Underground physics

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Why?

Why do physics underground?

- Expensive!
- Relatively Dangerous!
- Inconvenient Locations!
- Difficult to get air/water/electricity/equipment access!
- Sounds great, huh?

CDMS  SuperK  SNO  CUORE

http://www.sno.phy.queensu.ca/group/pics/sno6.jpg
http://today.slac.stanford.edu/images/2008/CDMS_icebox_lg.jpg
http://crio.mib.infn.it/wigmi/media/MauraPictures/CUORE-setup/SuperCUORE.png
Why?

To get away from backgrounds!

- Essential for some experiments
- CDMS can look for a SINGLE dark matter event!
- KamLAND looked for ~19 signal geoneutrinos in ~2 YEARS!
- Backgrounds must be VERY LOW!
Which Backgrounds?

- What backgrounds do we get away from?
  - Cosmic Rays
  - Alot of muons
  - Alot of muon Secondaries

![Graph showing cosmic ray backgrounds at different altitudes and depths.](image)

- Even at 25 m.w.e., the muonic and nucleonic contributions to the "star density" (nuclear interactions per gram of material per unit time) are about equal (<~0.01 inelastic interaction per kg per day). [Lal & P 1967]


![Graph showing neutron flux vs shielding depth.](image)
Muons

- **Muons:**
  - Created by decays of cosmic koans and pions: \( \frac{dN_\mu}{dE_\mu} \approx \frac{0.14 E^{-2.7}}{\text{cm}^2 \text{s sr GeV}} \left\{ \frac{1}{1 + \frac{E}{11 GeV}} + \frac{0.054}{1 + \frac{E}{850 GeV}} \right\} \)
  - Interactions with matter underground:
    - Ionization energy loss: more or less constant
    - Loss from bremsstralung, nuclear interactions, EM showers: proportional to \( E \)
  - Total Energy Loss: \( \frac{dE}{dX} = -\alpha - \frac{E}{\xi} \), \( \xi^{-1} = \xi_B^{-1} + \xi_{\text{pair}}^{-1} + \xi_{\text{hadronic}}^{-1} \)
  - General solution for energy: \(< E(X) > = (E_0 + \epsilon) e^{-X/\xi} - \epsilon.\)
  - Only high-energy muons go deep

<table>
<thead>
<tr>
<th>Location</th>
<th>Depth (km.w.e.)</th>
<th>( E_0^{\text{min}} ) (TeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KGF</td>
<td>( \leq 7 )</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>(many levels)</td>
<td>(deepest level)</td>
</tr>
<tr>
<td>Homestake</td>
<td>4.4</td>
<td>2.4</td>
</tr>
<tr>
<td>Mont Blanc</td>
<td>( \sim 5 )</td>
<td>( \sim 3 )</td>
</tr>
<tr>
<td>Fr jus</td>
<td>( \sim 4.8 )</td>
<td>( \sim 2.5 )</td>
</tr>
<tr>
<td>Gran Sasso</td>
<td>( \sim 4 )</td>
<td>( \sim 2 )</td>
</tr>
<tr>
<td>IMB</td>
<td>1.57</td>
<td>0.44</td>
</tr>
<tr>
<td>Kamiokande</td>
<td>2.7</td>
<td>( \sim 1 )</td>
</tr>
<tr>
<td>Soudan</td>
<td>1.8</td>
<td>0.53</td>
</tr>
</tbody>
</table>

(all from Gaisser)
Muons

• How do muons mimic signals?
  • Direct energy deposition in detector
    • Sometimes extremely high
    • Continuous: can deposit any amount of energy
    • Neutrons, radioisotopes

• How do we minimize this background?
  • Charge, high energy make muons easy to veto with:
    • Proportional or Scintillation Counters
    • Resistive Plate Chambers
    • Others
  • Muons can contribute largely to detector dead time in underground experiments.
Neutrons

\[ \mu^- + A(Z, N) \rightarrow \nu_\mu + A(Z - 1, N + 1). \]

- **Production methods:**
  - Muon capture: goes as \( Z^4 \)
  - Electromagnetic showers: goes as \( Z^2 \)
  - Spallation via virtual photon exchange
  - Secondary neutrons

- **Model with FLUKA, GEANT**

**Figure 2** Flux of cosmic ray secondaries and tertiary-produced neutrons in a typical Pb shield vs shielding depth. Neutron flux from natural fission and \((a, n)\) reactions is also shown. The nucleonic component is more than 97% neutrons.
How do neutrons mimic signals?

