Design, Construction, Operation, and Simulation of a Radioactivity Assay Chamber

Wesley Ketchum and Abe Reddy

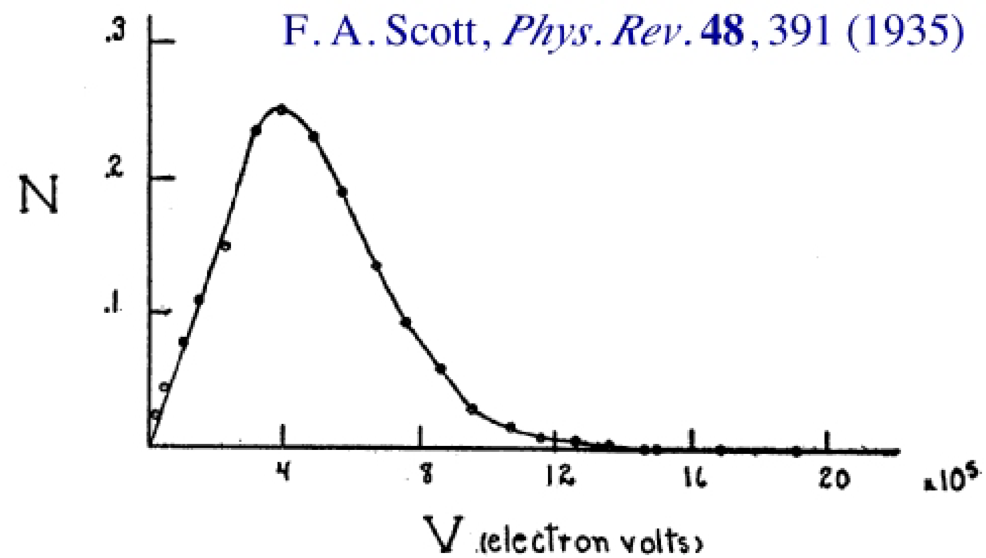
EWI Group, UW REU 2006

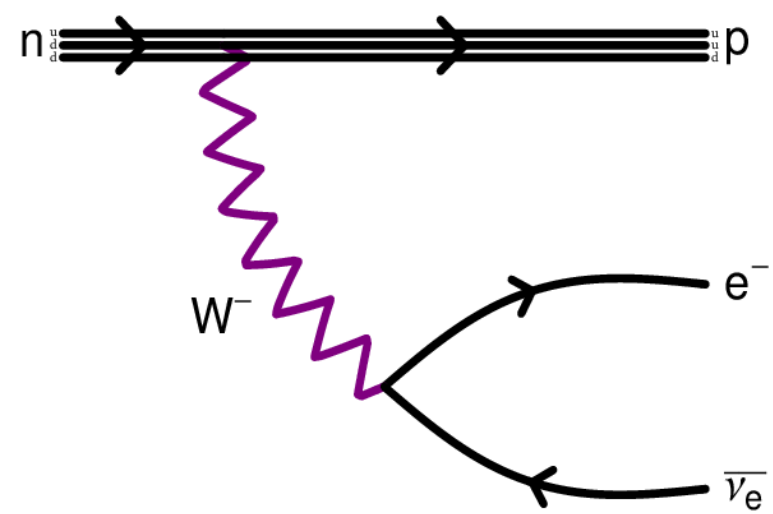
Outline

- Neutrino Physics Background
- Double Beta Decay and the Majorana Question
- Assay Chamber
  - Detector
  - Shielding
  - Results
- Chamber Simulation
  - Geant4
  - Efficiencies
  - Comparison to Observation

Neutrino History

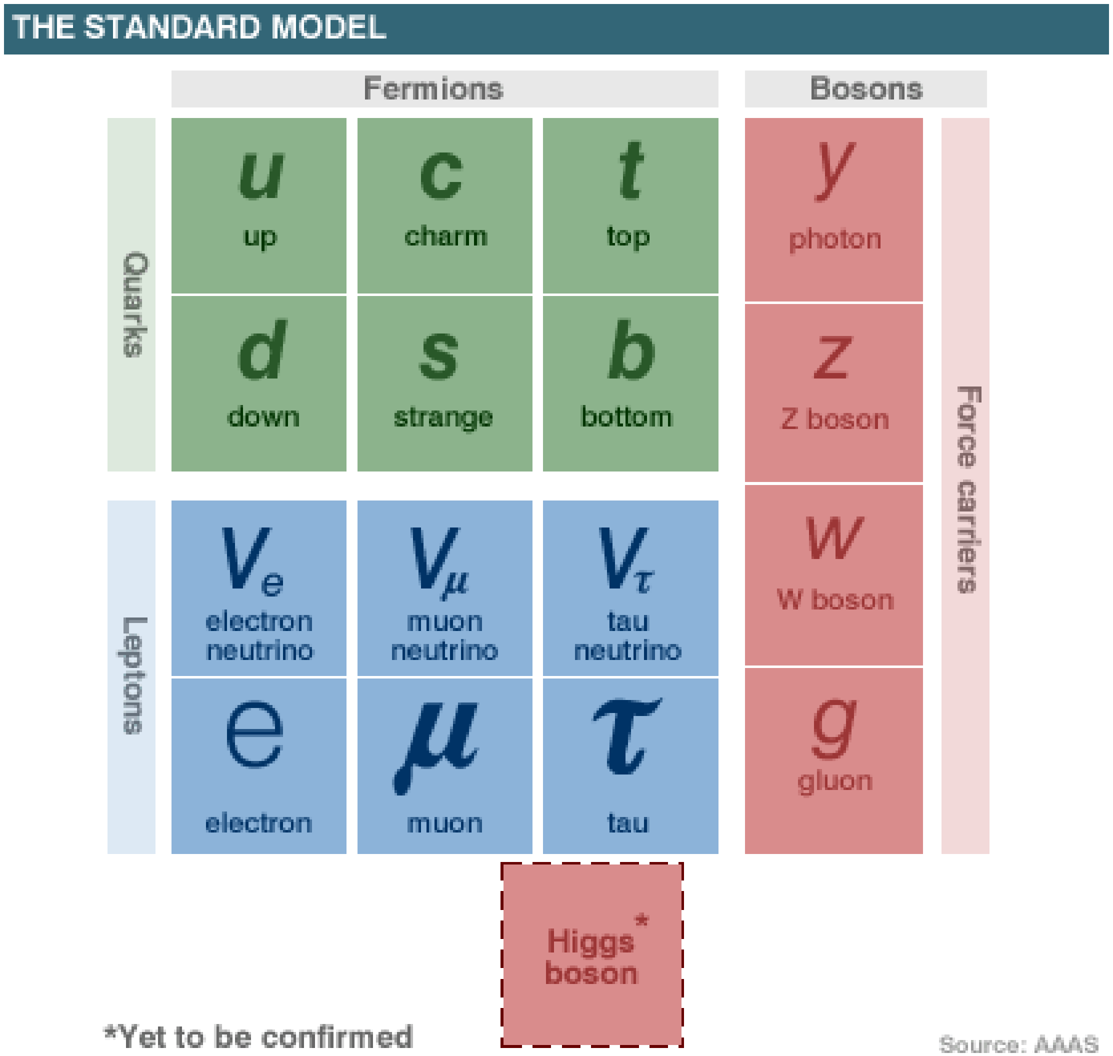
- Existence Postulated by Wolfgang Pauli in 1930
  - neutrino explained energy and angular momentum conservation in β^- decay
- Electron Neutrino (ν_e) first experimentally observed in 1956
- ν_μ and ν_τ experimentally observed in 1962 and 2000 respectively





http://en.wikipedia.org/wiki/Beta_decay

Neutrinos in the Standard Model

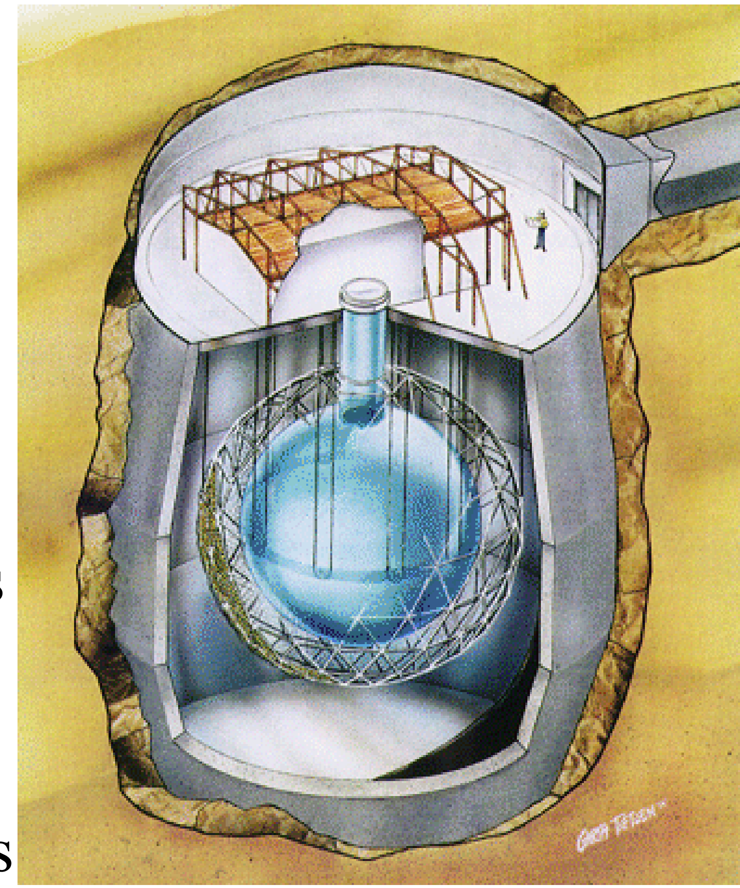


http://newsimg.bbc.co.uk/media/images/39873000/gif/_39873168_standard_model_416.gif

