Modeling Elastic Scattering & Decay Chains Using ReactorFsim

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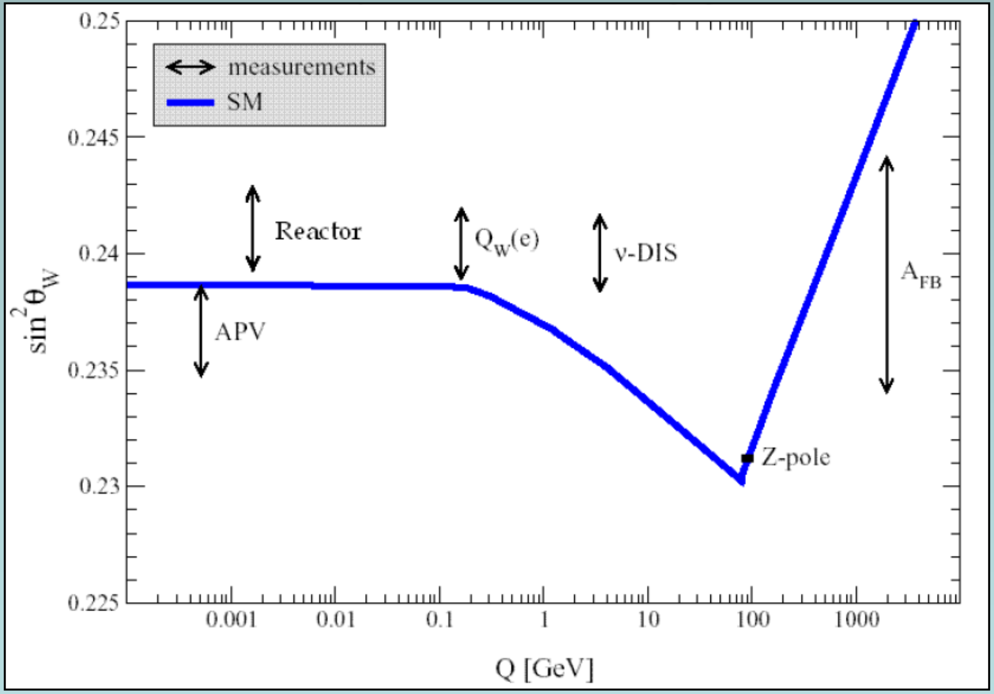
Measuring the Weak Mixing Angle

- Use anti-neutrino elastic scattering to make measurement of the weak mixing angle:



- Use inverse beta decay events as flux normalization.

- Outlined in Mike, Jon, and Janet's paper (hep/ex 0403048)

Major Issues

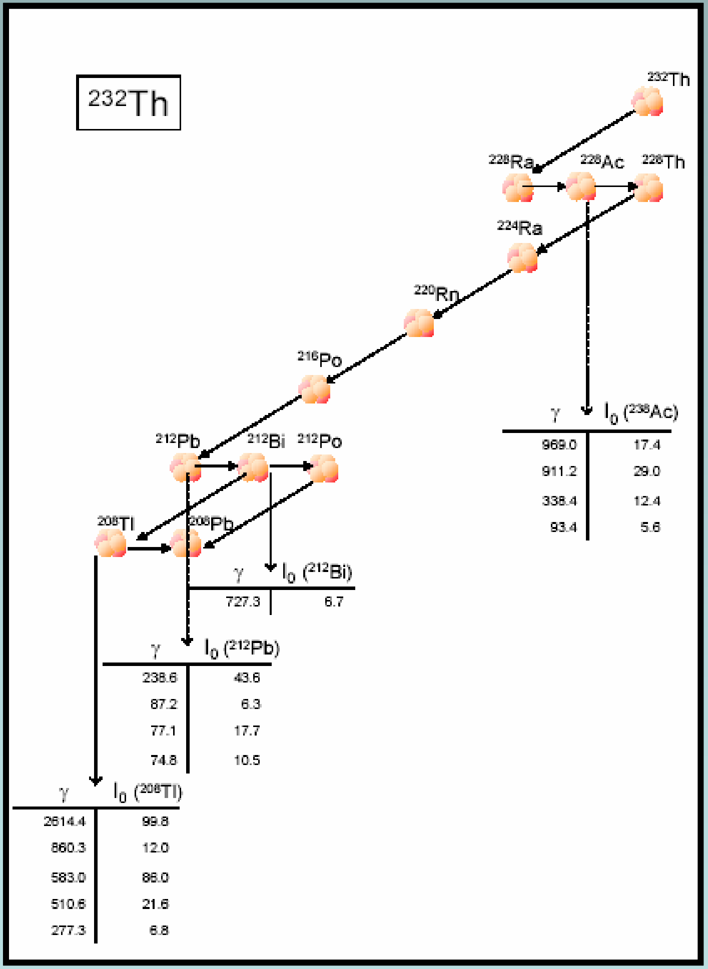
- Four major issues need to be addressed for a ~1% precision measurement:

    1. Fiducial volume
    2. Energy calibration
    3. Natural Radioactivity / Contamination
    4. Spallation

- Some topics previously addressed.