- Direct nuclear collisions: continuous spectra
- Create radioisotopes with various signals: discrete
  - Beta-neutron sources: \(^{8}\)He, \(^{9}\)Li, for example
  - Beta-only: \(^{9}\)C, \(^{12}\)B, \(^{12}\)N, for example
  - Gammas: \(^{60}\)Co, for example
- Q-values of decays could be in right range to mimic energy deposition of signal

Main backgrounds are determined by the energy scale of the experiment:

- Example: fast (Daya Bay) vs. slow (CDMS) neutrons
- \(^{60}\)Co (CUORE) vs. \(^{206}\)Pb (GERDA)
Other Sources of Radioactivity

- So, underground, we minimize cosmic-related background.
- Other backgrounds?
Other Sources of Radioactivity

• So, underground, we minimize cosmic-related background.

• Other backgrounds?
  • Natural radioactivity
  • Radiation in building materials
  • Radon
238U and 232Th, associated decay series: most common radionuclides; also 40K

From Formaggio
Natural Environmental Radioactivity

- On surface, cosmic ray photons are <1% the number of gamma rays from U/Th
- U/Th/K also common underground:
  - $^{232}$Th: 44 Bq/kg, $^{238}$U: 36 Bq/kg, $^{40}$K: 850 Bq/kg
- How to reduce: shielding!
  - Lead
  - Water
  - Anything with low radioactivity

Figure 8: Background spectra of an enriched Ge detector of the Heidelberg-Moscow collaboration (2.3 kg active volume) unshielded at 15 m.w.e. (top) and shielded with 40 cm lead at 3400 m.w.e. (bottom).
Radioactivity in Building Materials

- Shielding (i.e. Pb) contains medium-life radioactive isotopes
  - By protecting from some gamma backgrounds (U/Th/K), you introduce another!

- Other radioactive building materials
  - Bulk materials
  - Welds, solder

- Solutions:
  - Use relatively radiopure materials
    - Low-radioactivity metals and welding materials
    - Plastics or organics have radioactive nuclei ($^{14}$C), but much less
    - Aged shielding materials: CUORE uses ancient Roman Pb
  - Perform extensive radioactivity checks
Radon

- Part of Uranium/Thorium chains
  - Contains same signatures as part of U/Th chains
  - $^{222}$Rn is especially bad: h.l. $\sim 22$y

- Radon is tricky:
  - Gaseous
    - About 1300 Bq/m$^2$/s seeps up from the ground!
    - 1 mm$^3$ of air contains as much activity as that measured in solar neutrino exps!
  - Rn daughter clinging, plating on surfaces

- To avoid:
  - Don’t expose detector to air
  - Pump pure nitrogen
Where do we build underground exps?

- Factors to consider: overburden and cost
- Digging is a prohibitive cost: Daya Bay early estimate: $1600/m of tunnel
- Acceptable background level determines necessary overburden
- Avoid going far underground: background veto methods: timing and directionality cuts (accelerators), high event rate (Daya Bay),
What do we do underground?

- So, cosmic and other backgrounds reduced!
- What experiments does this make us want to do?
  - High-precision experiments
    - Double Beta Decay
    - Proton Decay
  - Weakly interacting particle searches
    - Neutrinos
    - Dark Matter (WIMPs)

DEAP/CLEAN

HyperK
(from Chen)

KamLAND

NEMO
(from Chen)
Neutrinoless Double Beta Decay

- double beta decay - rare nuclear process happens:
  - If Energetically allowed
  - If angular momentum suppresses single beta decays
- Neutrinoless double beta decay probes:
  - Dirac or Majorana?
  - Neutrino Mass
  - Mass higherarchy
- Detect peak at $0\nu\beta\beta$ Q-value
  - Many ways to do this!