- Weak interaction maximally violates parity
  - Neutrinos only observed as left-handed
  - Anti-neutrinos only observed as right-handed
- Since ν's are only left-handed, they are assumed to be massless

Challenging the Standard Model

- Modern neutrino detectors show neutrinos have mass
  - Atmospheric and reactor neutrinos observed to oscillate flavor
  - Sudbury Neutrino Observatory (SNO) observations consistent with oscillating neutrinos; also show the total neutrino flux agrees with standard solar models
    - 1,000,000 kg D_2O Cherenkov detector buried 6,800 feet underground
  - Oscillations caused by differences between flavor and mass eigenstates



http://www.sno.phy.queensu.ca/

Physics of Neutrino Oscillations

Flavor eigenstates can be written as linear combination of mass eigenstates:

$$|\nu_\ell\rangle = \sum_{i=1}^{3} U_{i\ell}^* \, |\nu_i\rangle$$

Propagation of mass eigenstates written as

$$|\nu_i(t)\rangle = e^{-i(\mathrm{Et} - \vec{p}\cdot\vec{x})} \, |\nu_i(0)\rangle$$

Energy rewritten as

$$\mathrm{E} = \sqrt{\vec{p}^{\,2} + m^2} \simeq \vec{p}^{\,2} + \frac{m^2}{2p}$$

So, if distance traveled is L, then

$$|\nu_i(L)\rangle = e^{-i\left(\frac{m_i^2 L}{2E}\right)} \, |\nu_i(0)\rangle$$

Which means mass eigenstates can cause constructive and destructive interference in flavor eigenstates, causing oscillation between flavor types:

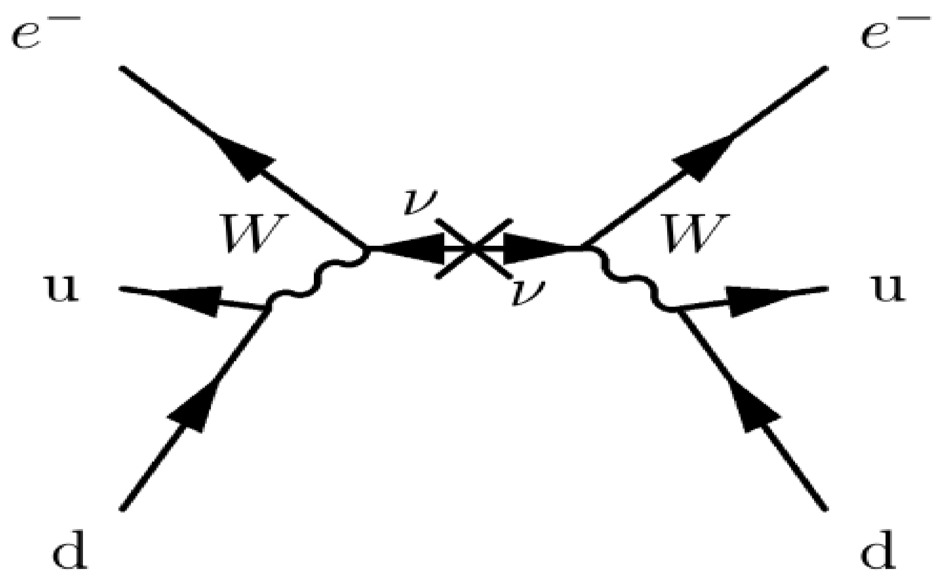
$$|\nu_\ell(L)\rangle = \sum_{i=1}^{3} U_{i\ell}^* \, e^{-i\left(\frac{m_i^2 L}{2E}\right)} \, |\nu_i(0)\rangle$$

Double β⁻ Decay

- For some nuclei, single β^- decay not allowed
  - e.g. ^{76}Ge cannot decay to ^{76}As because ^{76}As has less binding energy
- Instead, double β^- decay ($2\nu\beta\beta$) can occur:

$$^{76}\text{Ge} \Longrightarrow {}^{76}\text{Se} + 2e^- + 2\nu_e^*$$

  - $2\nu\beta\beta$ is rarest known radioactive decay---half-life of 10^{21} yr
- If neutrino is Majorana particle, neutrinoless double β^- decay ($0\nu\beta\beta$) is possible:

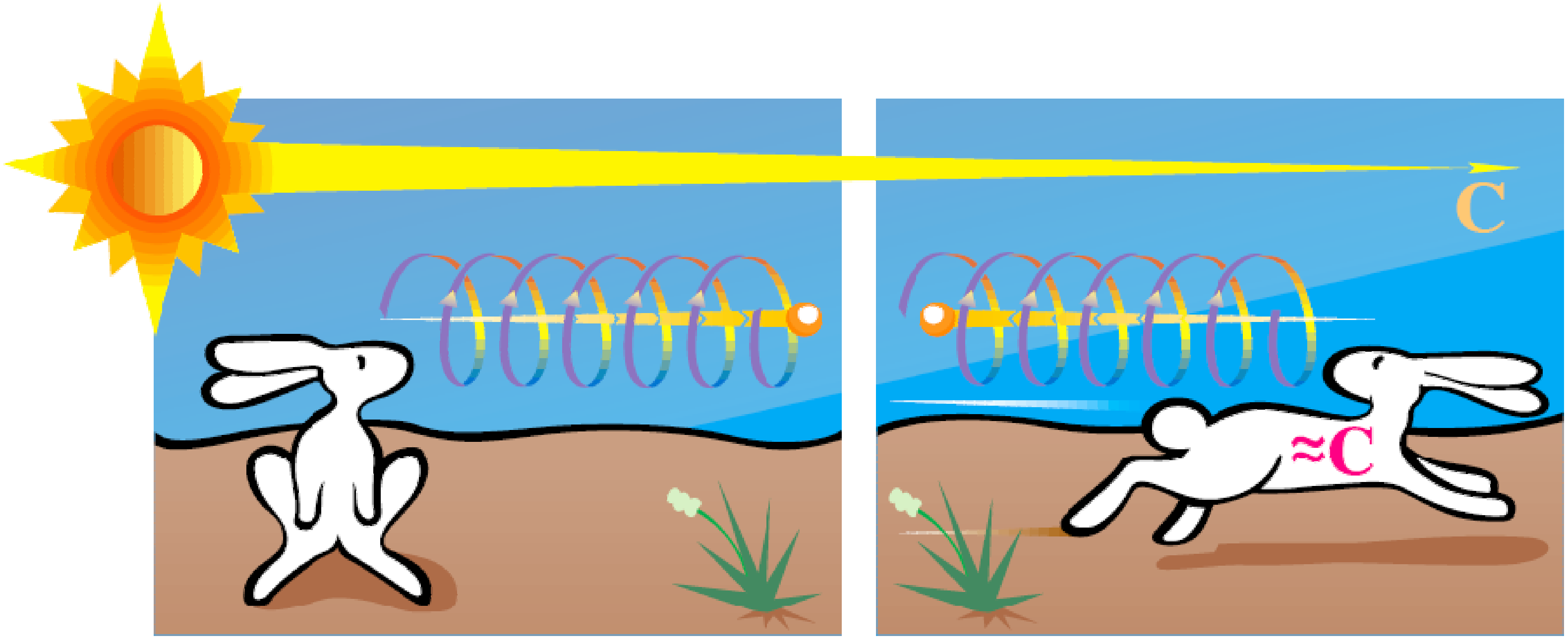


http://en.wikipedia.org/wiki/Double_beta_decay

The Neutrino as a Majorana Particle

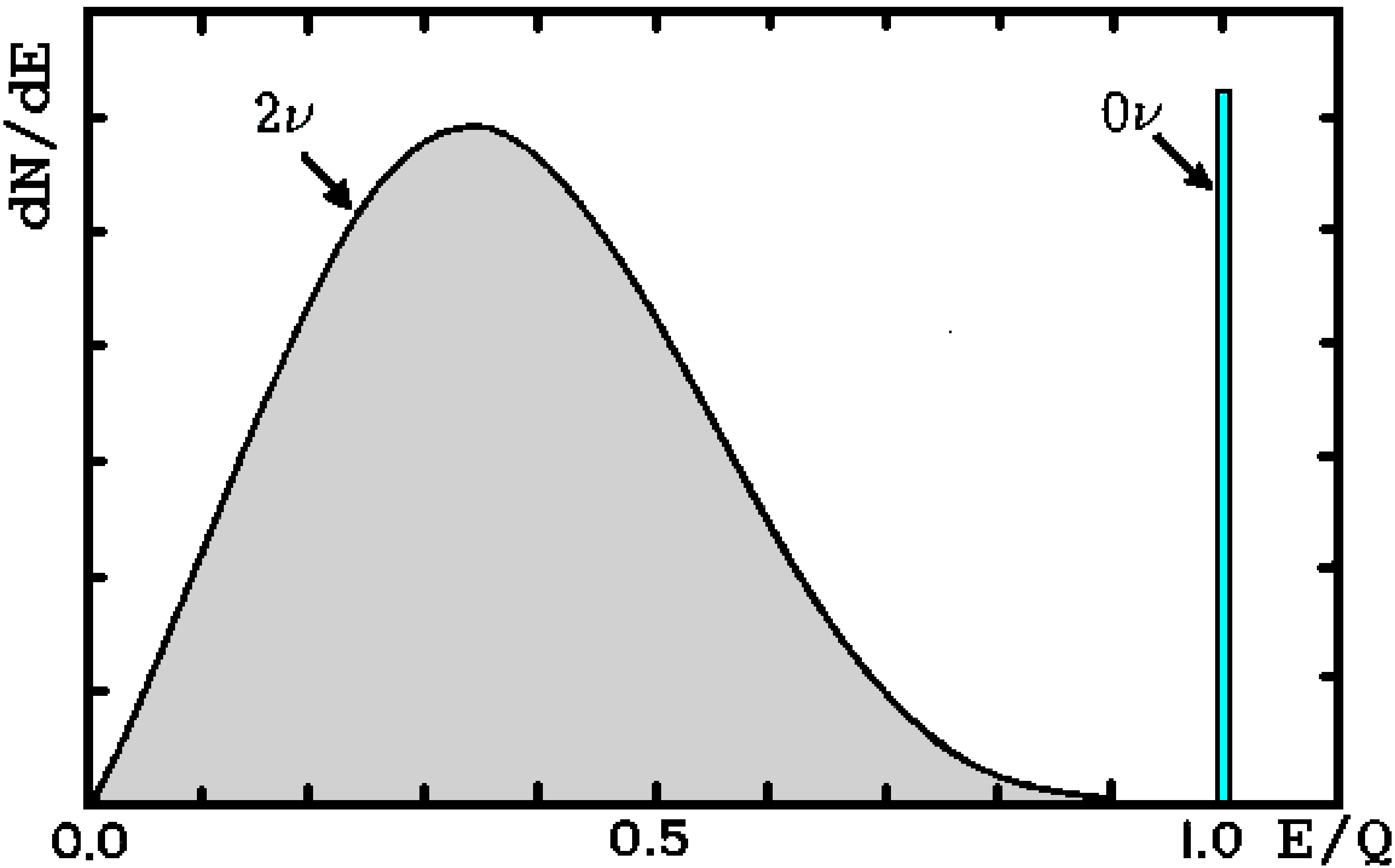
- Majorana particles are their own anti-particle
- Many believe it is plausible that neutrino is Majorana
  - Explains current observations of massive neutrinos
- Experiments attempting to detect $0\nu\beta\beta$ are only feasible way of testing whether neutrino is Majorana or not
  - EXO (^{136}Xe)
  - MOON (^{100}Mo)
  - GERDA (^{76}Ge)
  - COBRA (multiple sources)
  - CUORE (^{130}Te)
  - NEMO (multiple sources)
  - Majorana (^{76}Ge)

