Nuclear Data for the Antineutrino Detector Response: IBD Signal

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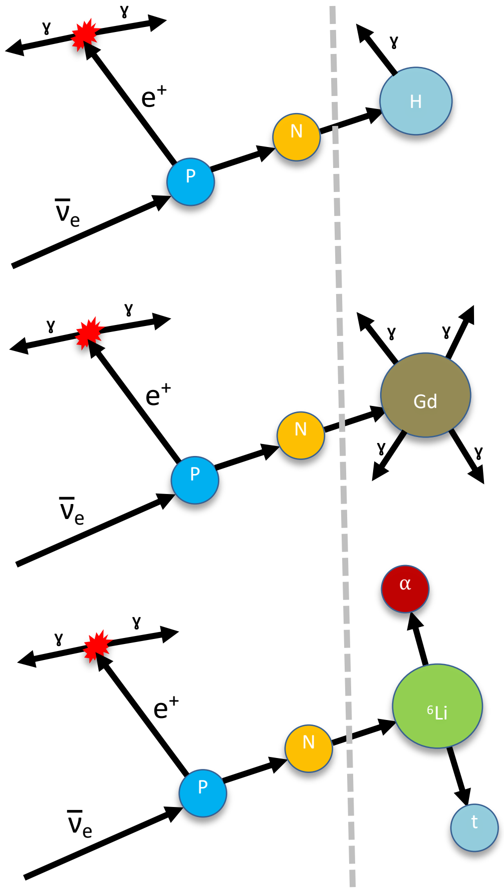
June 24, 2021

LLNL-PRES-823745

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Inverse Beta Decay



Positron/neutron coincident signature is key to background rejection in IBD detectors

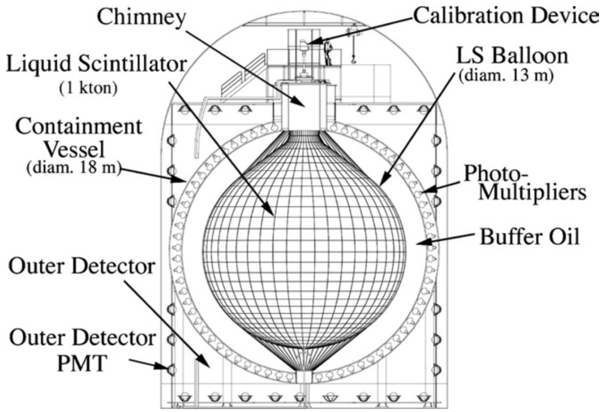
Prompt Signal: Positron

- Inherits the majority of the antineutrino kinetic energy
- Scintillation light is produced by the positron as it loses energy in the scintillator
- The positron will annihilate with an electron producing two 511 keV ɣs
- Electrons from Compton scattering and the photoelectric effect will also produce scintillation light
- Light from the positron and gammas is not distinguishable

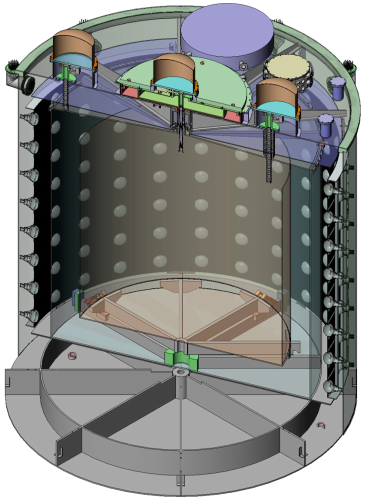
Delayed Signal: Neutron

- Inherits the majority of the antineutrino momentum
- Thermalizes over 10s-100s of μs until captured
- The capture agent determines the measurable delayed signal

