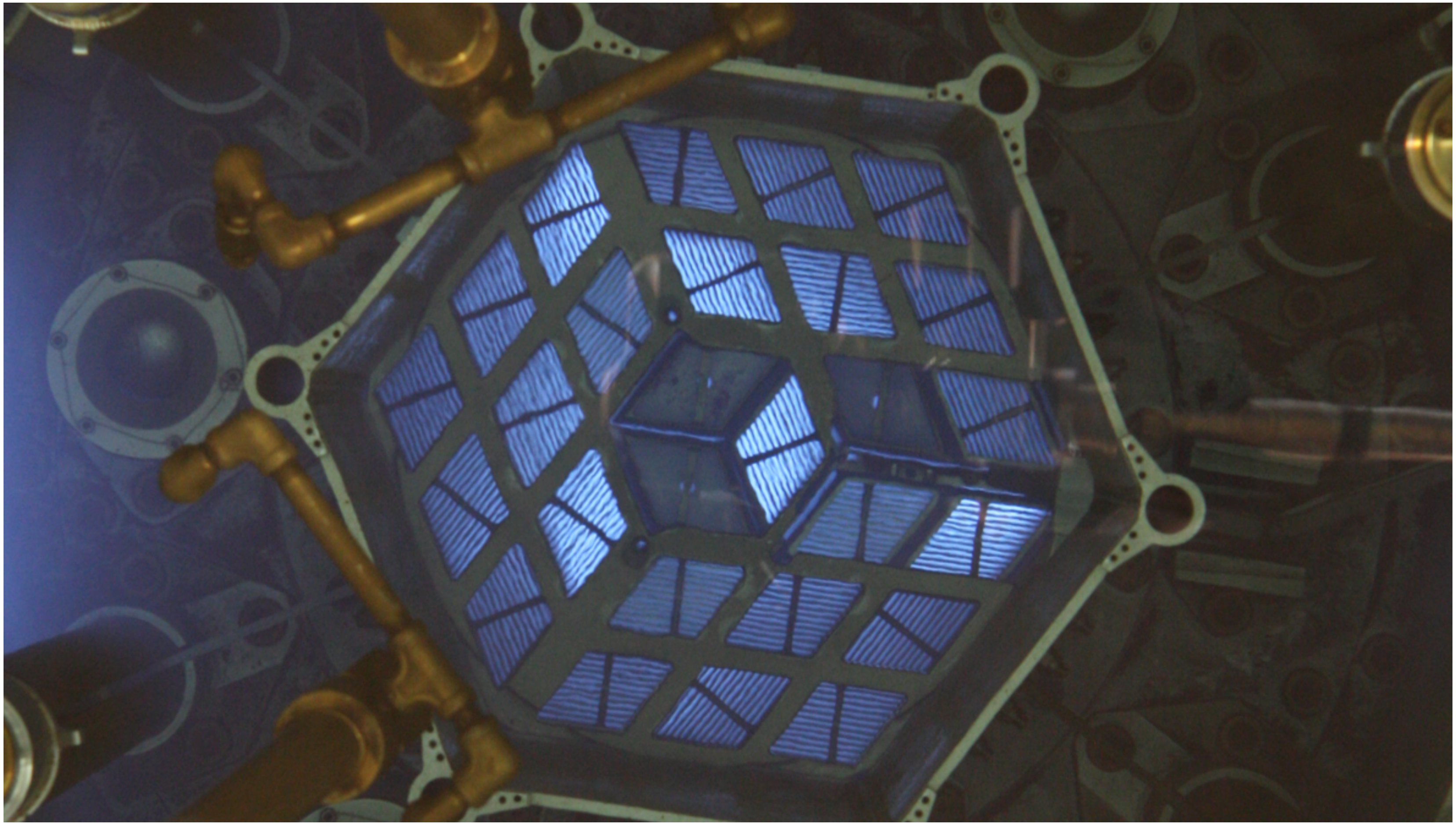
Motivations of This Work

- Issues of security and non-proliferation require methods for long-distance (~ 100m) detection of fissile materials
- Passive means are not adequate
- Most reliable approach is an active approach which “interrogates” an object with radiation beams
- These beams result in the production of fission gammas and neutrons
- Operation at a distance requires a new approach to radiation detectors
  - Previous work using neutron or photon interrogation has shown that good energy resolution is not required

MITR – Can You Find New and Old Assemblies?



Outline

1.	Motivations: the problem of nuclear security
2.	Cherenkov counters in long-range detection
3.	Experimental WCD
4.	Detector calibration and background suppression
5.	Conclusions and future work

The Problem of Global Nuclear Security

- Non-proliferation and nuclear defense in the post-Cold War era were presented with new problems:
  - Terrorist groups and sub-national actors are seeking nuclear materials and weapons instead of national weaponization
  - al Qaeda and Aum Shinrikyo
- Building nuclear weapons is no longer a daunting problem because of widespread of nuclear technologies and expertise
  - Pakistan, North Korea
- How do we ensure that the special nuclear materials are kept out of the hands of state and non-state actors?

U.S. Strategy: Multilayered Defense

Non-proliferation

- Improve control regimes
- Always less than perfect

Counter-proliferation

- Manipulate black market
- Determined adversaries will penetrate this layer

Detect active phase

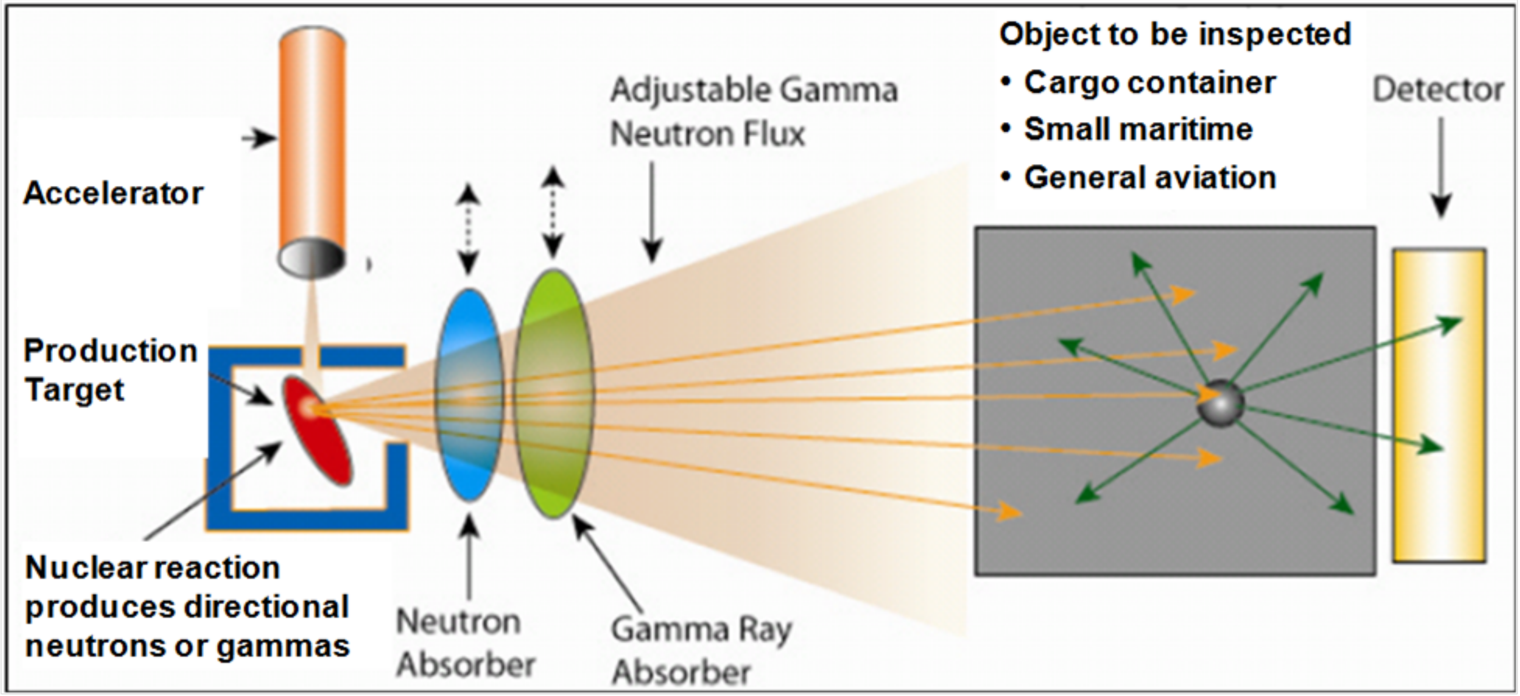
- Acquisition
- Weaponization
- Deployment

Where Are the Weaknesses?