Ambidextrous Neutrinos



- Since neutrinos have mass, there must be right-handed neutrinos and left-handed anti-neutrinos
  - There exists a frame where neutrino changes handedness
- Decay rate $0\nu\beta\beta$ related to neutrino mass
  - Estimated half-life > 10^{25} yr

Energy Spectrum of Double β^- Decay



http://www.unizar.es/lfnae/grafs/2beta.gif

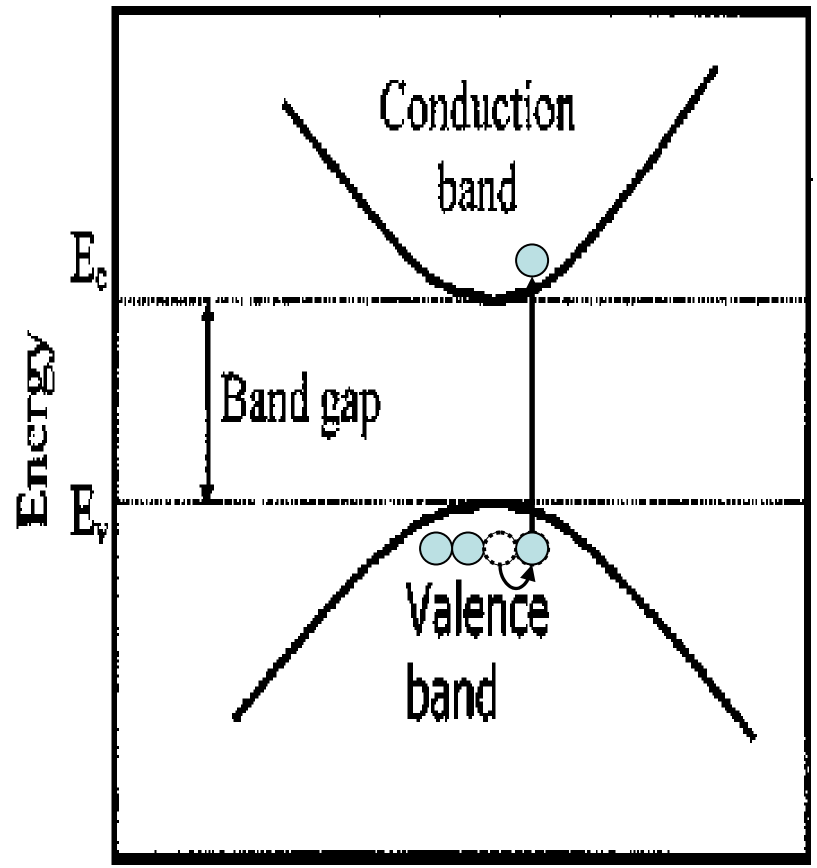
The Majorana Experiment

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

- Uses ultra-pure Ge (86% enriched ^{76}Ge) as both source and detector
  - Reduces materials required, reducing background noise
  - Ge detectors have good detection efficiency and good energy resolution
- In ^{76}Ge, $0\nu\beta\beta$ (if it occurs) has half-life of $\sim 10^{25}$ yr
  - In region of interest (~2039 keV), allowed background of < 1 count in

Germanium: Semiconductor Detector

- Intermediate band gap size (0.67 eV)
  - Impurities added can change gap
  - Ge cooled with liquid N_2 to reduce thermal excitation
- Photons or charged particles ionize atoms
  - Electrons excited into conduction band
  - Charge swept to nodes by reversed bias voltage, creating detectable signal



http://www.ieee.org/organizations/pubs/newsletters/leos/apr99/lasing1.gif

An Assay Chamber?

- Rough radioactivity measurement
  - Also of use for other experiments, like KATRIN
- Testing for Research and Development
  - Try new mounting techniques for crystal and cryostat
  - Test detector handling issues
  - Provide confirmation of simulations
- One major problem:
  - Lots of heavy labor
- The Solution . . .

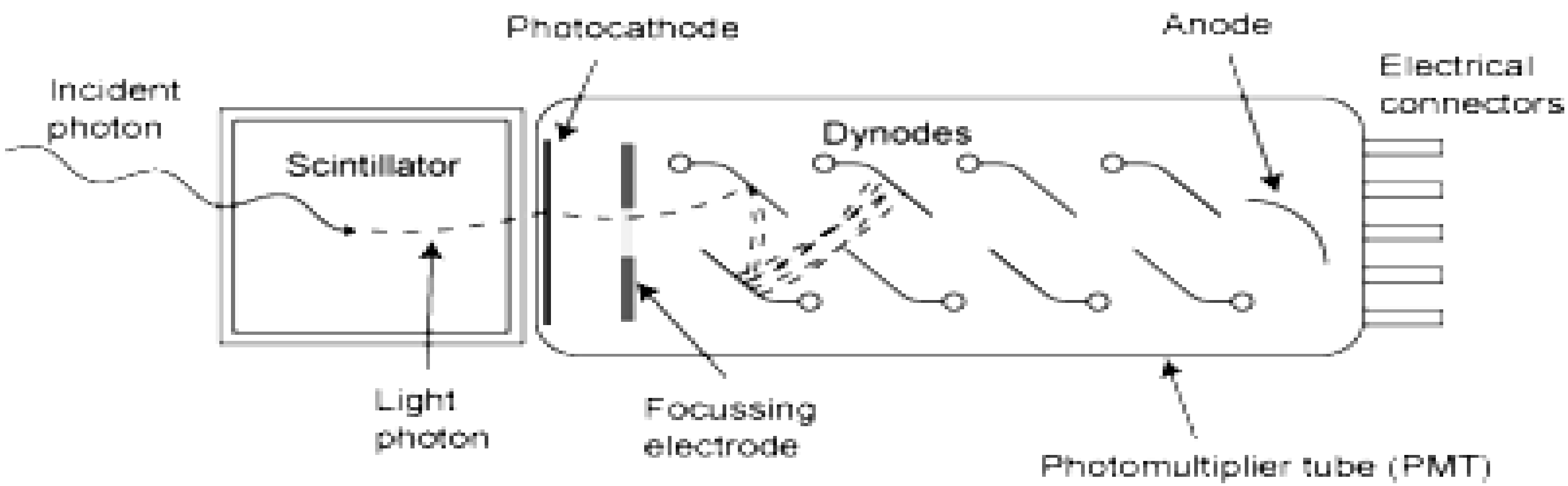

SERIES

Detector Setup

- Germanium crystal 70.9 mm long, 65.1 mm diameter
- In aluminum casing, attached to liquid N_2 cryostat
- Bias Voltage: 3500 V
- Output feeds into delay, then into ADC (Analog to Digital Converter)
- Detector must be shielded from background events
  - Active shielding to cancel cosmic rays (muons)
  - Passive shielding to reduce background radiation

Active Shielding: Scintillation Detectors

- Scintillating material emits light when hit by ionizing particles (such as muons) or radiation
  - Organic (crystal, liquid, plastic)
  - Inorganic (e.g. NaI(Tl) and BF_2)
  - Gas (noble gases + N_2)
  - Glass
- Connected to photomultiplier to create electrical signal



