Measuring the Antineutrino Spectrum Below 1.8 MeV

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Outline

Antineutrino production
Potential applications in nuclear engineering
Current measurement methods
Coherent elastic neutrino-nucleus scatters
Semiconductor detectors with Transition Edge Sensors
Antineutrino spectrum calculation for NE&SC
Cross-section determination
Final reaction rates in the detector
Current measurement setup
Future plans
Antineutrino Production

- Antineutrinos are produced in the beta decay process.
- Neutron rich fission products beta decay and release antineutrinos (~nearly 6 per fission event).
- Antineutrinos amount to ~5% of the released energy.
- Detected for the first time at a nuclear reactor.

\[ n^0 \rightarrow p^+ + e^- + \bar{\nu}_e \]

<table>
<thead>
<tr>
<th>Nucleus</th>
<th>$E_{Th}$</th>
<th>$\langle E_\nu \rangle$</th>
<th>$\langle N_\nu \rangle$</th>
<th>$f_i/F$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^{235}\text{U}$</td>
<td>$201.92 \pm 0.46$</td>
<td>$9.07 \pm 0.32$</td>
<td>$6.14$</td>
<td>$0.967$</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>$205.52 \pm 0.96$</td>
<td>$11.00 \pm 0.80$</td>
<td>$7.08$</td>
<td>$0.013$</td>
</tr>
<tr>
<td>$^{239}\text{Pu}$</td>
<td>$209.99 \pm 0.60$</td>
<td>$7.22 \pm 0.27$</td>
<td>$5.58$</td>
<td>$0.020$</td>
</tr>
<tr>
<td>$^{241}\text{Pu}$</td>
<td>$213.60 \pm 0.65$</td>
<td>$8.71 \pm 0.30$</td>
<td>$6.42$</td>
<td>$&lt;0.001$</td>
</tr>
<tr>
<td>$^{238}\text{U} \rightarrow ^{239}\text{Pu}$</td>
<td>$1.95$</td>
<td>$1.2$</td>
<td>$2.0$</td>
<td>$0.16$</td>
</tr>
</tbody>
</table>

Image by Joel Holdsworth

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Potential applications of antineutrinos

- Nuclear and particle physics, astrophysics, geothermal physics
- Reactor monitoring for total power, isotopes, burnup
  - Provide a way to calibrate ex-core detectors;
  - Measure power spikes and scram within a few seconds;
  - Detect presence of covert reactors or used nuclear fuel storage;
  - Measure U/Pu ratio;
  - Measure age of fuel, especially used nuclear fuel;
  - Determine reactor burning or breeding (antineutrino from capture different);
  - Advance fuels: tag and track may not work as well;
  - Post accident monitoring;


Current Measurement Methods

- Traditional method uses inverse-beta-decay (IBD) to measure antineutrinos:
  \[ \bar{\nu}_e + p \rightarrow e^+ + n \]
  - Cross-section of interaction (~10^{-42} barns), size tons-kilotons
  - Threshold of interaction 1.806 MeV
  - High maintenance, require photomultiplier tubes

- Necessitate the following characteristics:
  - NEED 1: An efficient detector providing high signal to noise quickly
  - NEED 2: Can provide detailed spectrum information
  - NEED 3: Ease of operation: low cost, low maintenance, portable

- ALTERNATIVE: coherent elastic neutrino-nucleus scatter (CNS)
Coherent elastic neutrino-nucleus scatter (CNS)

- A mechanism for the antineutrino to scatter of a nucleus, the electrons, or the nucleons
- Postulated and formulated in 1974 by Freedman

\[
\frac{d\sigma_{\text{CNS}}}{dT_R} = \frac{G_F^2 M}{2\pi} \left[ (q_\nu + q_A)^2 + (q_\nu - q_A)^2 + \left( 1 - \frac{T_R}{E_\nu} \right)^2 - (q_\nu^2 - q_A^2) \frac{M T_R}{E_\nu^2} \right]
\]

\(\sigma_{\text{CNS}}\) is the coherent neutrino scattering cross-section
\(G_F\) is the Fermi coupling constant
\(q_\nu\) and \(q_A\) vector and axial charges
\(N\) is the number of neutrons
\(T_R\) is the recoiled nucleus’ kinetic energy
\(M\) is the mass of the detector nucleus
\(E_\nu\) is the energy of the anti/neutrino
\(Z\) is the atomic number