In testimony before a Senate subcommittee in 2002, Capt. W. Schubert, the Transportation Department's maritime administrator stated that U.S. seaports experience particular "susceptibility of container shipments as a delivery system for an enemy's weapons, with over 12 million TEU's/year arriving at our shores".

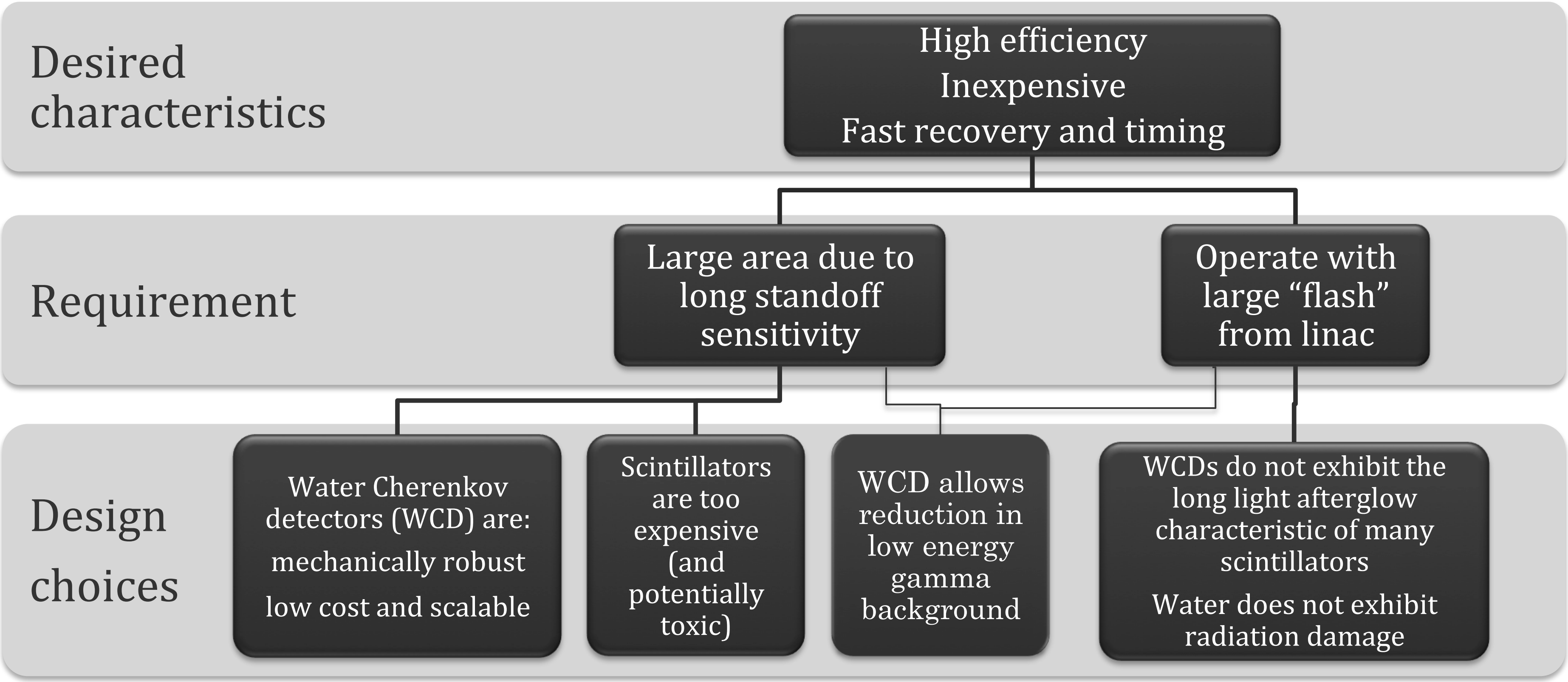
TEU = twenty-foot equivalent unit

Stand-off Active Interrogation Detection: Concept



- Gamma rays and neutrons induce nuclear reactions in suspect SNM materials
- These induced reactions emit radiation characteristic of specific SNM
- Other materials won’t be mistaken for SNM because of unique time and energy “fingerprint” of radiation signature

Gamma Detectors for Active Interrogation



Desired characteristics

High efficiency
Inexpensive
Fast recovery and timing

Requirement

Large area due to long standoff sensitivity

Operate with large "flash" from linac

Design choices

Water Cherenkov detectors (WCD) are:
mechanically robust
low cost and scalable

Scintillators are too expensive (and potentially toxic)

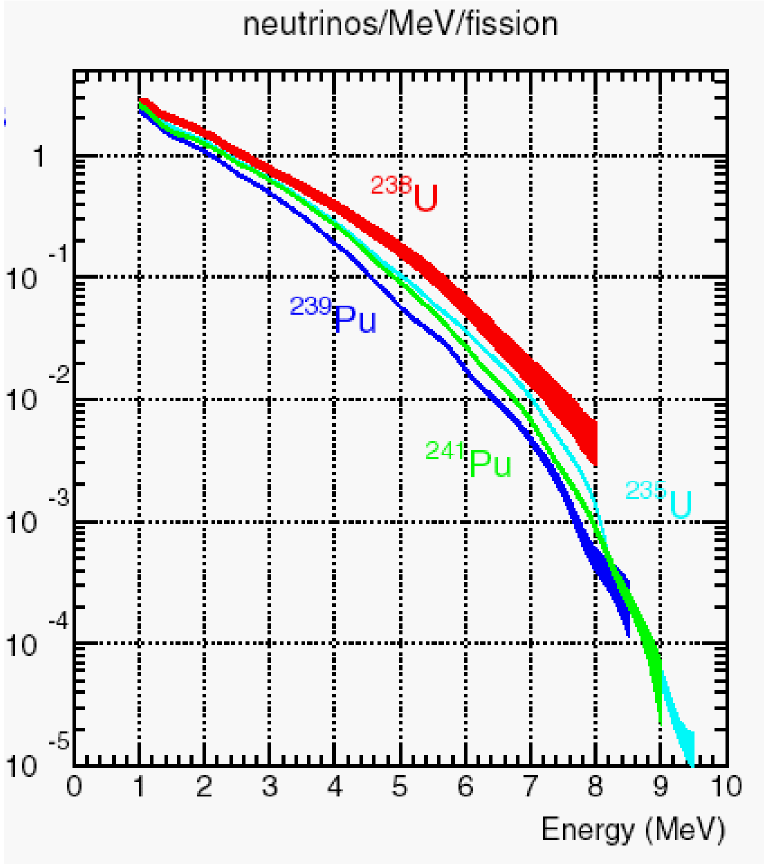
WCD allows reduction in low energy gamma background

WCDs do not exhibit the long light afterglow characteristic of many scintillators
Water does not exhibit radiation damage

Resolution is not required because the energy spectrum of fission gamma rays is continuous. Energy of interest is 3-10 MeV. Capability of placing an energy cut is important.