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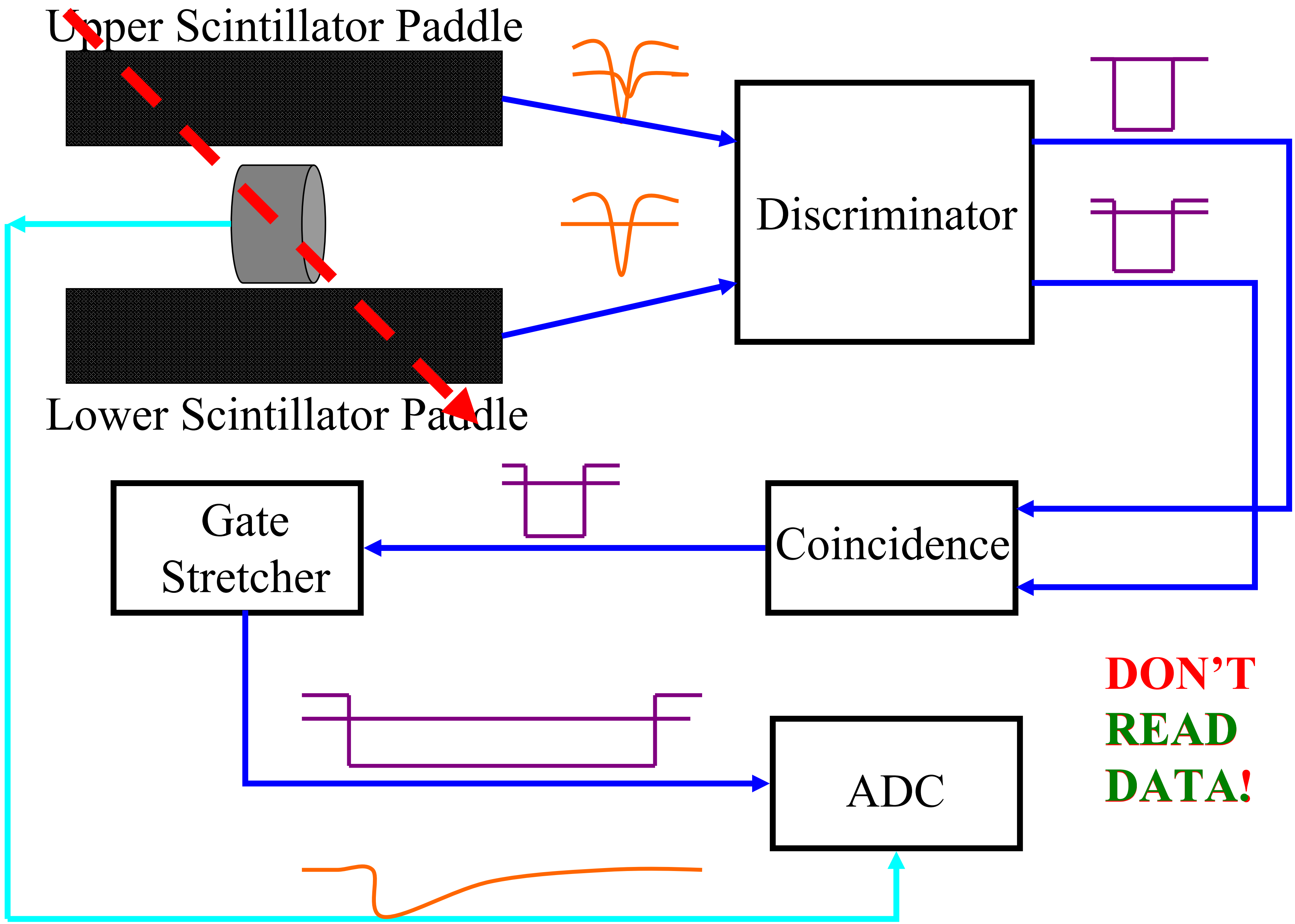
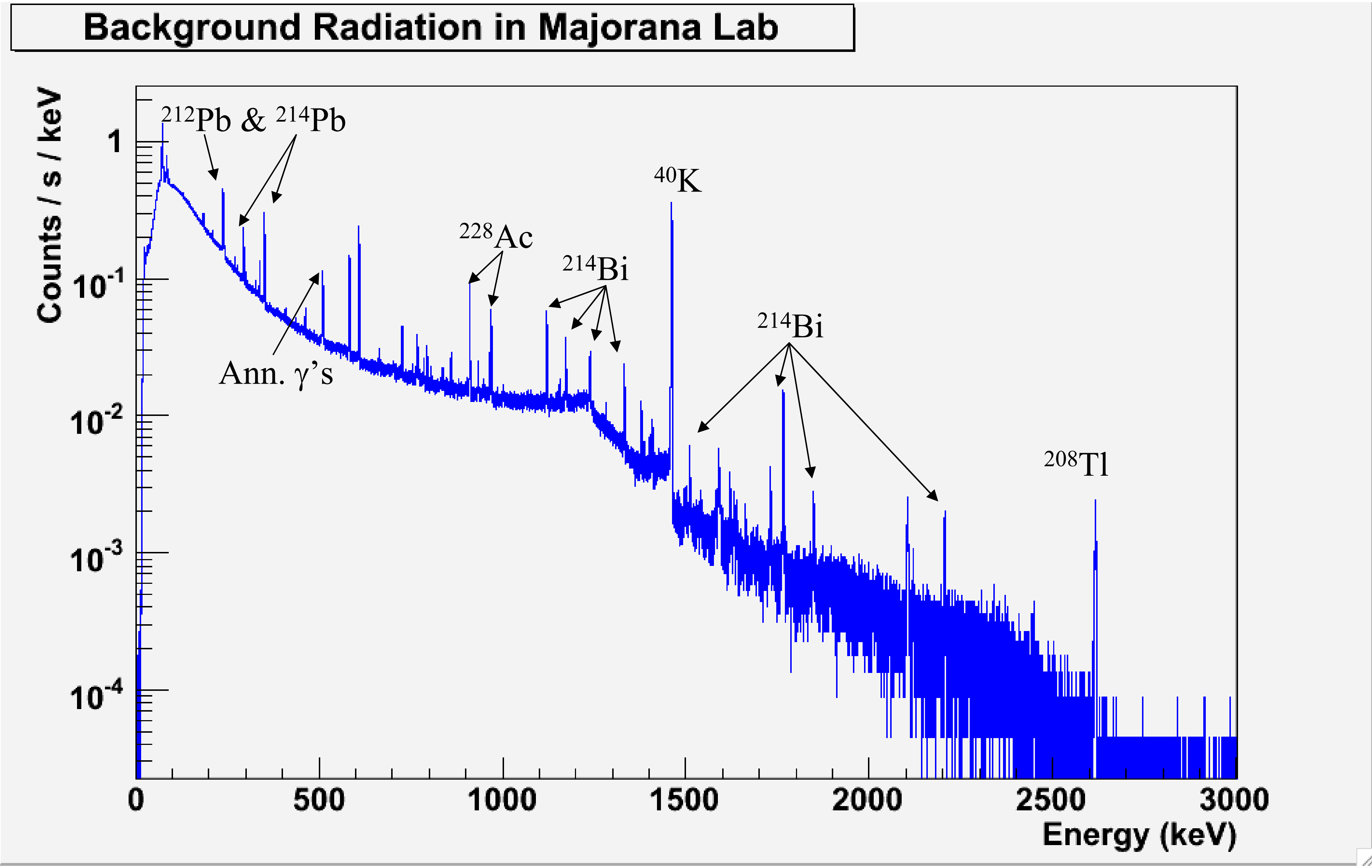
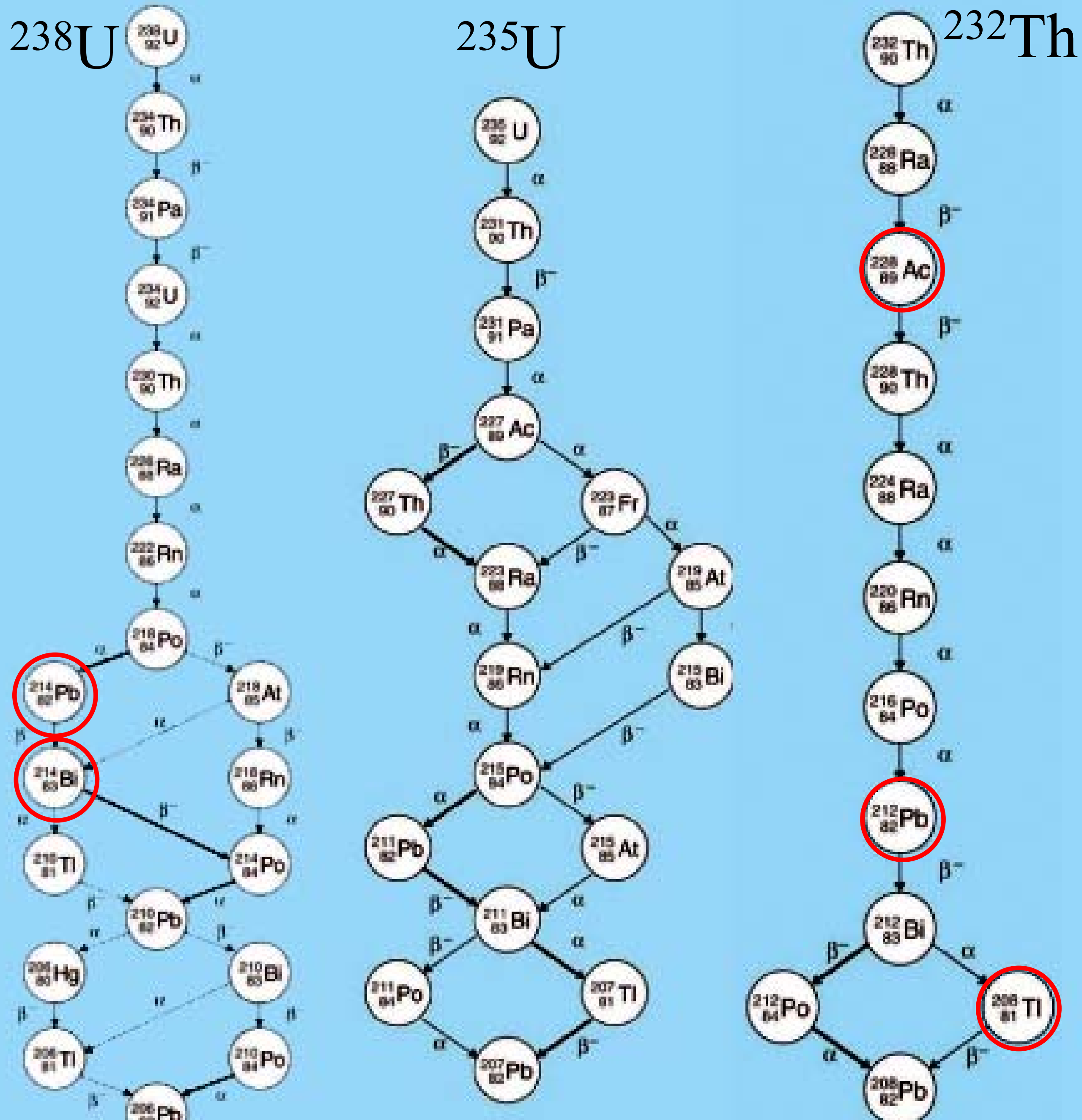
Cosmic Ray Veto:

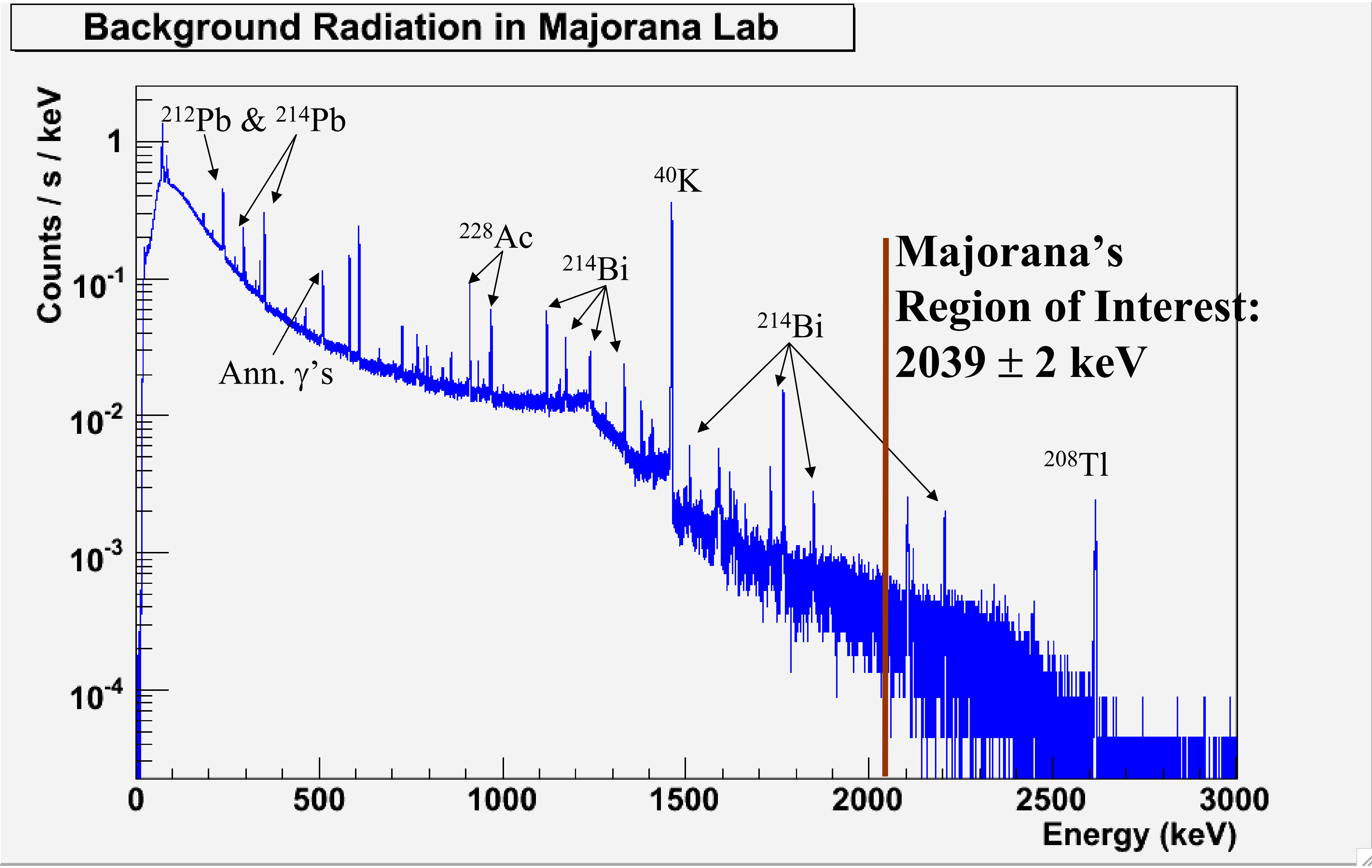




Background Radiation in Majorana Lab
Counts / s / keV
1
10^-1
10^-2
10^-3
10^-4
0
500
1000
1500
2000
2500
3000
Energy (keV)
212Pb & 214Pb
Ann. γ's
228Ac
214Bi
40K
214Bi
208Tl

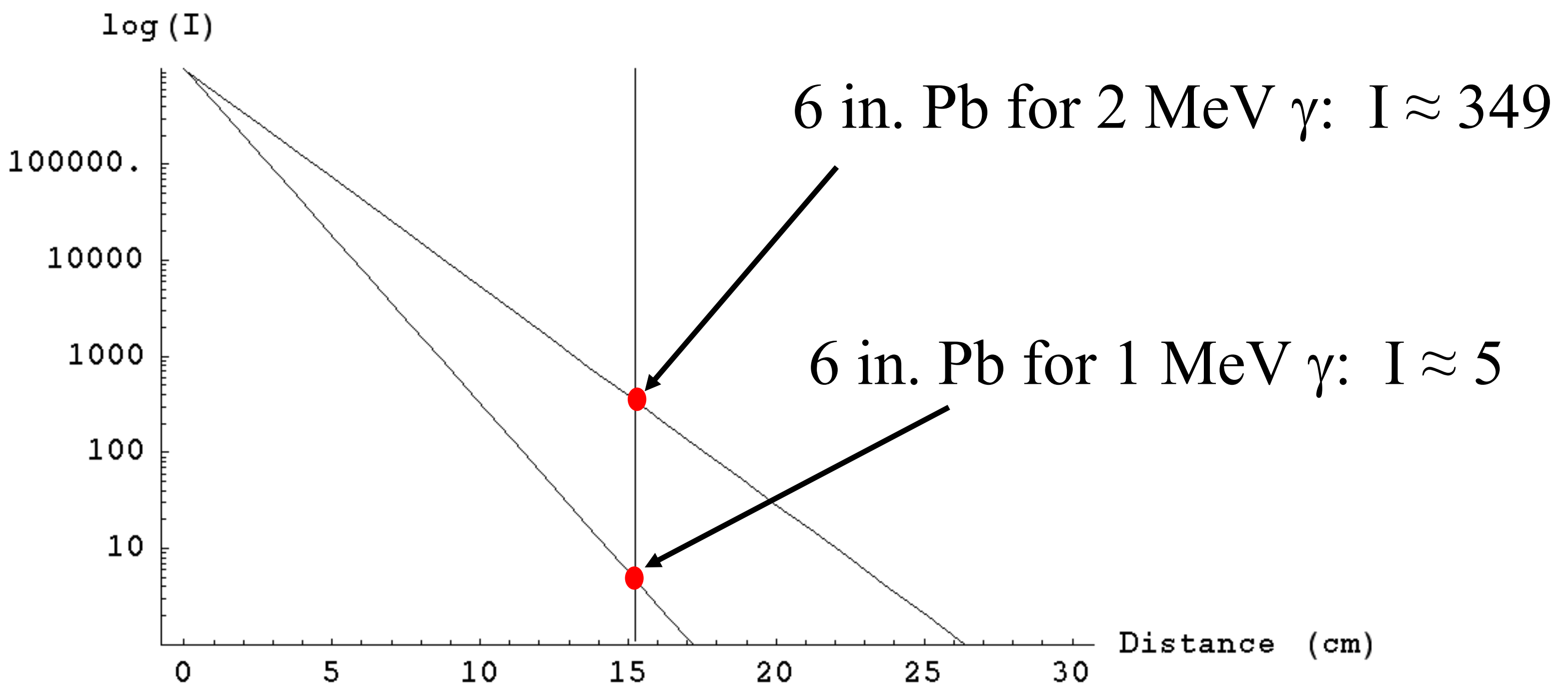


http://www.euronuclear.org/info/encyclopedia/images/decay1.jpg



Background Radiation in Majorana Lab
Counts / s / keV
1
10-1
10-2
10-3
10-4
212Pb & 214Pb
Ann. γ's
228Ac
214Bi
40K
214Bi
208Tl
Majorana's
Region of Interest:
2039 ± 2 keV
0
500
1000
1500
2000
2500
3000
Energy (keV)

