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

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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 $\beta^-$ decay
- Electron Neutrino ($\nu_e$) first experimentally observed in 1956
- $\nu_\mu$ and $\nu_\tau$ experimentally observed in 1962 and 2000 respectively


http://en.wikipedia.org/wiki/Beta_decay
Neutrinos in the Standard Model

- 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$_2$O 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

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

Energy rewritten as

$$E = \sqrt{\mathbf{p}^2 + m^2} \approx \mathbf{p}^2 + \frac{m^2}{2p}$$

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 $\beta^-$ Decay

- For some nuclei, single $\beta^-$ decay not allowed
  - e.g. $^{76}\text{Ge}$ cannot decay to $^{76}\text{As}$ because $^{76}\text{As}$ has less binding energy
- Instead, double $\beta^-$ decay ($2{\nu}\beta\beta$) can occur:
  \[ ^{76}\text{Ge} \rightarrow ^{76}\text{Se} + 2e^- + 2{\nu}_e^* \]
  - $2{\nu}\beta\beta$ is rarest known radioactive decay---half-life of $10^{21}$ yr
- If neutrino is Majorana particle, neutrinoless double $\beta^-$ decay ($0{\nu}\beta\beta$) is possible:

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 $\beta^-$ Decay

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

- 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 ($\sim 2039$ 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\textsubscript{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

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 . . .
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 BF₂)
  - Gas (noble gases + N₂)
  - Glass

- Connected to photomultiplier to create electrical signal
Cosmic Ray Veto:

Upper Scintillator Paddle

Lower Scintillator Paddle

Gate Stretcher

Discriminator

Coincidence

ADC

DON’T READ DATA!
Background Radiation in Majorana Lab

Majorana's Region of Interest: 2039 ± 2 keV
Lead Attenuation

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

6 in. Pb for 2 MeV \( \gamma \): \( I \approx 349 \)

6 in. Pb for 1 MeV \( \gamma \): \( I \approx 5 \)
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
Region of Interest: 2039 ± 2 keV

Background Radiation Outside (Blue) and Inside (Red) Lead House

Counts/s/keV

Energy (keV)

Ann. γ's

40K
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
- 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 Efficiency

- 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
• 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.
- $^{60}\text{Co} \rightarrow ^{60}\text{Ni} + e^- + \nu_{e}^*$
  - Creates 2 photons: 1.17 MeV and 1.33 MeV
QuickTime™ and a TIFF (Uncompressed) decompressor are needed to see this picture.
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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 $^{60}\text{Co}$ 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 $\text{N}_2$ through house
  – Second detector
Any Questions?