From Chen

<table>
<thead>
<tr>
<th>isotope</th>
<th>Q-value [MeV]</th>
<th>natural abundance</th>
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<tbody>
<tr>
<td>$^{48}\text{Ca}$</td>
<td>4.27</td>
<td>0.19%</td>
</tr>
<tr>
<td>$^{150}\text{Nd}$</td>
<td>3.37</td>
<td>5.6%</td>
</tr>
<tr>
<td>$^{96}\text{Zr}$</td>
<td>3.35</td>
<td>2.8%</td>
</tr>
<tr>
<td>$^{100}\text{Mo}$</td>
<td>3.03</td>
<td>9.6%</td>
</tr>
<tr>
<td>$^{82}\text{Se}$</td>
<td>3.00</td>
<td>8.7%</td>
</tr>
<tr>
<td>$^{116}\text{Cd}$</td>
<td>2.80</td>
<td>7.5%</td>
</tr>
<tr>
<td>$^{130}\text{Te}$</td>
<td>2.53</td>
<td>34%</td>
</tr>
<tr>
<td>$^{136}\text{Xe}$</td>
<td>2.48</td>
<td>8.9%</td>
</tr>
<tr>
<td>$^{76}\text{Ge}$</td>
<td>2.04</td>
<td>7.8%</td>
</tr>
</tbody>
</table>

From P. Vogel [hep-ph 0807.2457]

From S. Sangiorgio
Neutrinoless Double Beta Decay

• Possible detection methods:
  • Bolometers: Cuore, Cuoricino - Detect phonons
  • Liquid TPC: EXO - Scintillation, tracking, radioassay
  • Scintillator: CANDLES, SNO+: Detect scintillation light
  • Tracking: NEMO - Track electrons

• Major Backgrounds:
  • Natural radioactivity in experiment
  • Any decay depositing energy near or above experiment’s Q-value
Proton Decay

- Various conservation violations: B, L, B+L, B-L, etc.
- Non-Standard model processes!
  - for example: $p \rightarrow e^+ + \pi^0$; $p \rightarrow K^+ + \bar{\nu}$
- Limits set on various processes
  - Predicted by various GUT models
- Experiments: Cerenkov detectors
  - Detect relativistic particles
    - products of
    - cosmic muons
    - muon secondaries
    - neutrino interaction products
    - other backgrounds
  - Past and current: See chart
  - Future: HyperK, UNO, Memphys

- Backgrounds: atmospheric neutrinos

From Chen
Dark Matter

• Dark Matter: What is it?
  • Possible answer, say supersymmetric theories: WIMPs

• How to detect them?
  • Nuclear recoil: keV of energy deposited

• Experiments
  • See figure: many bkg. discrimination methods

• Backgrounds
  • Exact expected energy is unknown
  • Theory: < 200keV nuclear recoil
  • Any low-energy non-WIMP nuclear recoil is a background
Neutrinos!

- Why look for neutrinos?
  - Understanding neutrinos, standard model
    - Oscillation: mass splitting, oscillation parameters
    - Fundamental symmetries: lepton conservation, CP violation
    - Experiments: Daya Bay(!), KamLAND, SuperK, MINOS, SNO
  - Understanding extraterrestrial sources
    - The sun: composition, nucleosynthesis, etc.
      - Experiments: Borexino, SNO, KamLAND
    - Supernovae: early warning system, neutrino mass
      - SuperK, IMB
  - Understanding Earth’s geology
    - U/Th geoneutrinos: terrestrial power flux
      - Experiments: KamLAND

- How to see them:
  - Water Cerenkov
  - Liquid scintillator detectors
  - Liquid Argon TPC

figure from P. Vogel

From Formaggio
Neutrinos!

- **Backgrounds:**
  - Backgrounds largely depend on desired energy range:
    - Example: Borexino results
    - Example: SNO+ sensitive to CNO \( \nu \)
    - Example: Kamland and \(^{210}\)Pb, \(^{85}\)Kr, \(^{40}\)K
  - Varied \( \nu \) energies, many different backgrounds
  - Backgrounds also depend on detection method:
    - Daya Bay: muon-induced radioisotopes
  - Aside: KamLAND: main bkg: neutrinos!
    - geoneutrinos vs. reactor neutrinos
Summary

- Underground physics experiments are defined by their low-background requirements
  - Reduce cosmic related backgrounds by going underground, vetoing muons
  - Reduce terrestrial backgrounds by shielding, using very clean building materials.
- A wide variety of nuclear physics discoveries can be made underground
  - The nature of the neutrino
  - The identity of dark matter
  - Discovery of new physics
- The future is waiting... underground!
References

• Chen, Mark, *Experimental Overview*, Talk given at OCPA 2008 Underground Physics Workshop, Hong Kong, 

• Chu, Ming-chung, *The Aberdeen tunnel experiment*. Talk given at OCPA 2008 Underground Physics Workshop, Hong Kong,


• Poon, Allen, *Backgrounds in Underground Experiments*, Talk given at OCPA 2008 Underground Physics Workshop, Hong Kong,

• Samuele Sangiorgio: conversation and various talks