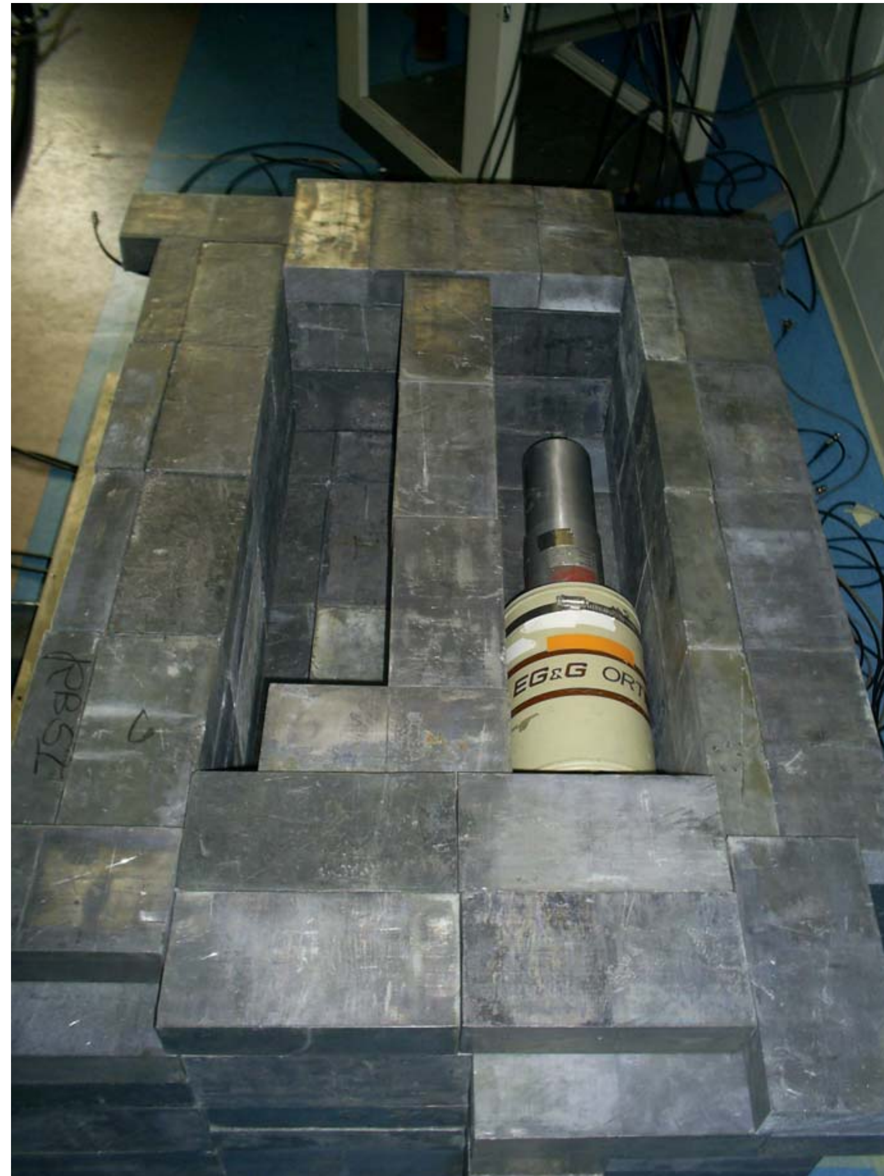
Lead Attenuation

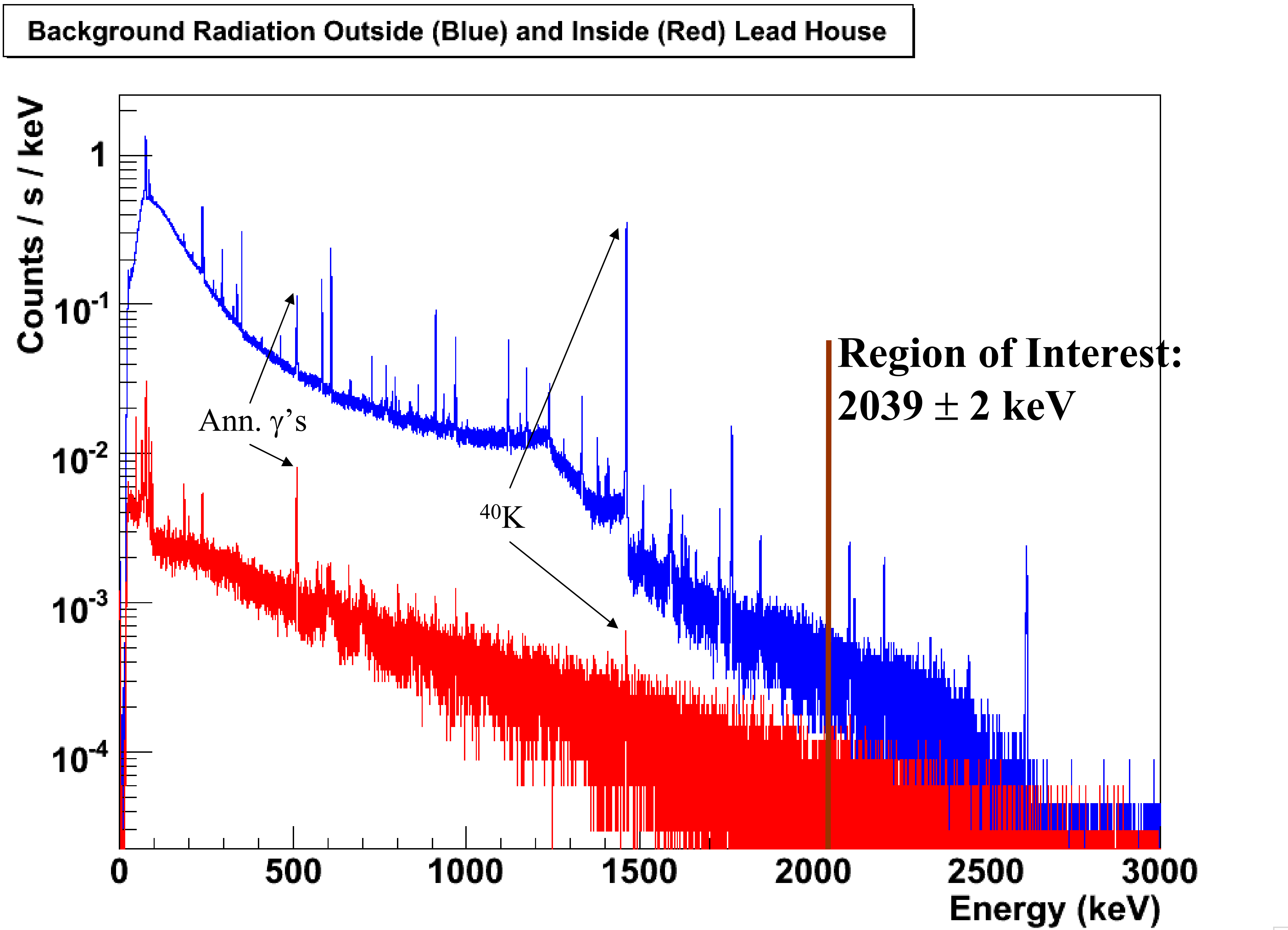


- Attenuation follows formula: $I = I_0 e^{-\mu x}$
  - Measures photons that are *not scattered*
  - μ is mass attenuation coefficient
    - Varies with material and energy of photons
  - Here, I_0 = 1,000,000 photons

Pb House

- Built on 1 in. Al plate 10 in. off ground
  - Room for large scintillator underneath
- 44 x 28 x 22 in.
  - Room for second detector
- > 6 in. on all sides
- 4 x 2 in. hole for cables and LN_2 lines
- Sources moved in and out through roof





Background Radiation Outside (Blue) and Inside (Red) Lead House
Counts / s / keV
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
500
1000
1500
2000
2500
3000
Energy (keV)
Ann. γ's
^{40}K
Region of Interest:
2039 ± 2 keV

Quick Analysis

- Sensitivity:
  - 0.239 nCi for 1.17 MeV ^{60}Co source (~ 9 Becquerel)
- Resolution
  - about 1.0 keV at 1460.8 keV (^{40}K)
  - about 1.5 keV at 2614.5 keV (^{208}Tl)

Simulation of the Detector Setup Using Geant4

Motivation

- Test geometries to optimize setup
  - Active Shielding
  - Detector Orientation
  - Lead Attenuation
- Compare to observations
  - Calculate radioactivity of materials

What is Geant4?

- a toolkit for the simulation of the passage of particles through matter.
- areas of application
  - High energy physics
  - high energy, nuclear and accelerator physics
  - Medical science
- Uses C++
- Developed at CERN

- Monte Carlo Simulation
- Calculates the probability of all interactions at each step then chooses the interaction that limits the length of the step