- First measured by the COHERENT group in 2017
  - Measurements performed for high energy neutrinos (not completely coherent w.r.t. nucleus)
  - At lower energies as in from nuclear reactor (<10 MeV)
General Procedure

1. Determine the antineutrino flux for reactor of interest
2. Calculate the CNS cross-sections for the detectors of choice
3. Convolve the antineutrino flux and CNS cross-sections to determine reaction rates
1. Determine the antineutrino flux for reactor of interest (10 m from 1-MW NE&SC core-Texas A&M)
   • Ab-initio or the summation method, for a given fissile isotope determine all fission products that decay by β-decay, obtain the β-decay spectrum, sum-up and subtract from β_max energy (our choice)
   \[
   \rho(E_\nu) = \sum_i CY_i \sum BR_i P_i(E_\nu)
   \]
   \(i\) is fission product index, \(CY_i\) is cumulative yield if isotope, \(BR_i\) is branching ratio, \(P(E_\nu)\) is the neutrino energy distribution

   \[
   P_i(E_\nu)dE_\nu = F(Z, E_\nu) \left[ (E_{\beta max} - E_\nu)^2 - m_0^2c^4 \right]^{1/2} \\
   \times \frac{E_\nu^2(E_{\beta max} - E_\nu)dE_\nu}{F_i} \times F(\alpha)(E_\nu)
   \]

   \(F(Z, E_\nu)\) is the fermi function, \(F(\alpha)(E_\nu)\) is a correction factor for spin-parity-forbidden/allowed states


- 545 fission products for \(^{235}\text{U}\)
- 586 fission products for \(^{238}\text{U}\)
- 568 fission products for \(^{239}\text{Pu}\)
- 605 fission products for \(^{241}\text{Pu}\)

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The differential cross-section as a function of nucleus recoil energy is integrated up to

\[ T_{R}^{Max} = \frac{2E_{\nu}^2}{M + 2E_{\nu}} \]

The resulting cross-section for Ge and Si indicate germanium is more efficient over all energies.

Detector threshold of 20 eV nuclear recoil

<table>
<thead>
<tr>
<th>Detector Technology</th>
<th>Flux-weighted cross-section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Germanium CNS</td>
<td>$4 \times 10^{-4}$ pb</td>
</tr>
<tr>
<td>Silicon CNS</td>
<td>$3.2 \times 10^{-5}$ pb</td>
</tr>
<tr>
<td>IBD</td>
<td>$1.88 \times 10^{-6}$ pb</td>
</tr>
</tbody>
</table>
Reaction Rates in the Detector

\[ R(E_\nu) = N\sigma_{CNS}(E_\nu)\phi(E_\nu) \]

- At 20 eV nuclear recoil, minimum detectable neutrino energy on Si \(\sim 0.5\) MeV, on Ge \(\sim 0.8\) MeV (100 kg detector at 10 m)
  - \(\sim 43.4\) events/day in Ge and \(\sim 7.8\) events/day in Si
  - Antineutrinos missed nearly 32% in Ge and 19% in Si
- At 100 eV nuclear recoil, minimum detectable neutrino energy on silicon \(\sim 1.14\) MeV, on germanium \(\sim 1.84\) MeV
- The current inverse-beta-decay (IBD) threshold at \(\sim 1.8\) MeV
  - \(\sim 2.1\) events/day with water based and \(\sim 1.8\) events/day with organic scintillation based IBD detectors
  - Antineutrinos missed nearly 50%


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MINER experiments plan

1. 2-10 m proximity to core (rate enhancement)
2. Moveable Core tests short baseline oscillation
3. 4 kg (max=30) detector payload
Summary and Future Plans

• Shown detector’s response as a function antineutrino energies for CNS semiconductors (below 1.8 MeV)
  • Ge more efficient than Si detectors
  • Si provides lower threshold for detection
  • Both semiconductors can be developed to provide more efficient and smaller detectors (possibly cheaper)
• Formulate detector response beyond reaction rates
• Perform analysis for different cases: fuel cycles, burnup history, power levels
• Perform spectrum reconstruction of antineutrino energies from the detector response function above
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\[ F_a(E_v) = C \left(1 - \frac{E_v}{E_{\text{max}}}\right)^n \]

\[ F(Z, W) \approx a \frac{W}{p} + \left[ \frac{c}{1 + (d/p^2)} \right] \]

where \( a = 2\pi\alpha Z \), \( C = b - a \), \( b = a/(1 - e^{-a}) \), and \( d = \left(\frac{1}{2}\right)(b - 1) \)