Reactor Monitoring with Antineutrinos – Another Application of WCD

- Non-cooperative monitoring of reactors?
- Finding smaller units remotely?
- Oscillation experiments have introduced the idea of distant reactor monitoring
- Neutrinos (and antineutrinos) cannot be stopped -> use neutrinos to achieve the above goals
  - Cross section of neutrino capture on hydrogen is $\sim 10^{-42}$ cm^2
- But neutrinos cannot be stopped…how can we detect them?
  - Antineutrinos are byproduct of nuclear fission
  - Produced in large quantities (order of 10^{20} antineutrinos per second) in a typical reactor
- Use large detectors



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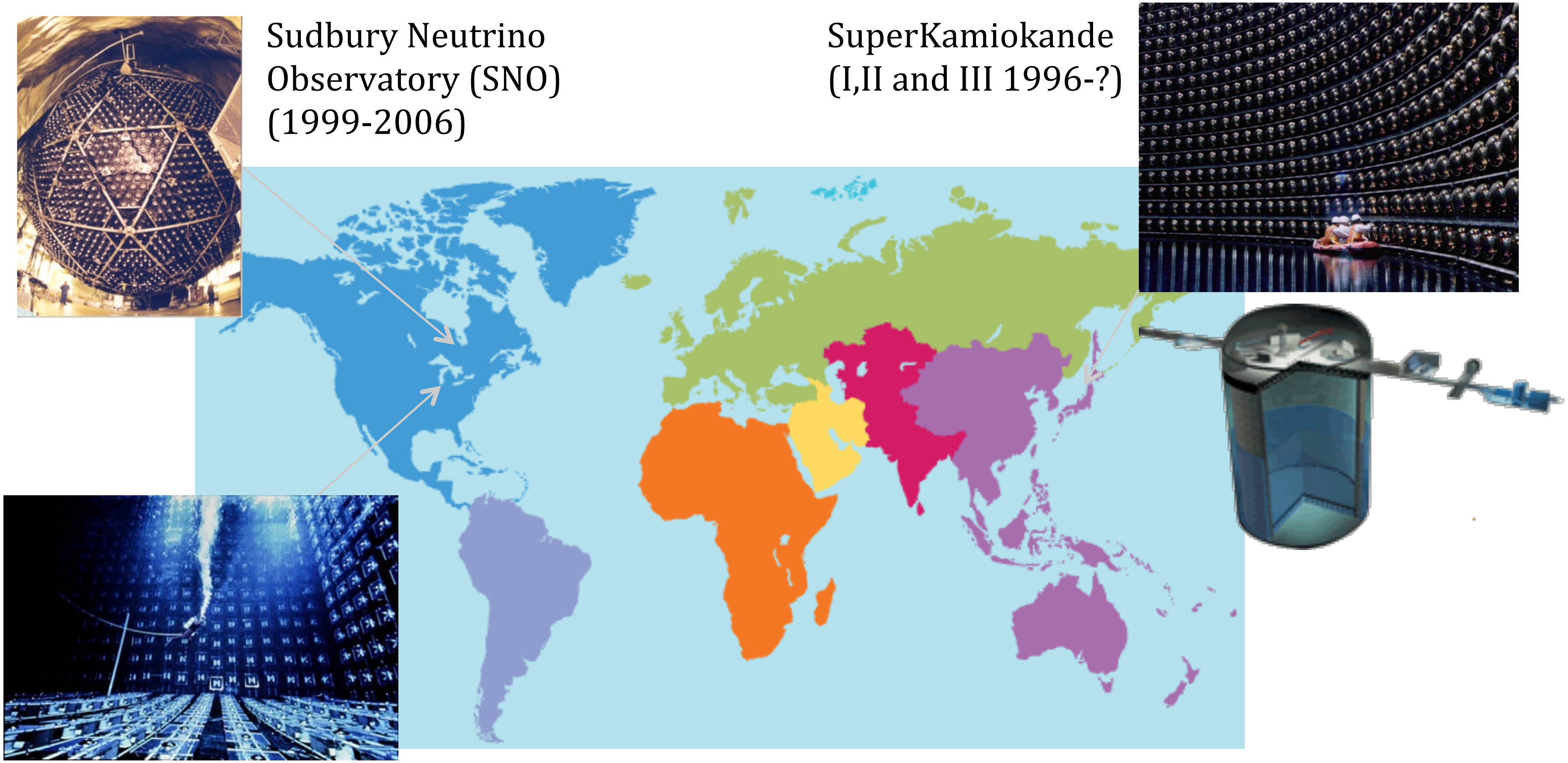
Cherenkov in High Energy Physics: Past, Current and Future



Sudbury Neutrino Observatory (SNO) (1999-2006)

SuperKamiokande (I,II and III 1996-?)

The IMB Neutrino Detector (1982-1990)

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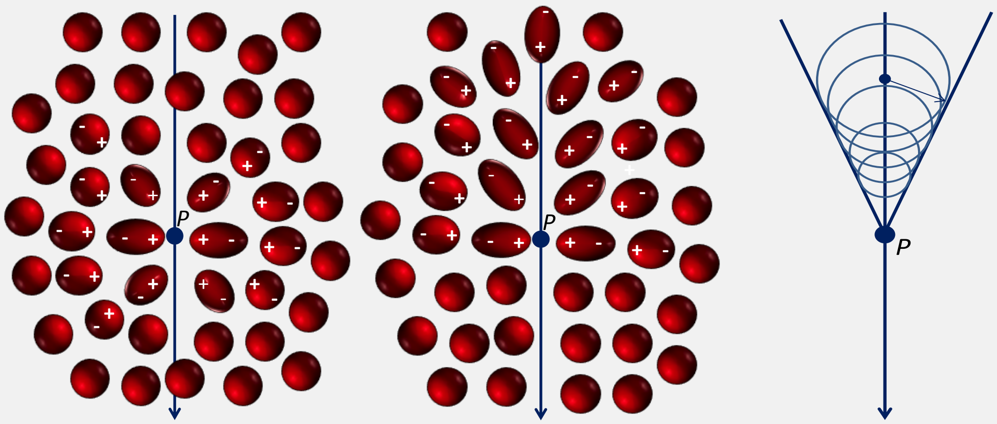
Concept of Cherenkov Radiation

Cherenkov radiation is

- light in a form of a forward cone
- a response to the motion of charged particle traveling at a speed exceeding the phase velocity of light in the medium.



v < c/n

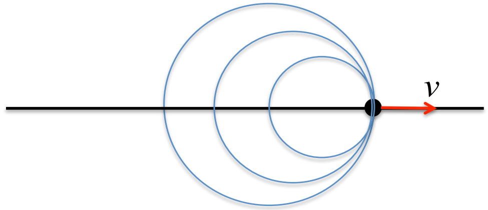
v > c/n

a cone of dipoles develops behind P

Slow moving particles create symmetrical polarization; thus, no electric field at long distances and no radiation. Fast moving particle result in polarization along the axis of motion.

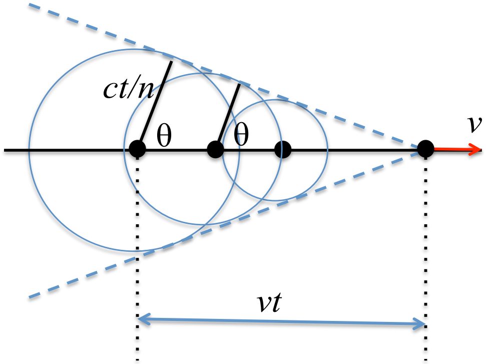
The dipole field is collapsed with the emission an electromagnetic pulse (Cherenkov radiation). Radiation would be emitted perpendicular to the surface of this cone.