Cosmic Muons

- Wrote class to simulate background from muons

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

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TIFF (Uncompressed) decompressor
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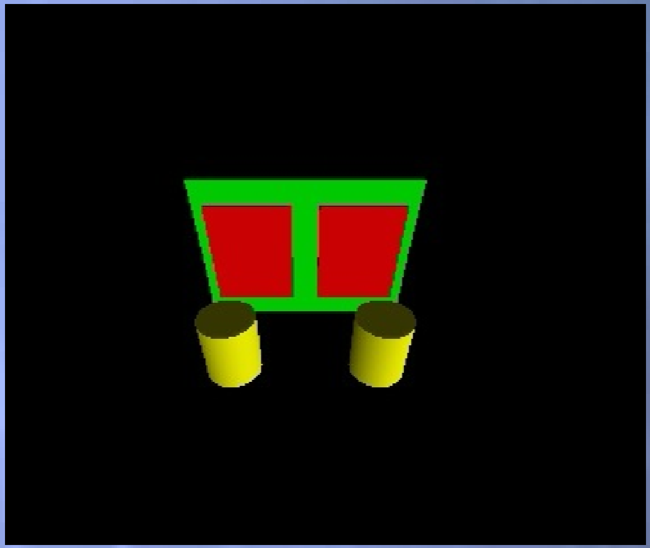
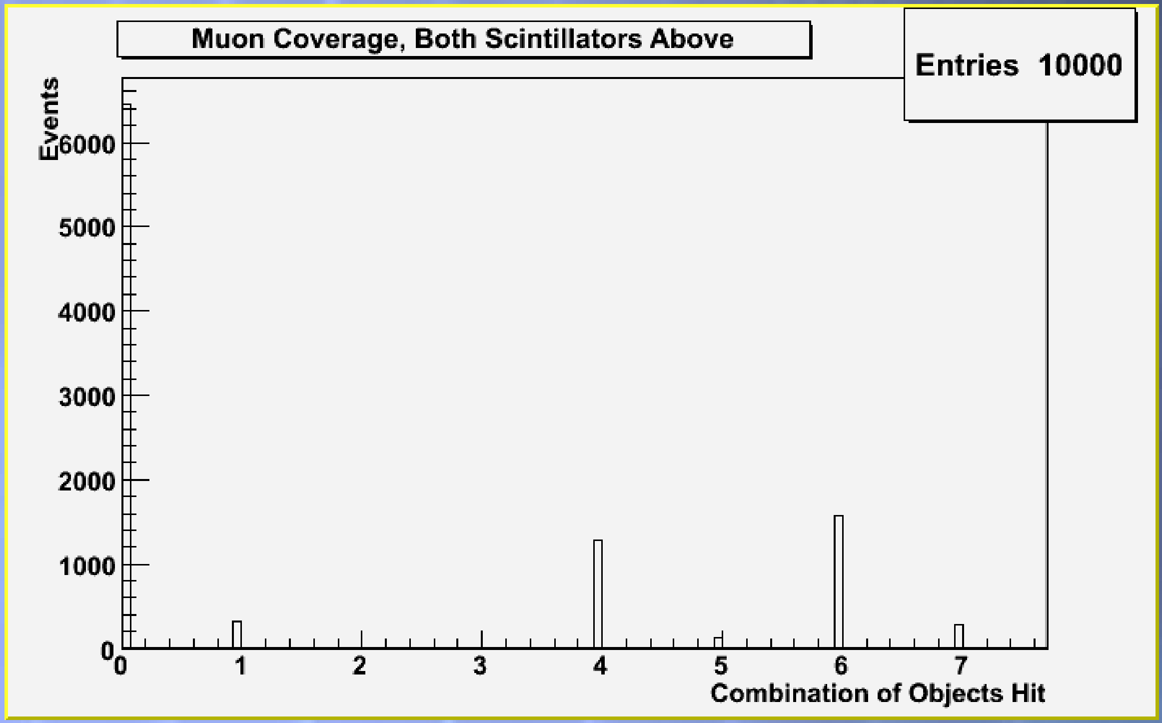
- Cosine Squared Distribution
- Adjustable for geometry

Cosmic Muon Coverage

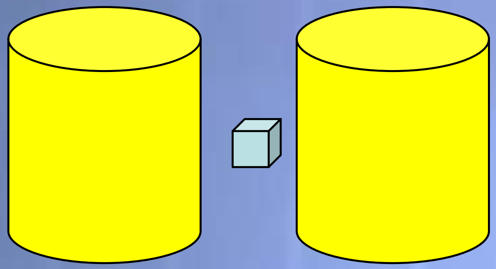
- Tracked energy deposition in each volume
- Of cosmic muon hits in the detector, only 40% were vetoed



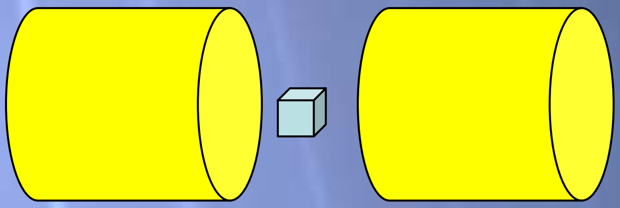


Detector Orientation Efficency

- End to End or Side by Side
- Isotropic gamma source
- 1 and 2 MeV gammas
- Source placement

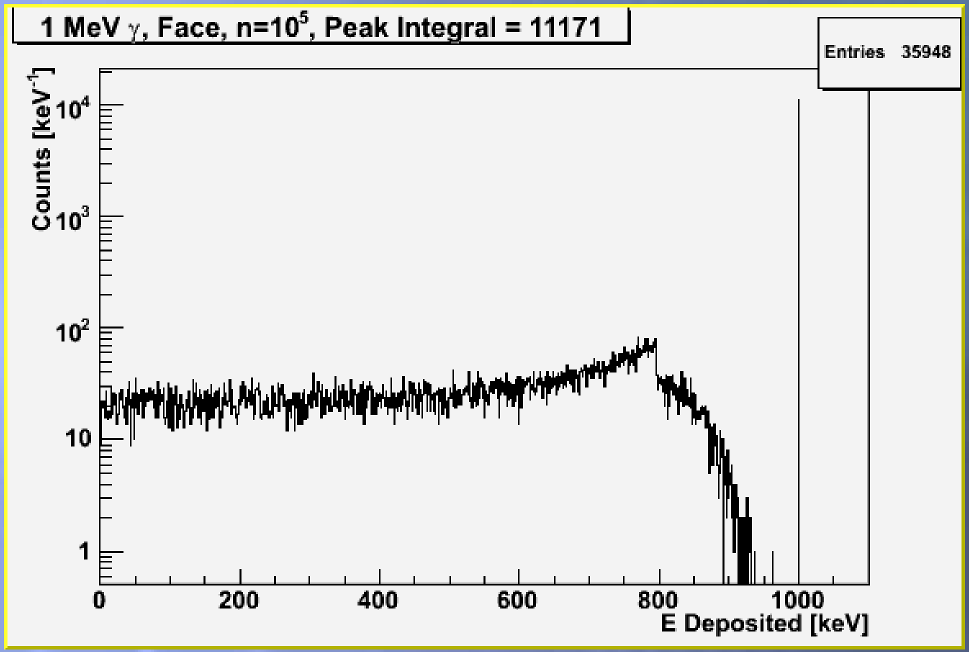


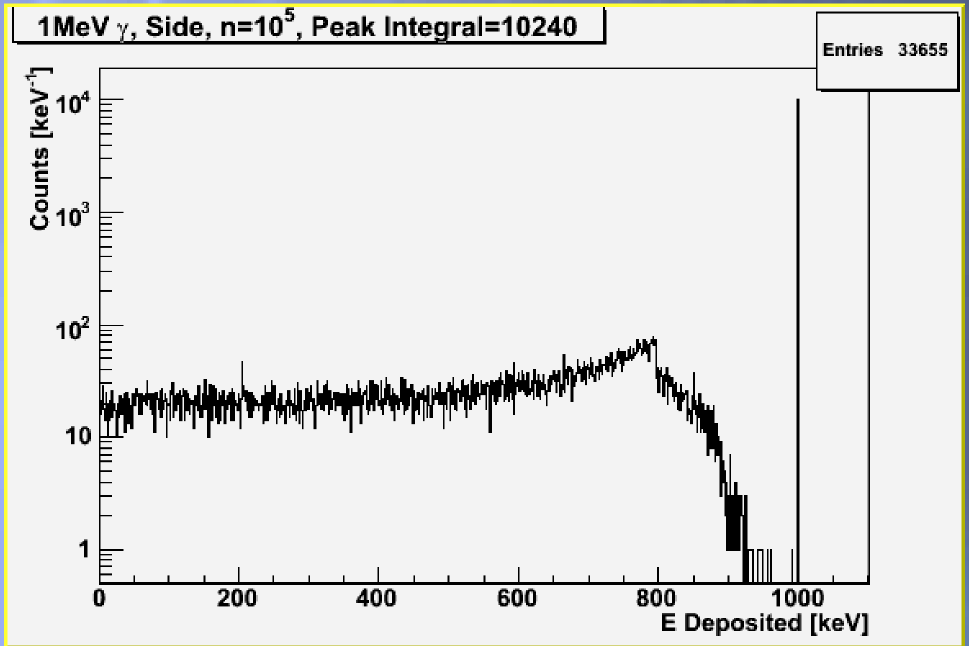
Side to Side



End to End

- Placing the source on the face rather than the side gave a 10% greater efficiency in capturing 1 MeV gammas
- Similar for 2 MeV