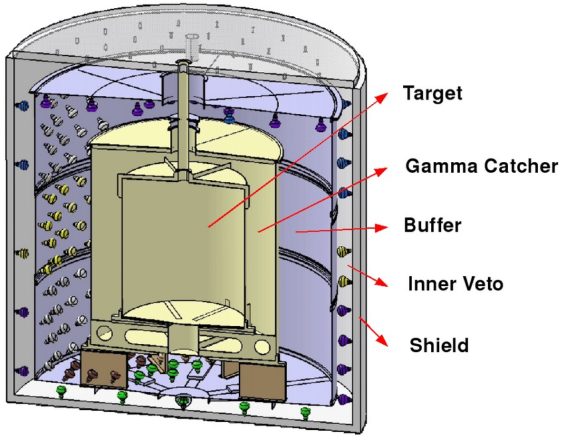
IBD detectors



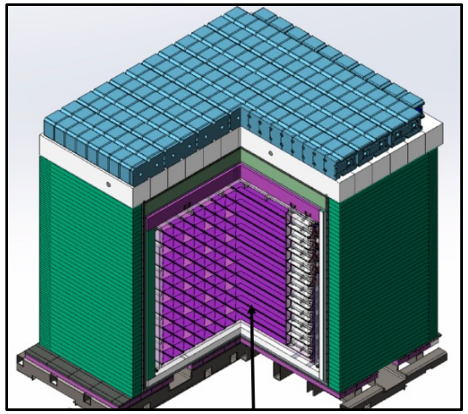
KamLAND



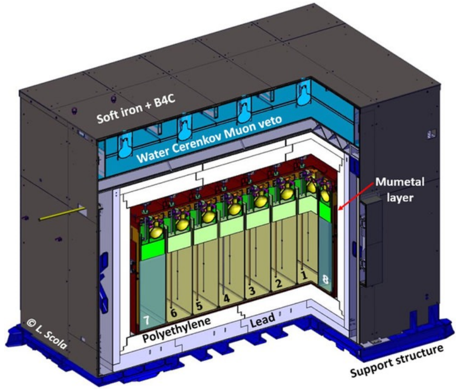
Daya Bay



Double Chooz



PROSPECT



STEREO

Detector Material

- Hydrogenous target material → Organic Scintillators*
- Target material is detector material
- Optional additional neutron capture agent (Gd, ^{6}Li)

*AIT/NEO will use water-based LS for IBD detection

Signal Selection

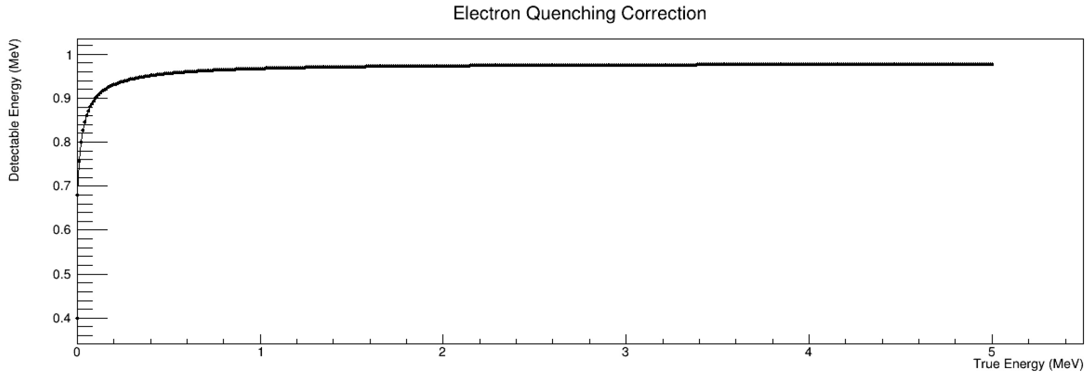
- Prompt/Delayed timing coincidence
- Prompt/Delayed proximity
- Capture agent identifier
- Prompt/Delayed particle identification