Properties of Cherenkov Radiation



① Kinetic energy threshold

$$v \geq \frac{c}{n}$$



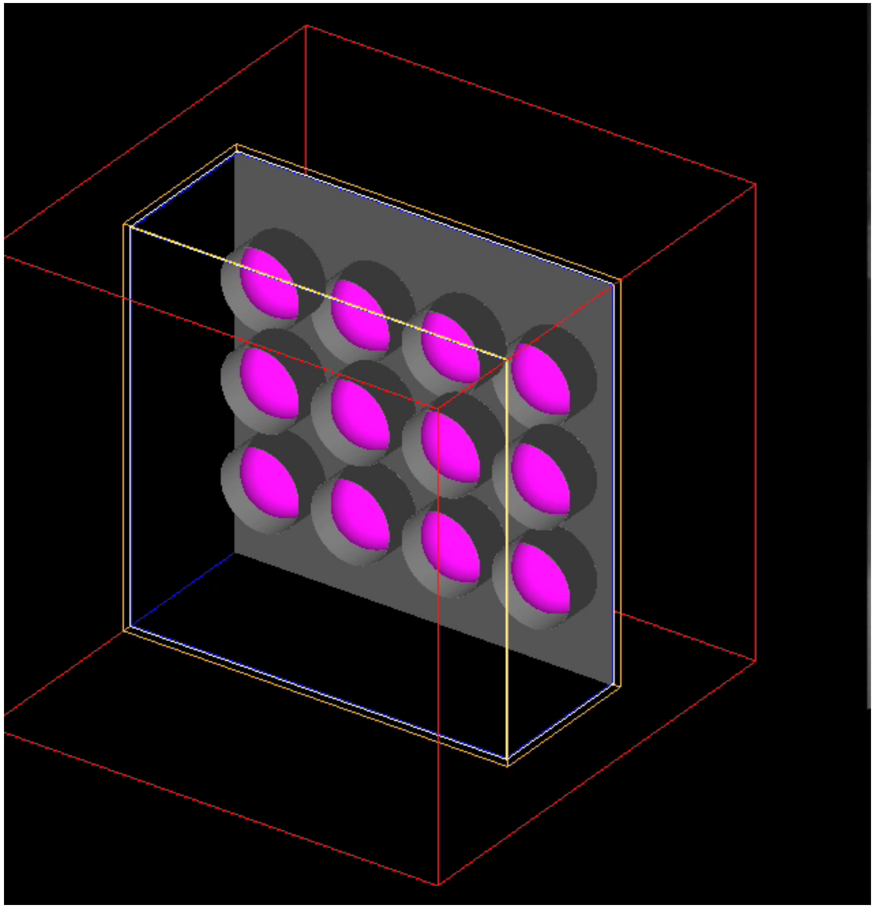
② Cherenkov light cone angle

$$\cos\theta = \frac{1}{\beta n}$$

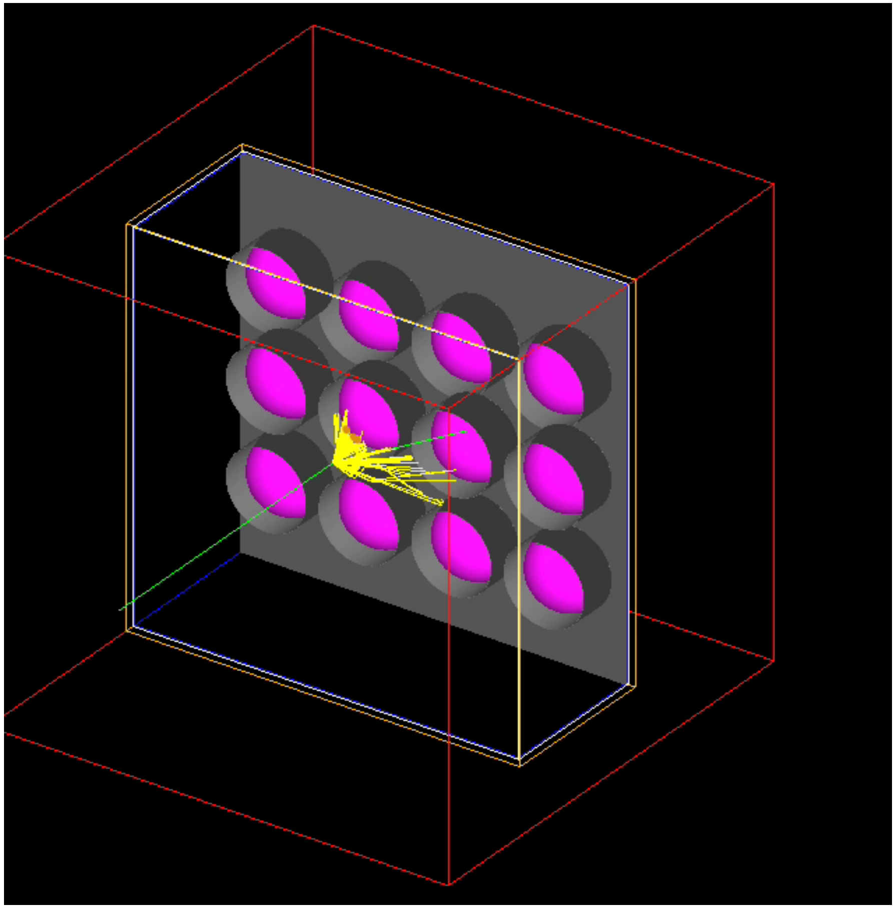
Light yield:

$$\frac{d^2N}{dx\,d\lambda} = \frac{2\pi\alpha}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2}\right)$$

Cherenkov Light in Small Detectors



1 MeV gamma ray



10 MeV gamma ray

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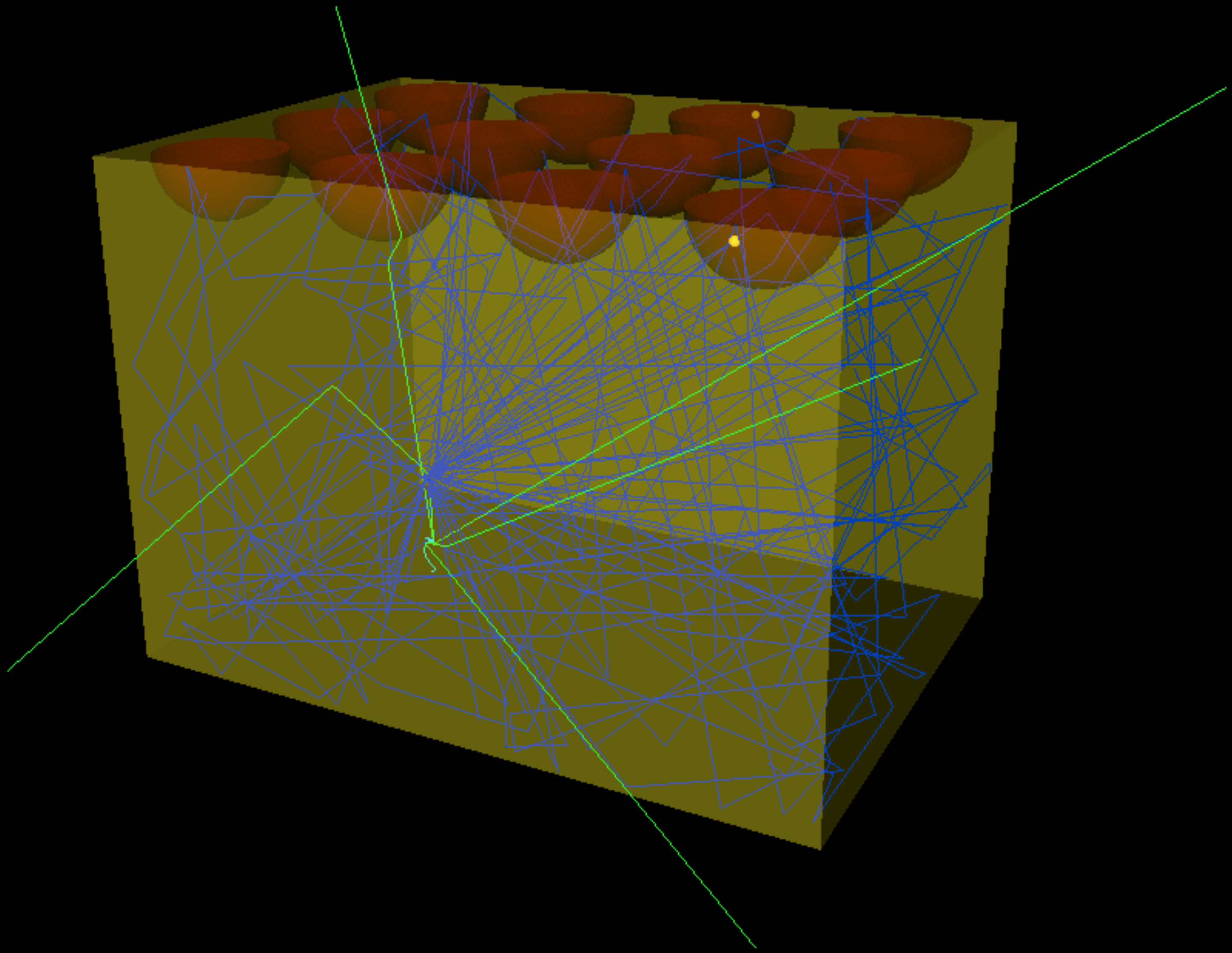
Principles of Water-Based Neutron and Gamma Detection