Lead Attenuation

- Beam of gammas shot through 6 inches of lead at detectors

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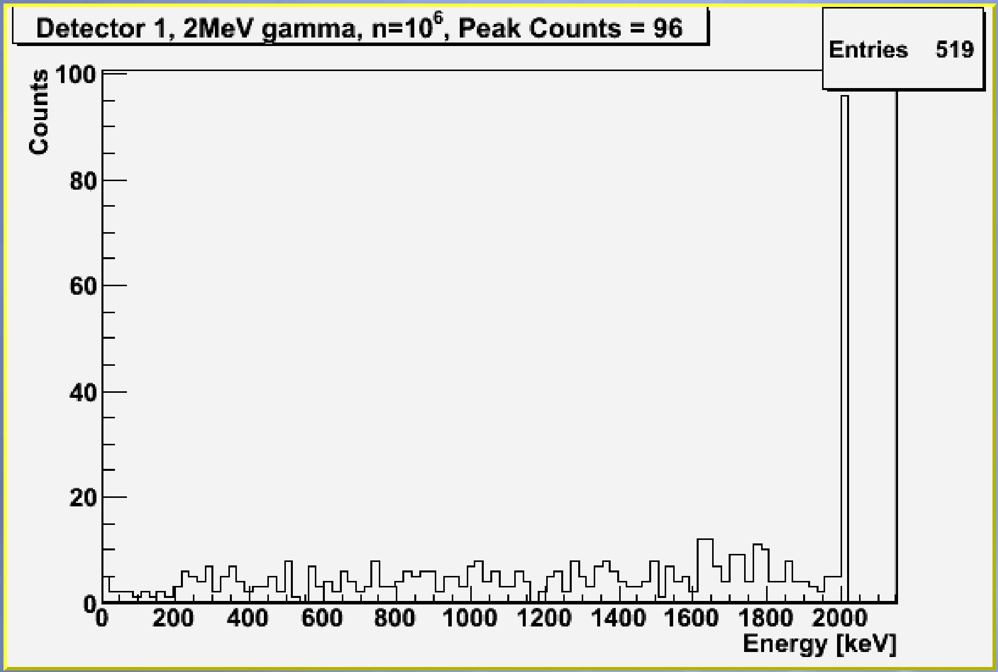
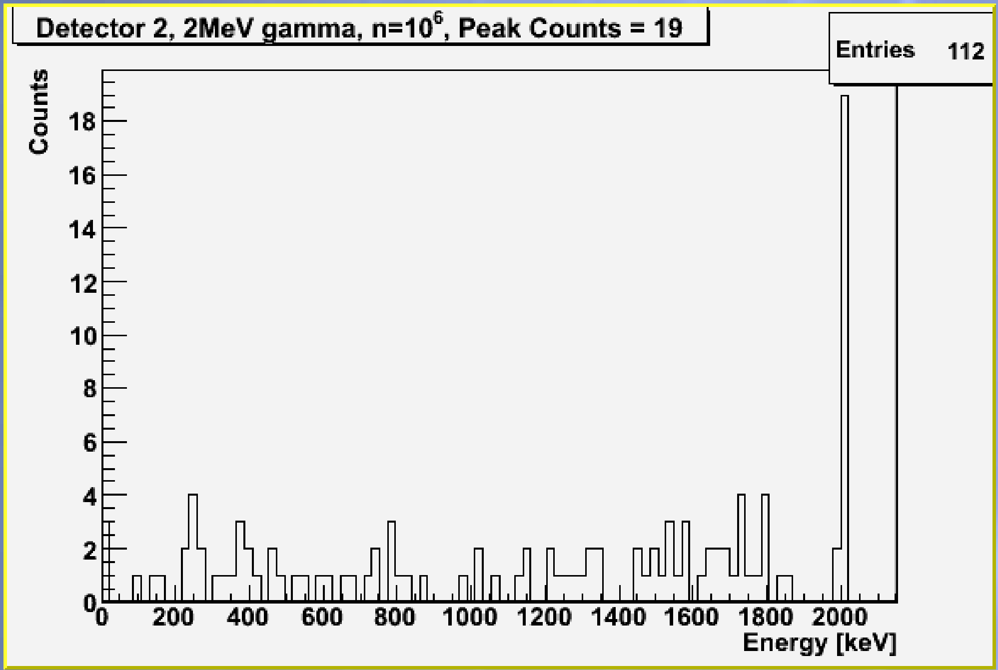
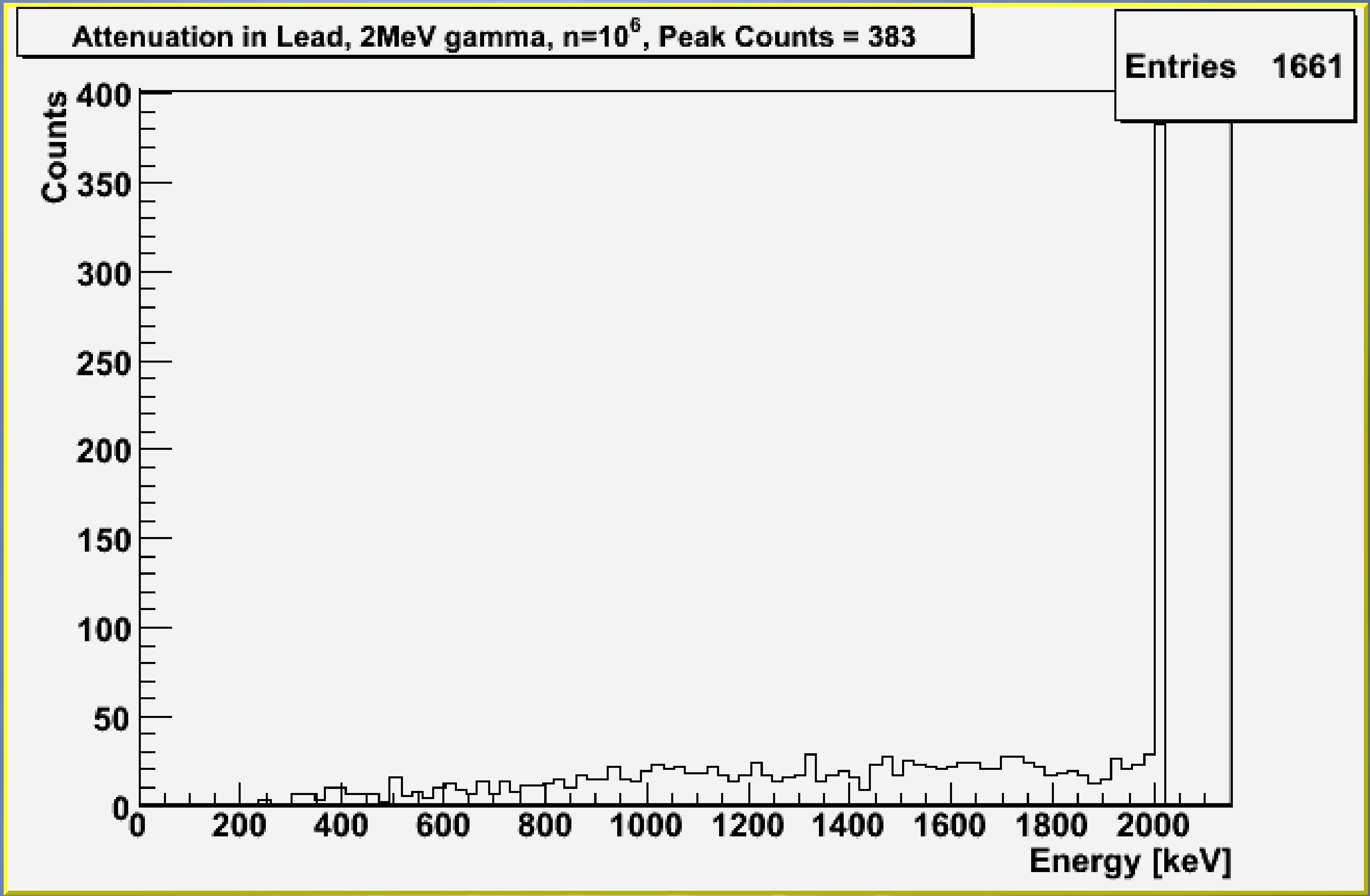




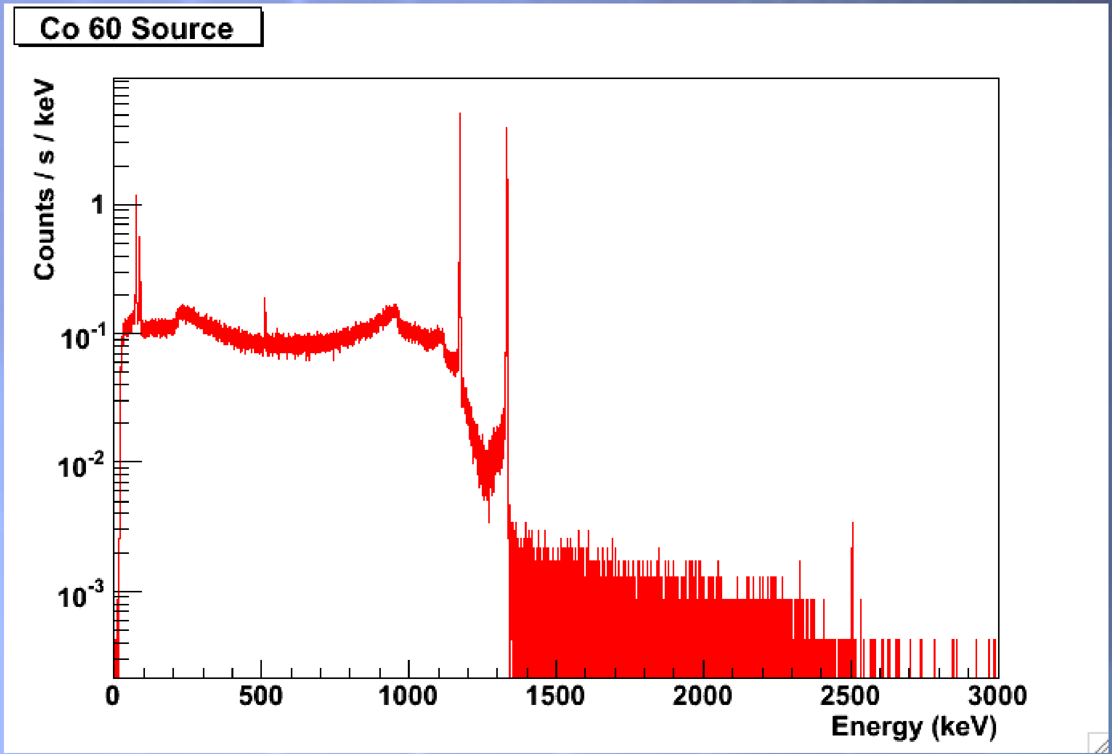
- Used the Energy spectrum to determine attenuation
- Slightly lower than calculations



- Spectrum of gammas hitting inner wall

Cobalt 60

- Simulation of Cobalt 60 source inside the house agrees well with actual data.
- $^{60}Co \rightarrow {}^{60}Ni + e^{-} + \nu_e{}^{*}$
  - Creates 2 photons: 1.17 MeV and 1.33 MeV



Observation (Red) and Simulation (Black)

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Summary

- What we did
  - Built radioactivity assay chamber with intrinsic germanium detector and active and passive shielding volumes
  - Developed simulation of assay chamber using Geant4
- State of the System
  - Observation agrees well with simulation for ^{60}Co source
  - Radioactivity of materials can be calculated by comparing future measurements with simulations
- Improvements for the Future
  - Better scintillator coverage
  - Copper shielding inside lead
  - Pump N_2 through house
  - Second detector

Any Questions?