Natural Backgrounds

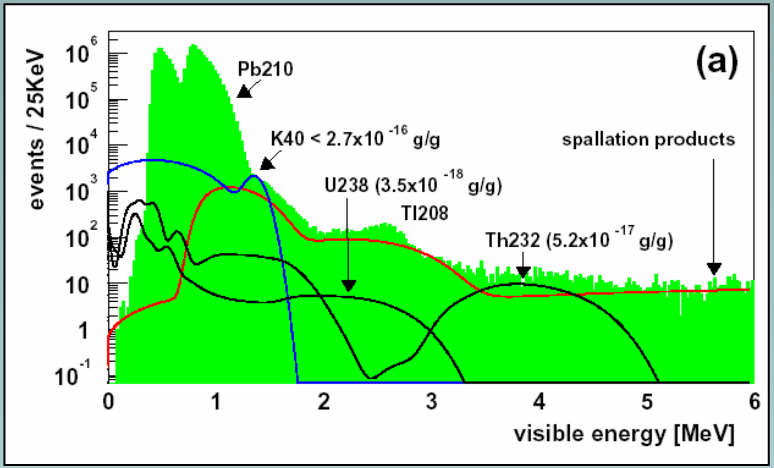
- Main issues come from U & Th contamination.
- Weak mixing angle looks at energies above 3 MeV (lower is better).
- ^{208}Tl from ^{232}Th one of the main concerns.

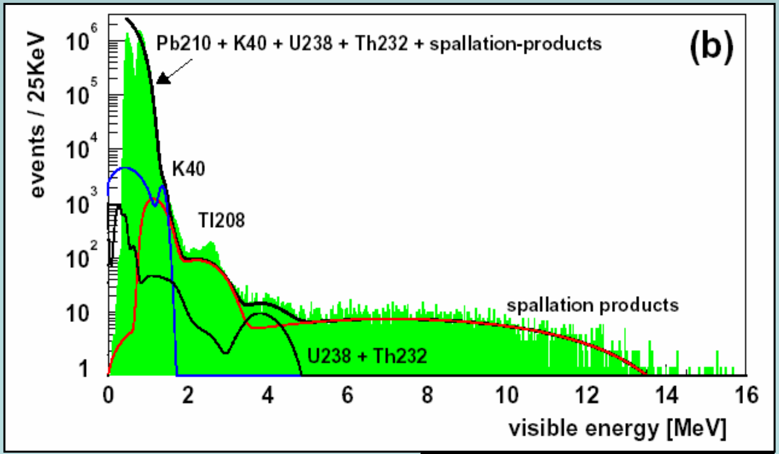


Braidwood Neutrino Experiment

Purification

- Scintillator typically can achieve high levels of purity
- From KamLAND:
    - $3.5 \pm 0.5 \times 10^{-18}$ g/g ^{238}U
    - 5.2×10^{-17} g/g ^{232}Th
- Usually due to ingress of radon.
- Also of concern, radon implanted in acrylic (only gamma from ^{208}Tl seen).





O. Tajima (Ph.D.)

Techniques for Reduction

- Purification:
  - Use low levels of radioactivity in Gd-base
  - Purification of final doped scintillator
- $e^-/^{208}Tl$ Separation:
  - Use timing/vertex separation of ^{208}Tl source and ES track
  - Use log-likelihood to separate events.
- Tagging
  - Use timing of scintillator to distinguish a particles in detector.
  - Use (α,α) coincidences to tag parent decay

Gd Metal ~ 10^{-10} (Yb Level)

Doping (0.1%) ~ 10^{-13}

↓

Reduction Factor ~ 1000
~ 10^{-16}

↓

Reduction Factor ~ 10
~ 10^{-17}

Devil's in the details…

- Separation Technique:
  - The separation of ^{208}Tl events using track reconstruction/timing requires good knowledge of timing/track resolution, scattering effects, etc.
  - Proof of principle illustrates >1000 reduction is possible. What other factors would smear the technique?
  - A call for a more detailed simulation.