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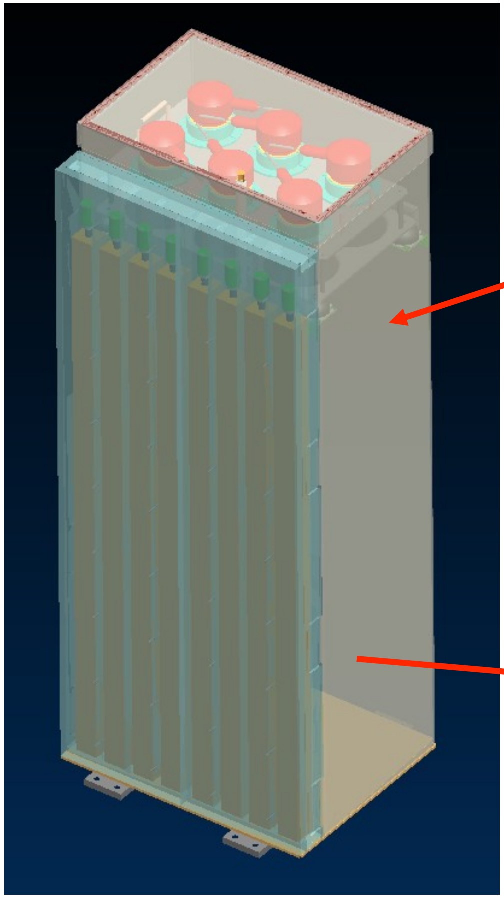
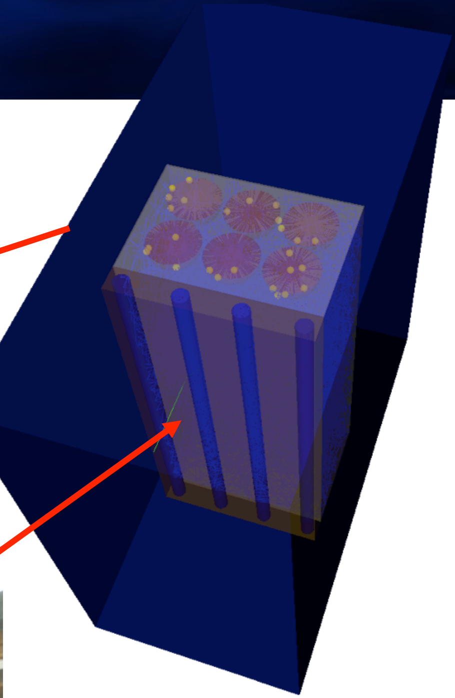
AI Detector Tank Concept



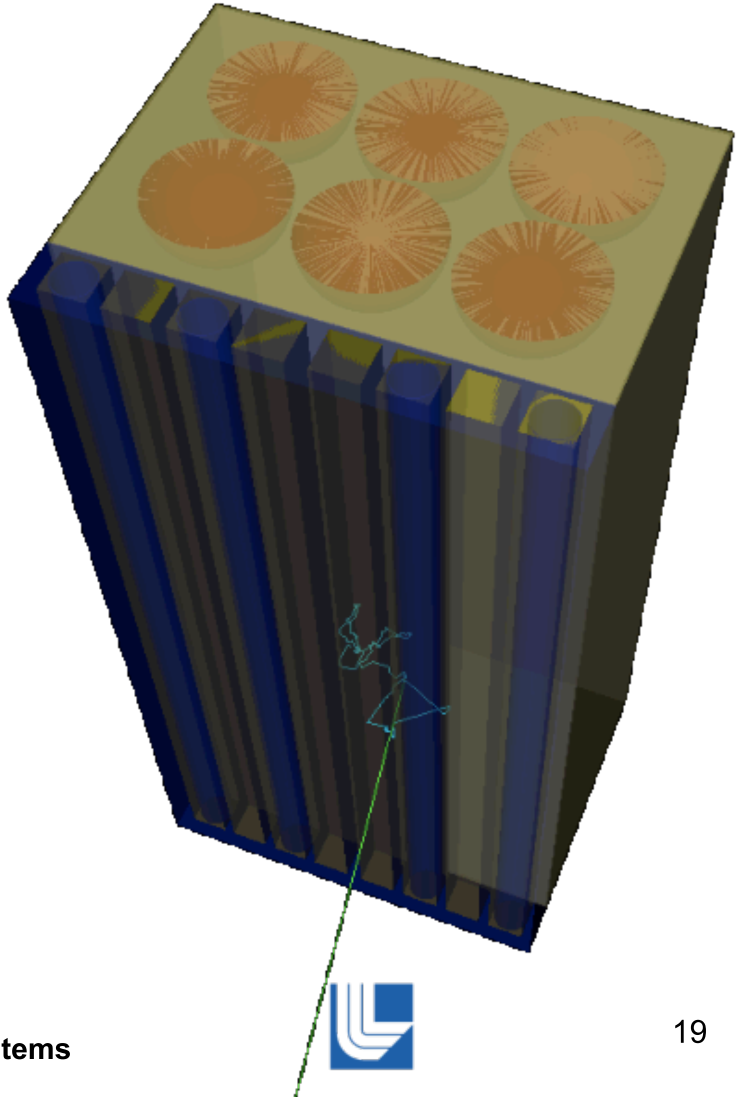


Geant4 Model

- The Geant4 toolkit provides a flexible framework for the simulation of particle transport and interaction with matter

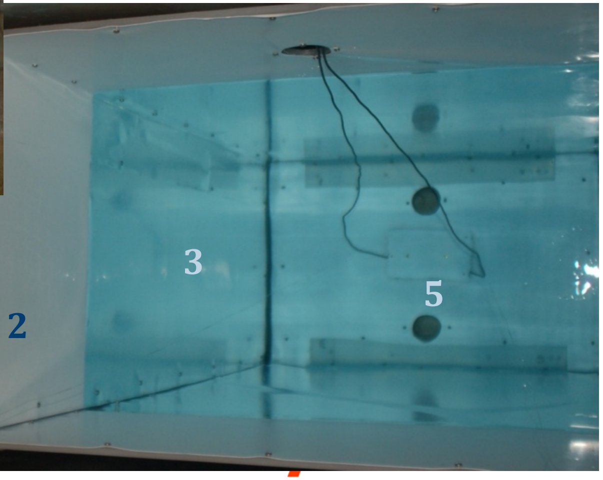
- Full detector simulation has been developed in Geant4 with the purpose of:
  - Optimization of detector performance
  - Confirming suitability of the WCD for gamma detection
  - Understanding of detector behavior

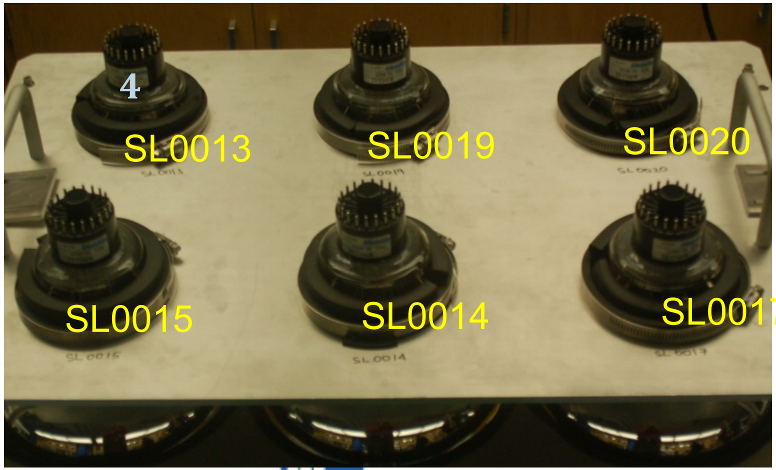
- All relevant physical interactions were modeled in detail including nuclear and electron interactions and optical performance of the detector components.