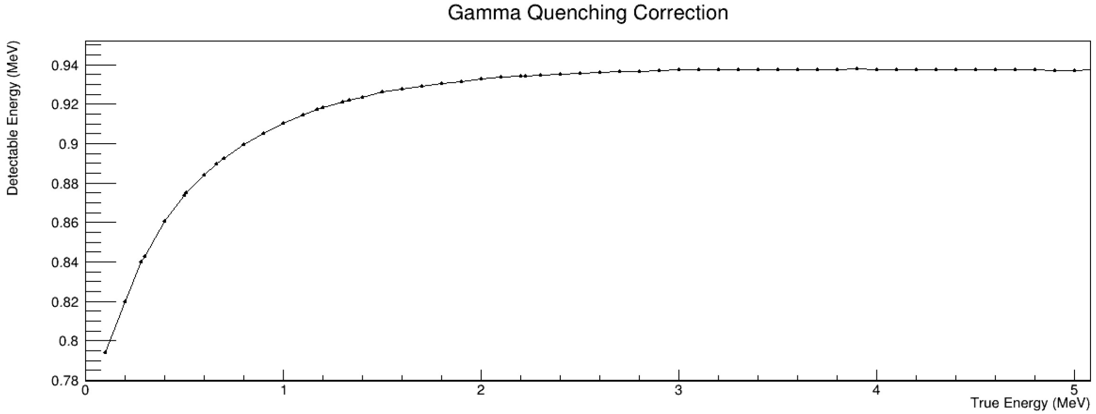
Prompt Signal: Energy Scale

- Precision antineutrino measurements rely on accurately measuring the positron energy
- Scintillation light is produced with a non-linear quenching described by the phenomenological Birk's Law

$$dL = S \frac{dE}{1 + K_b \, {dE}/{dx} + \cdots}$$

L: Light Yield
S: Scintillation Yield
E: Energy deposition
dE/dx: Stopping Power
K_b: Quenching Parameter





- This quenching, along with Cherenkov radiation production result in an energy dependent energy scale.
- This effect is more prominent in gamma energy reconstruction. Gamma calibration sources are needed to set the positron energy scale.

Prompt Signal: Data Needs

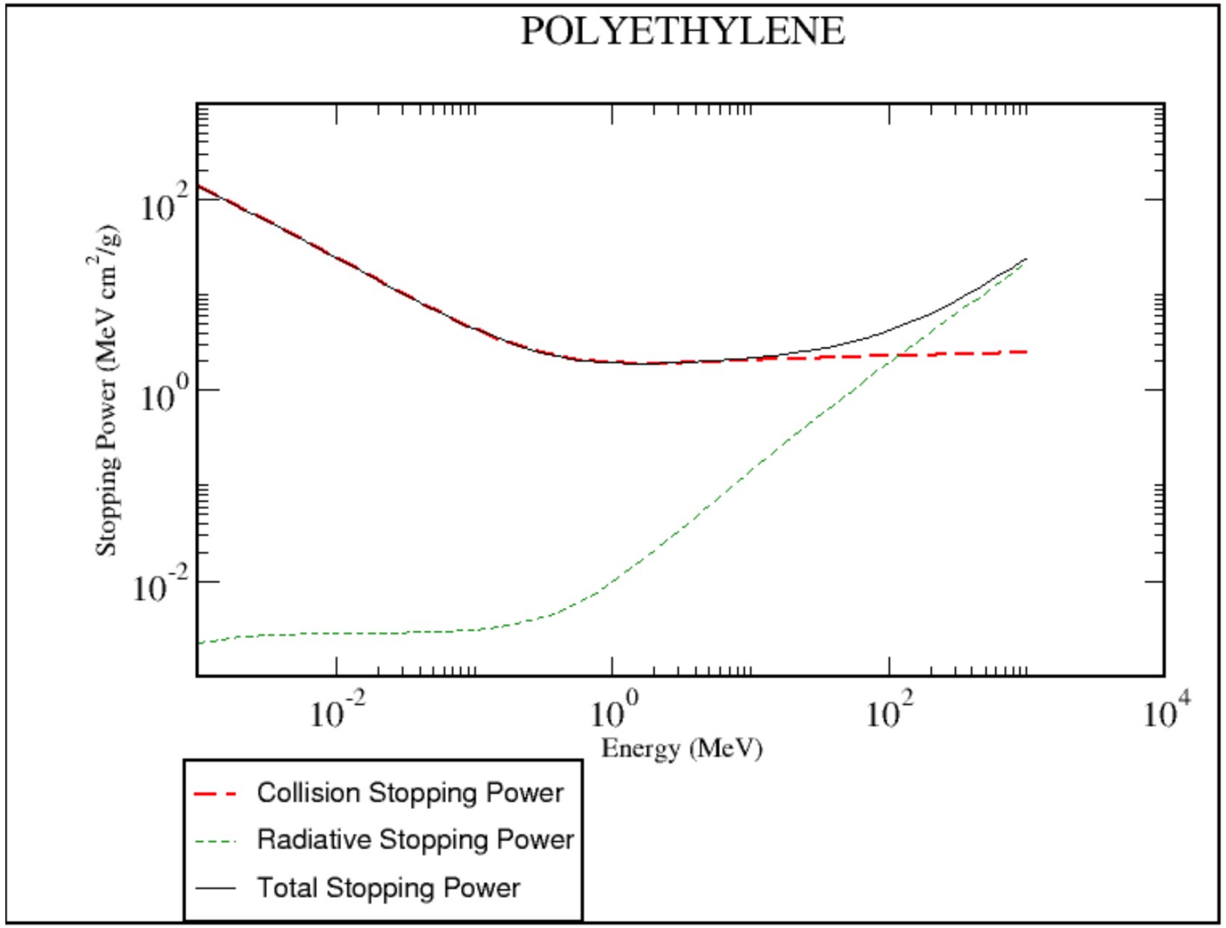
Data required for prompt signal simulation:

- Stopping power
  - calculated from Bethe-Bloch formula (i.e. NIST ESTAR)
  - Primarily will be a hidden calculation within a simulation framework (i.e. Geant4)
  - Depends on accurate material component ratios and density

- Scintillation yield - provided by manufacturer and/or bench measurements

- Quenching parameter - determined by bench measurements, and/or in-situ calibrations

- Database of yield/quenching values does not exist

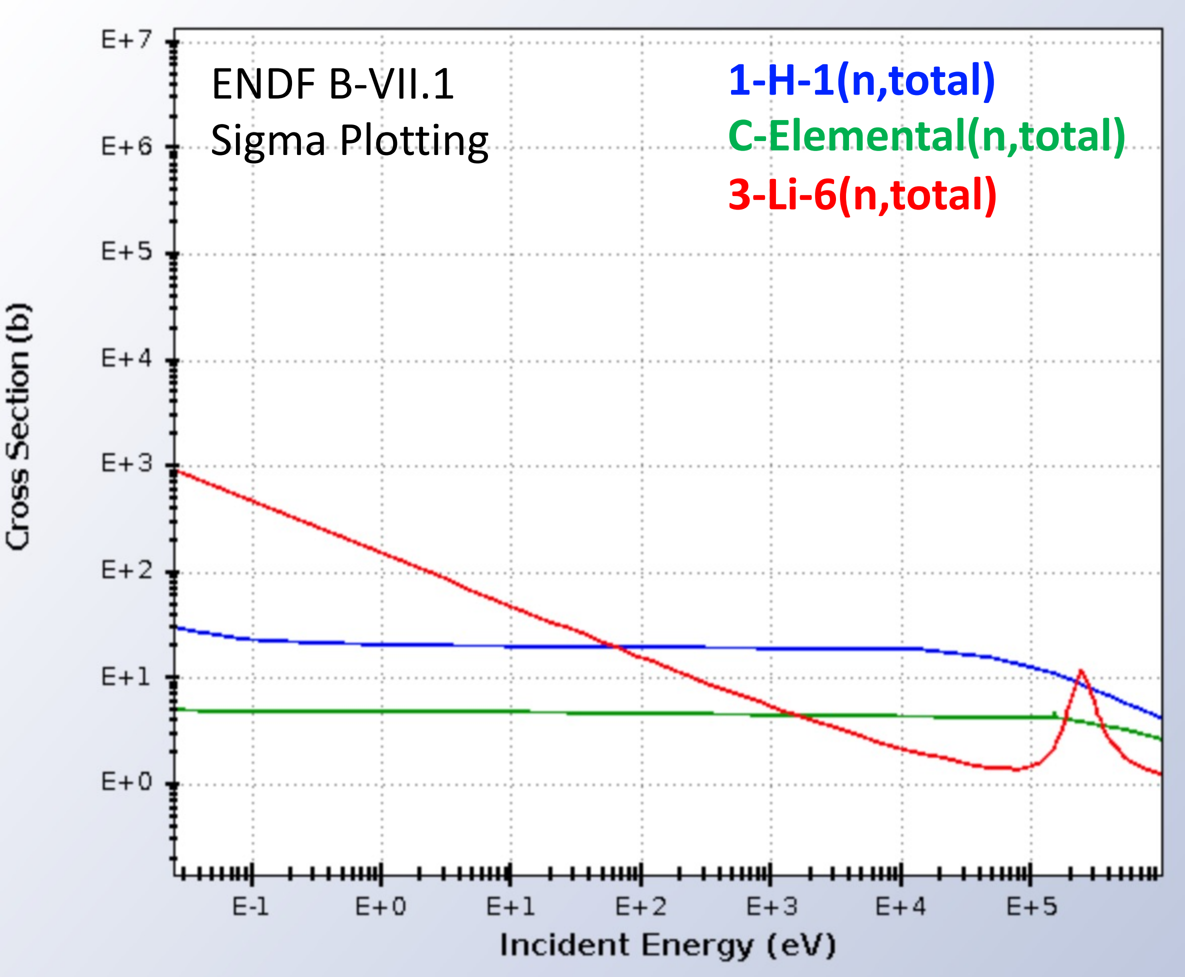


NIST ESTAR: Stopping Power and Range Tables for Electrons

Delayed Signal: Neutron Transport

- Neutron mobility is a primary concern
  - Detection efficiency will likely depend on a distance cut between the prompt and delay
  - Neutrino directionality measurements are very dependent on the neutron drift cloud
  - Neutron capture ratios are important for efficiency estimation

Nuclear Data:
- Neutron scattering cross sections on detector components
  (thermal – ~100 keV)
- Neutron capture cross sections on detector components



Delayed Signal: Neutron Capture

- Neutron capture signatures are important for signal/background discrimination

- The signature of interest depends on the neutron capture agent in the detector
  - Hydrogen - 2.2 MeV single gamma ray
  - Gadolinium - cascade of multiple gamma rays totaling 8-8.5 MeV
  - Lithium-6 – alpha and triton totaling 4.78 MeV

- There are multiple simulations of the Gd gamma cascade following neutron capture, but this process would benefit from additional modelling/validation