- Other needs:
  - Would be desirable to simulate the whole decay chain of a given isotope
  - Have a tool that can do generic decays (rather than dialing in by hand)

The DecayChain
&
ElasticScattering
Classes

What do they do?

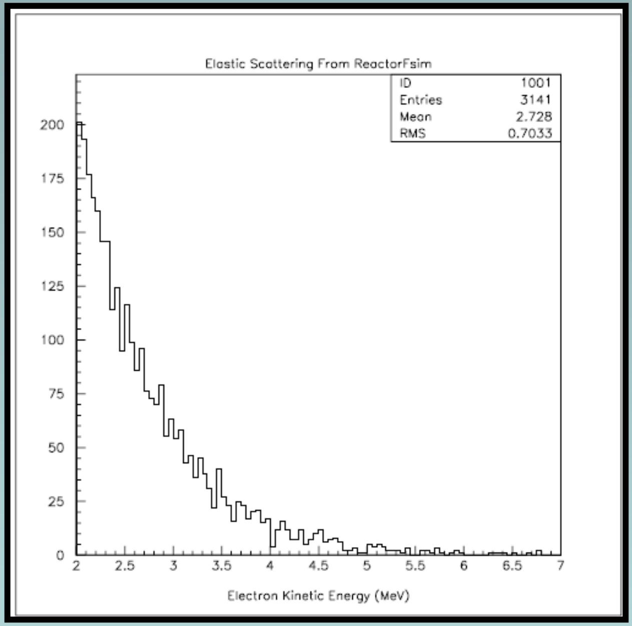
ElasticScattering Class

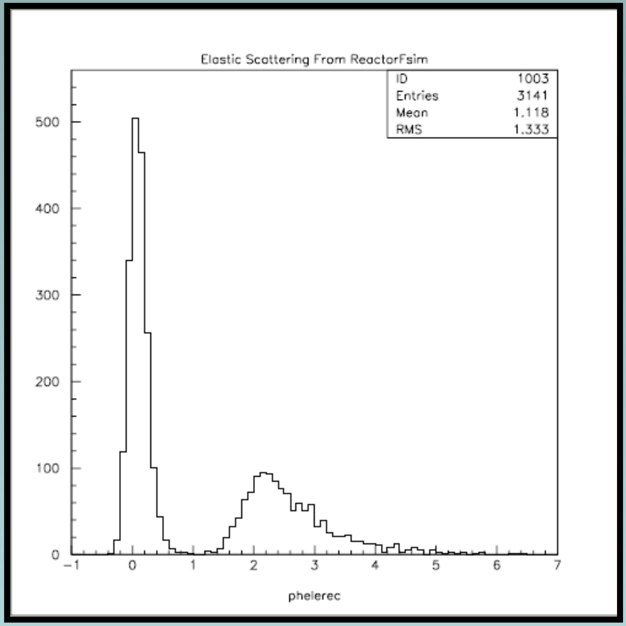
- Simulate neutrino elastic scattering in the same way as reactor events.
- Can be used as stand-alone, with ReactorFsim or with GEANT4
- Can change weak mixing angle value and introduce neutrino magnetic moment.

DecayChain Class

- Simulate full decay chains of a given sequence.
- So far, takes into account all gamma/beta decays, as well as alpha decays.
- Can start at any point in the decay
- Very easy to add your own decay sequence (adding a few lines to a text file)
- Can be used as stand-alone, with ReactorFsim or with GEANT4

Sample Output





- ElasticScattering already added to the ReactorFsim infrastructure.
- Does need to be verified.