Simple Design

1. Light-tight aluminum body, which measures 0.75m x 0.5m x 2m
2. Polypropylene insert for support of high efficiency (98.5%) diffuse reflector (Gore)
3. DI(deionized)-grade filtered water
4. Cherenkov photons are detected with six 20-cm hemispherical Hamamatsu PMTs
5. Two UV light emitting diodes (LEDs)





Tank HW Assembly & Prototype CD Tests

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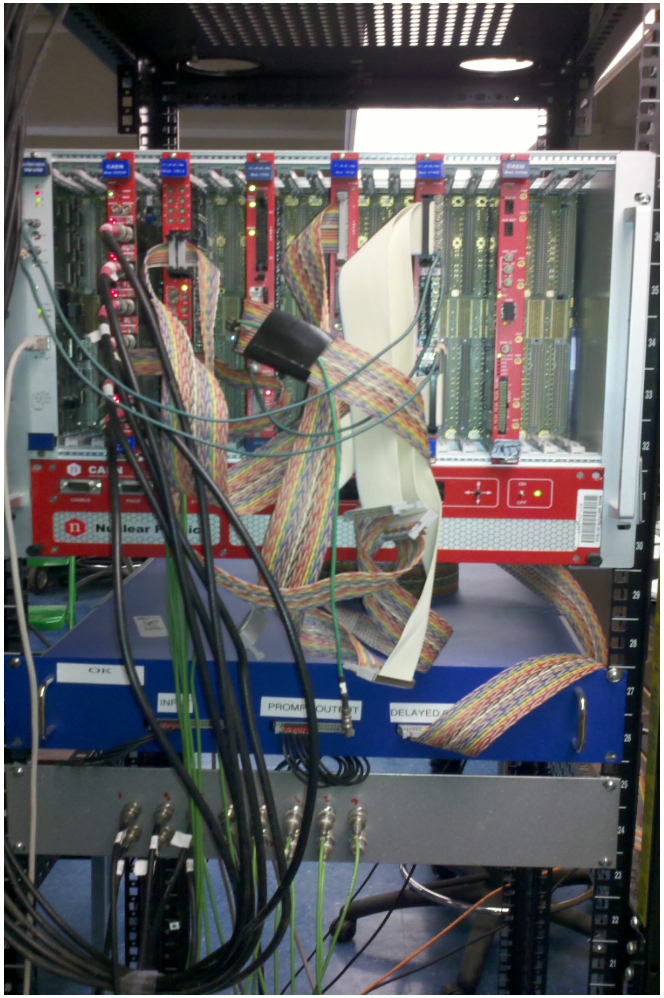
Detector Testing with QDC: Calibration and Efficiency

Source	Activity as of 1/06/2011	Characteristic Radiation
^{137}Cs	1.57E+05 dps	$\gamma_1 = 661.7$ keV
^{60}Co	1.44E+04 dps	$\gamma_1 = 1332.5$ keV $\gamma_2 = 1173.2$ keV
^{232}Th	1.11E+07 dps	$\gamma_1 = 2614.5$ keV and other gammas
^{241}AmBe	2.44E+04 dps (neutrons)	Neutrons and $\gamma = 4430$ keV



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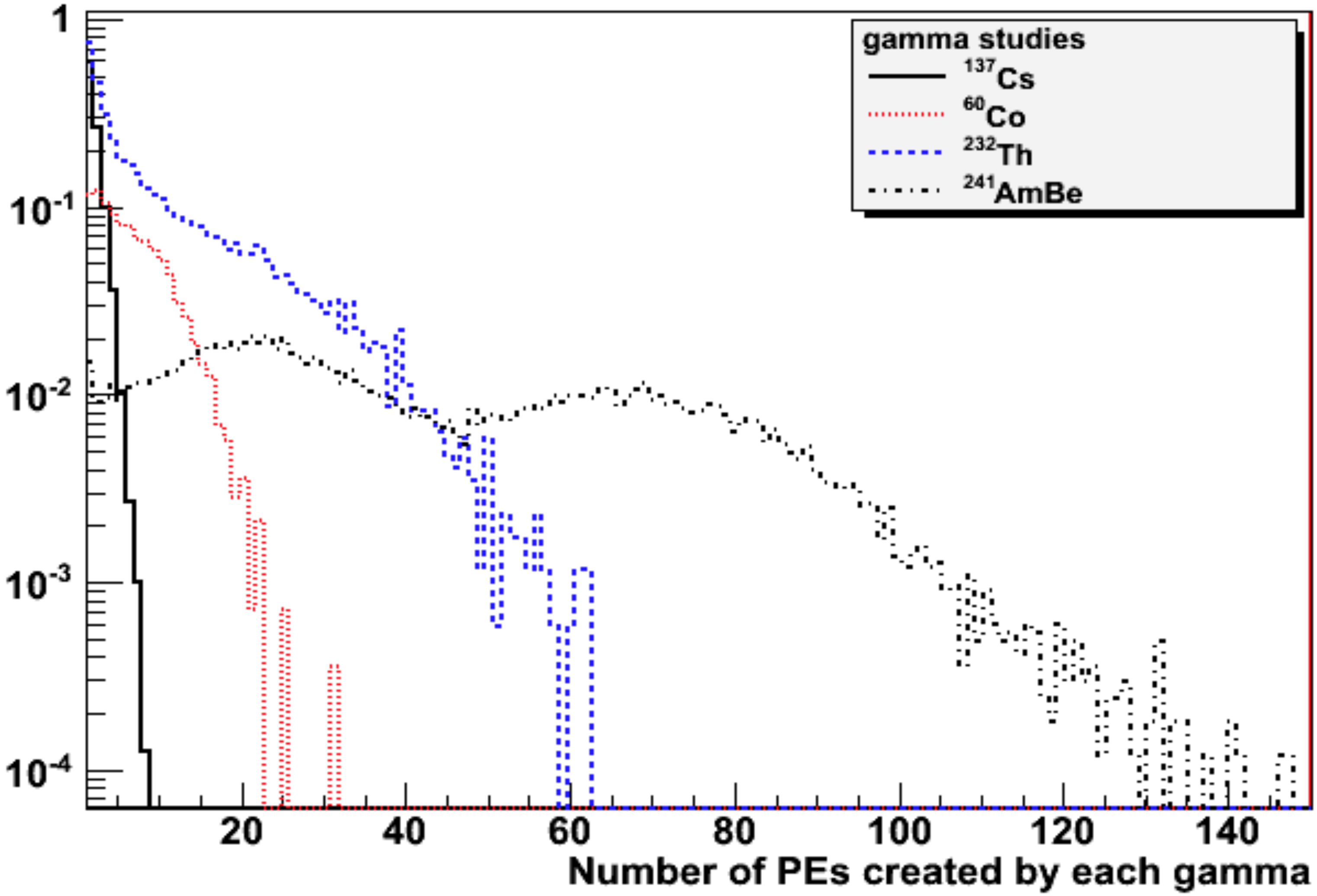
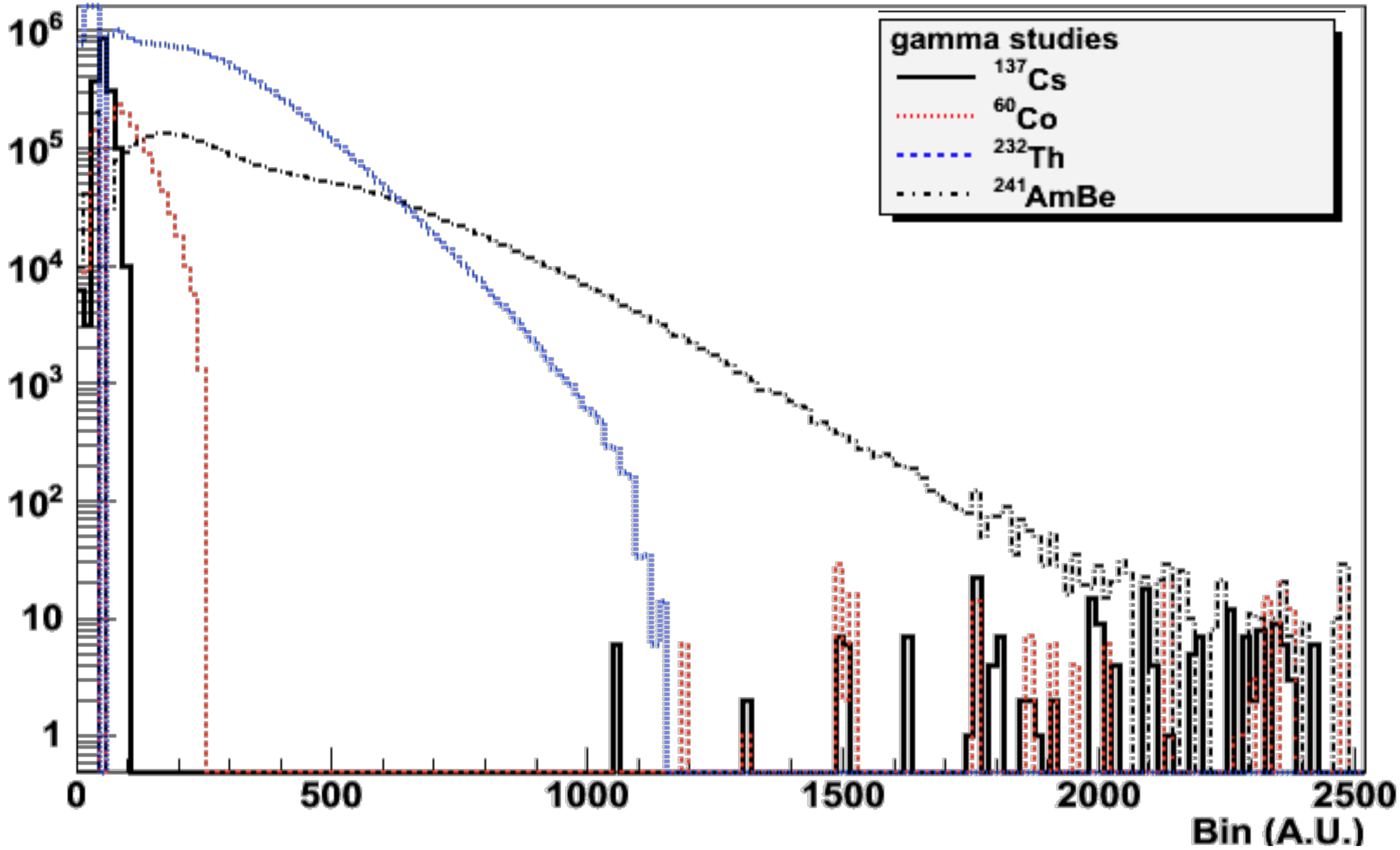
Computational Integrated Spectra (Four Sources Normalized)