- Other neutron capture agents may be present in detection material (i.e. Chlorine) which will compete with the desired neutron capture process. Improvements to neutron capture cross sections and response for any materials potentially in a detector can help improve response simulations.

Nuclear Data Interface: Simulation

- The majority of the interaction with nuclear data for IBD signals will be through simulation codes such as Geant4
- There are a large number of optional data libraries that can be included in Geant4 for "optional physics processes"
  - https://geant4.web.cern.ch/support/download
  - https://geant4.web.cern.ch/support/data_files_citations
- There are competing data files for some of these processes
  - https://www-nds.iaea.org/geant4/
- Multiple models for neutron transport may be used within Geant4, and it can be difficult to find the model or combination of models that best reflect your experiment
  - Different energies ranges for some models
  - Some models based on ENDF data
- Requires experience/research to appropriately configure for the desired physics.

Conclusion

- There are no large gaps in nuclear data that are hindering our understanding of IBD signals.
- For the positron signature, there are data needs that do not fall under the nuclear data designation, these data are usually measured/calculated by each experiment.
- Neutron transport, capture and capture response are the main areas where nuclear data impact IBD signal characterization
- The majority of this data is utilized with simulation codes like Geant4, and will be hidden from the user
- The primary nuclear data need for IBD signals is ensuring that accurate and current nuclear data is utilized by these simulation codes, and that the codes are validated to ensure they reproduce the physics.