Components to DecayChain

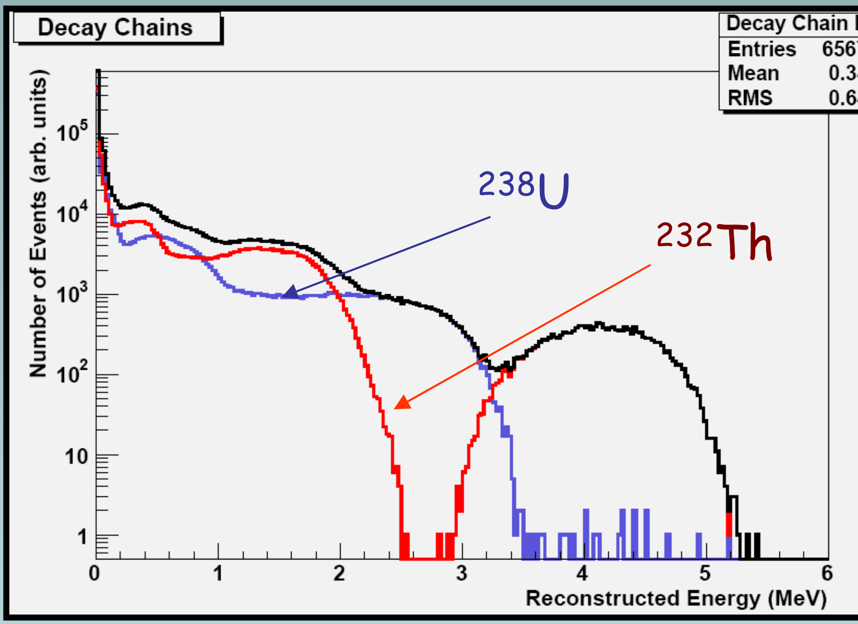
FourVector.cpp

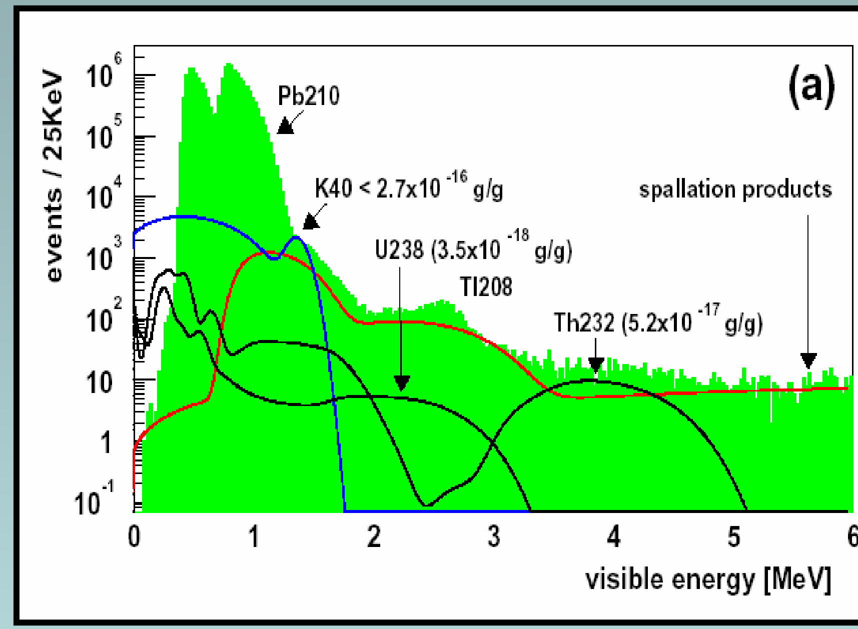
- Generic 4-Vector object (you can add, subtract, dot product, etc)
- Can use to find the energy, proper length, mass, momentum, kinetic energy, etc.
- In principle, keeps identity of the particle (sort of)

FermiFunction & BetaFunction

- Calculates beta decay shape based on type of decay (allowed, forbidden, etc.).
- Does both β^+, β^- and subsequent gamma cascade.
- Expanded to also take care of alpha decay (no info on recoil yet.)

DecayChain Output





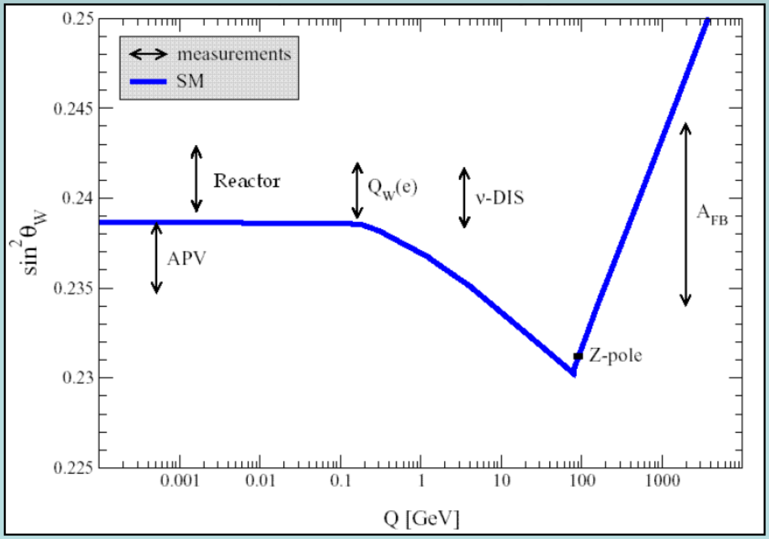
- Full chain can be run in equilibrium or forced decay mode.
- Does branching, should branching occur.
- ReactorFsim does not yet recognize how to store the events (yet).