Experimental Integrated Spectra (Four Sources, QDC DAQ)



So, We Got the Data…How Do We Calibrate?

The goal of calibration was to verify that it is possible to place a **meaningful** the energy cutoff (i.e. E > 3 MeV)

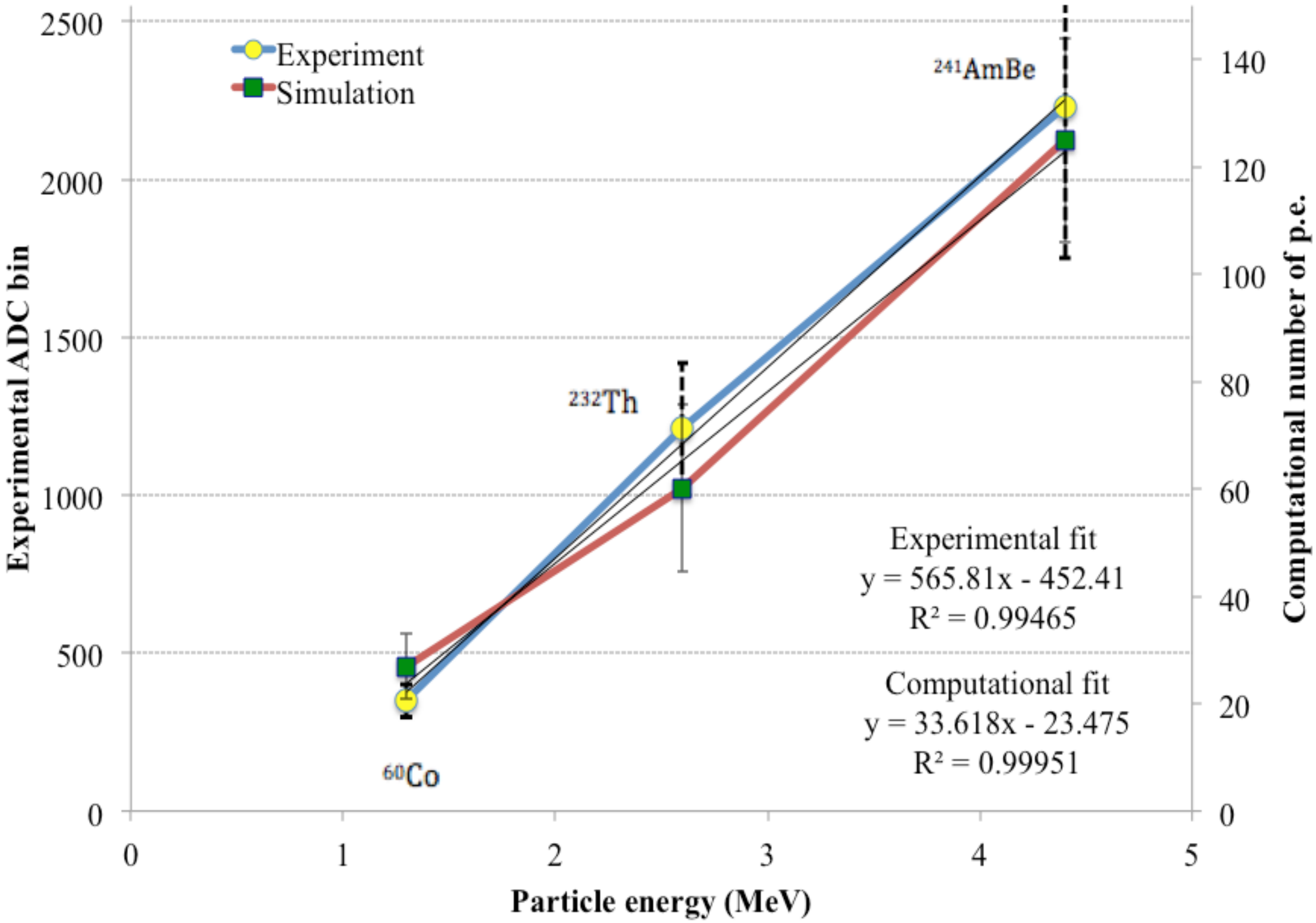
Cherenkov detectors are not easy to calibrate using sources alone

- There are no clearly defined peaks

What does the spectrum mean?

- The "terminal end" of the spectrum is the maximum of energy deposited by a particle (recall Compton scatter)
- We are interested in setting energy cutoffs in remote detection application
- Can we use the terminal end of the spectrum as such indicator?