Summary

- Multiple techniques being invoked to suppress errors and backgrounds in the elastic scattering measurement.

- Simulation tools developed to allow more detailed checks in the future for both elastic scattering events and radioactive backgrounds.

- Looking forward toward compatibility into a GEANT4-based system.



An Aside : Signal Extraction and Pulls

- Typical Methods:
  - Vary likelihood function by a known, fixed systematic. Estimate error based on total likelihood variation.

  Or..

  - Use correlation matrices to minimize χ^2 and extract limits.

- Drawbacks:
  - No correlations are taken into account. Tends to over-estimate errors.
  - Uses correlation, but limited to use χ^2 statistics.

Solution? Use correlations & Poisson statistics.

Pull Method : Methodology

- Form likelihood from both data *and* calibration data:

$$P_{total} = P_{\nu} \cdot P_{cal}$$

$$\Delta\mathcal{L} = -\vec{\alpha}^{T}_{min}\mathcal{S}^{-2}\vec{\alpha}_{min}$$

- Second term acts as a constraint to likelihood.

- Minimize w.r.t. known systematics, thus extracting systematics as a function of the existing data.

$$\vec{\alpha}_{min} = (\sum_{j}^{N_{data}} \vec{\beta}_j - \vec{\nabla}\Phi)^T \mathcal{S}^{-2}$$

Derivative wrt systematics

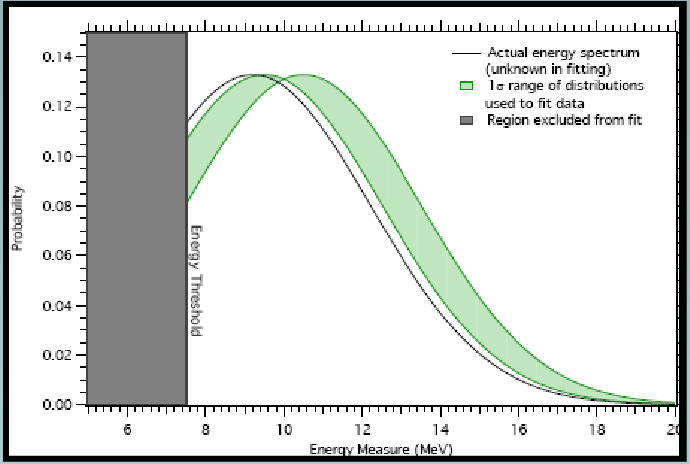
Total derivative

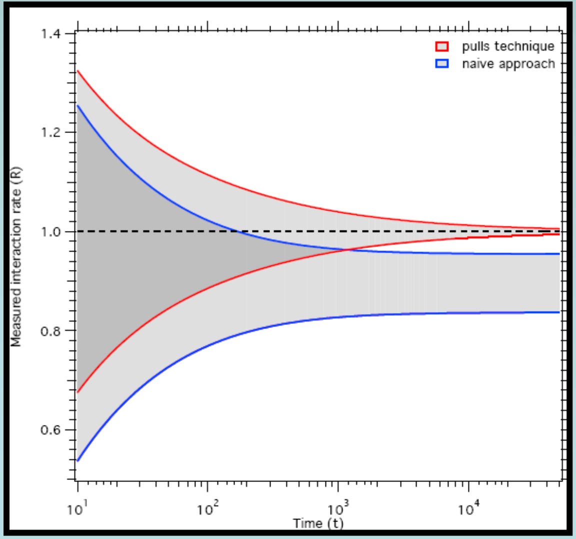
$$\mathcal{S}^2 = \sigma^{-2} + \sum_{j}^{N_{data}} \vec{\beta}_j \times \vec{\beta}_j^T$$

Correlation matrix

A Simple Example

- Gaussian distribution with systematic (energy scale) slightly shifted from true (nominal) distribution.
- Typical technique is limited by systematic, while pull technique adjusts from information in the data itself.
- Work and plots on right from Miles Smith (former UW student)





Braidwood Neutrino Experiment

Many Uses

- The pull technique has been used on a number of different settings (SNO radon analysis, oscillation fits, structure functions, etc., etc.)
- Not limited by statistics if one uses Poisson formalism.
- Can be used in MINUIT or analytically.
- Extremely powerful in constraining systematics that effect more than one system.
- Handy for constraining systematics for elastic scattering measurement and others.