Fitting the Peaks and Comparing



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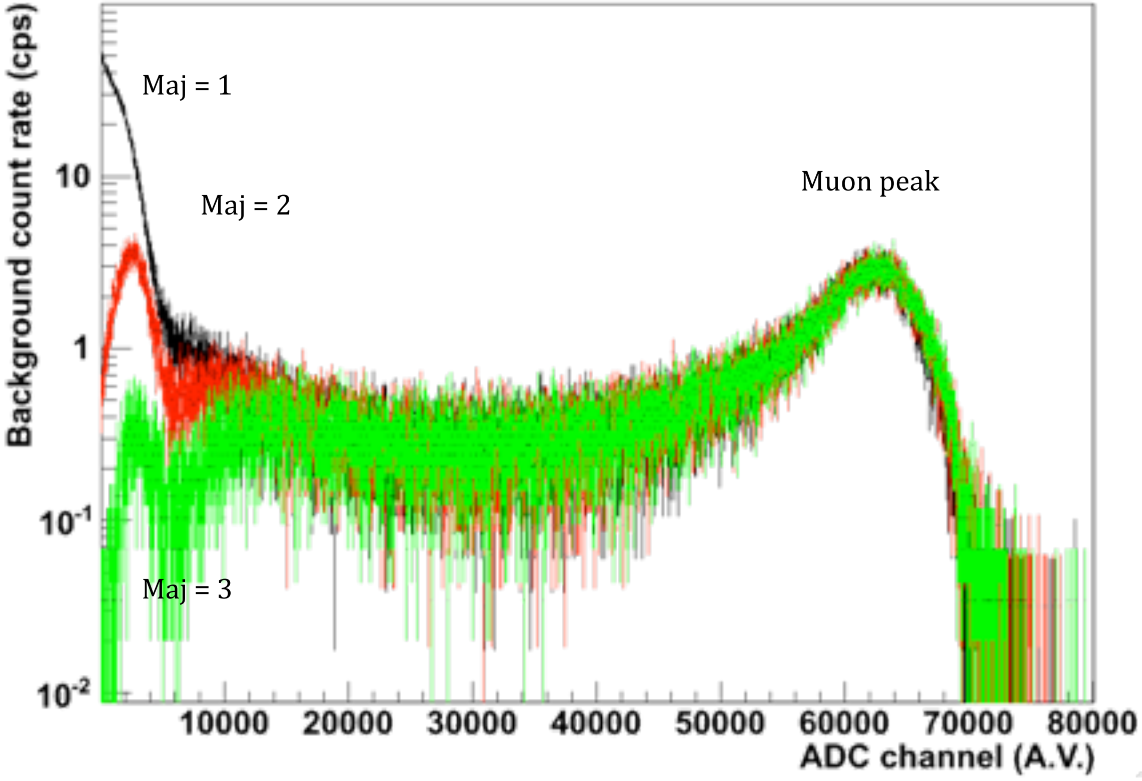
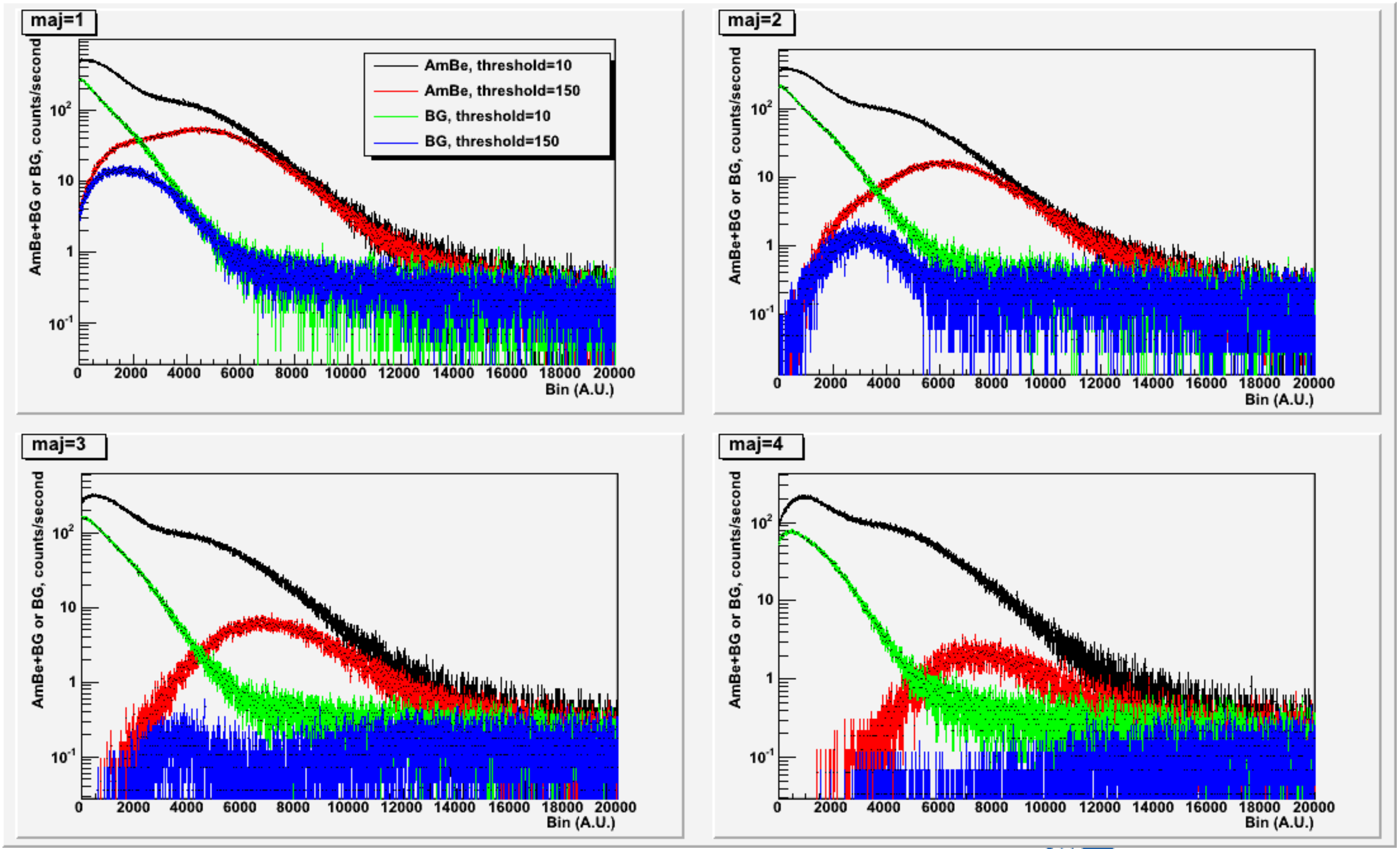
Background Suppression

- Background (BG) rejection
  - Two approaches considered: using majority and setting threshold
  - Simple BG subtraction is difficult in the field.
  - BG subtraction alone is not recommended because the method is to subtract large one number from another large number which can lead to poor spectrum resolution
  - Preliminary experimental measurements with ADC showed that significant suppression of BG is possible



Comparing AmBe Source (+BG) and Background



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Summary

- “Small” size Cherenkov detectors are not common – think SuperK
- The objective of constructing a detector of less than a ton which is capable of detecting gamma rays of various energies was accomplished
- Significant background suppression was possible using a combination of PMT majority and energy threshold
- One of the significant limitations of the Cherenkov detector was found to be energy resolution.
    - the radiation expected from photofission does not have readily identifiable peaks in the 3 to 10 MeV range
    - consideration of resolution was not a major contributor to the detector design.
- Such novel detectors are becoming a promising tool in non-proliferation and safeguards

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Final Remarks

"In regard to nuclear proliferation and arms control, the fundamental problem is clear: Either we begin finding creative, outside-the-box solutions or the international nuclear safeguards regime will become obsolete."

-M. ElBaradei, Washington Post, June 14, 2006, page A23.