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Event by Event Classification of (α, n) and IBD Interactions at SNO+

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The SNO+ Experiment

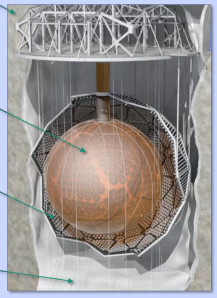
Multi-purpose liquid scintillator detector.
Main objective to detect 0νββ decay [1].
Also sensitive to long baseline neutrino oscillation from reactor $\overline{\nu}_e$ [2, 3]

2 km overburden

6 m radius acrylic vessel (AV) filled with liquid scintillator

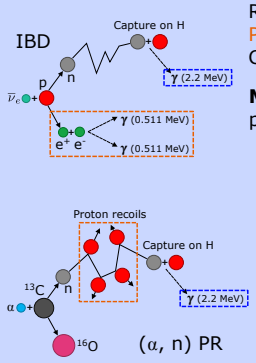
Over 9000 PMTs + outward looking PMTs

Surrounded by ultra-pure water



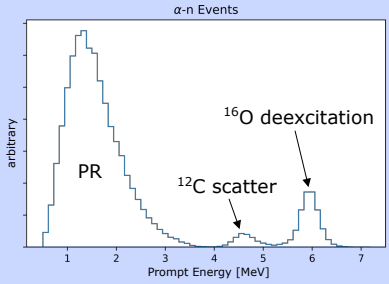
- Based on the Sudbury Neutrino Observatory (SNO)
- Ultra low radioactive and cosmogenic backgrounds
- Load ^{130}Te to produce 0νββ!

IBD vs (α, n)



Reactor $\overline{\nu}_e$ detected via inverse beta decays (IBD) on protons. Prompt-delayed event structure: e^+ annihilation and neutron capture. Coincidence tagging removes almost all backgrounds.

Main remaining **background** is **^{13}C(α, n)^{16}O** events, mimicking this prompt-delayed signature [2, 3]. Three possible prompt events:



- **Proton recoil (PR):** neutron recoils on protons.
- **^{12}C scatter:** neutron scatters off a ^{12}C, which releases a γ.
- **^{16}O deexcitation:** ^{16}O produced in excited state, releases a γ or e^+e^- pair.

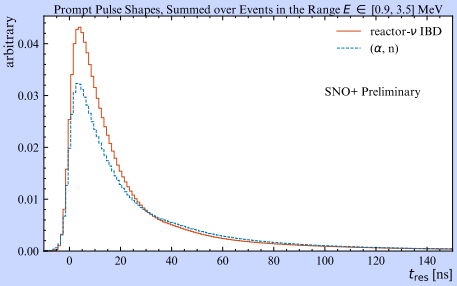
Pulse Shapes

The pulse shape of an event is its **light emission over time**. At SNO+ it is constructed from the PMT residual hit times:

$$t_{\text{res}} \equiv t_{\text{hit}} - t_{\text{evt}} - t_{\text{TOF}}$$

t_{hit} is a single PMT hit time, t_{evt} the event time, and t_{TOF} the straight line time-of-flight between the event and the PMT [4].

PR events last longer, so the pulse shape has a **longer tail**.
The **scintillation timing** is also different for β's and protons.



The **β timing** was calibrating using in-situ tagged ^{214}Bi and ^{214}Po decay pairs [5].

The **proton timing** is being calibrated with a combination of tagged low-energy (α, n) events, and an ^{241}Am ^{9}Be (AmBe) source [1]. This can produce similar PR events via the ^{9}B(α, n)^{12}C interaction.

The Classifier

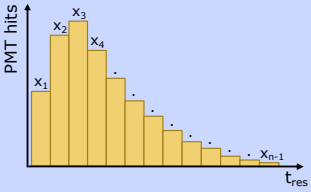
The **Pulse shape** is **correlated** with the event **energy** (E) and radial **position** (R) in the detector, in non-trivial ways. A likelihood ratio based on averaged PDFs does not capture this.

A **Fisher discriminant** is used, which finds the **projection vector** that best separates two multi-dimensional datasets, accounting for their covariance matrices.

Construct a vector $\vec{x}$ for each event from **binned t_{res} and** its **radial position**:

$$\vec{x} = (x_1, x_2, \ldots, x_{n-1}, x_n)$$

$$\Rightarrow \sum_{i=1}^{n-1} x_i \approx N_{\text{hit}} \propto E$$



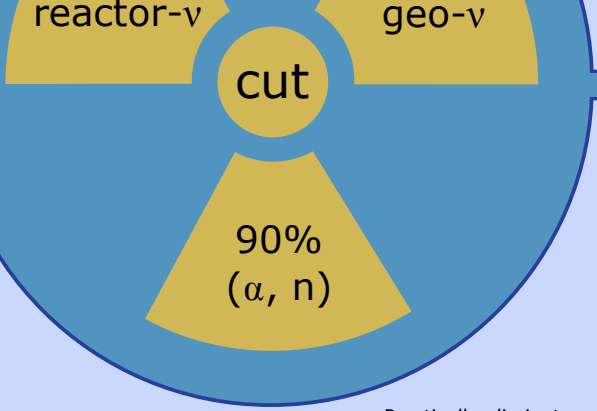
Select samples of simulated IBD signal (S) and (α, n) background (B) events, with similarly uniform E and R^3 distributions.

Compute projection vector $\vec{a}$, from sample means μ and the "within-class" covariance matrix W [6]:

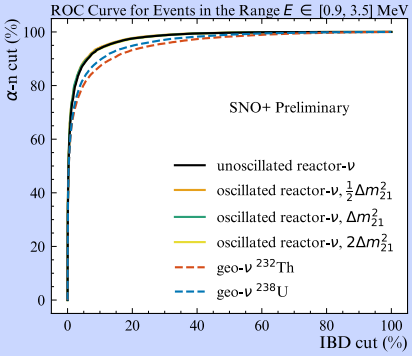
$$\vec{a} \propto W^{-1}(\vec{\mu}_S - \vec{\mu}_B)$$

Classify each event via the test statistic:

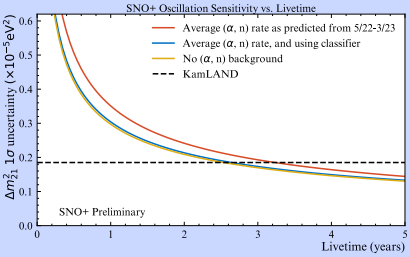
$$\mathcal{F} = \vec{a} \cdot \vec{x}$$



Classifier applied to simulated IBD and (α, n) events from expected distributions, assuming different neutrino oscillation scenarios:



Performance is independent of oscillation.
Out-performs log-likelihood classifier.
Example cut: 90% (α, n), 6% reactor-ν and 11% geo-ν.

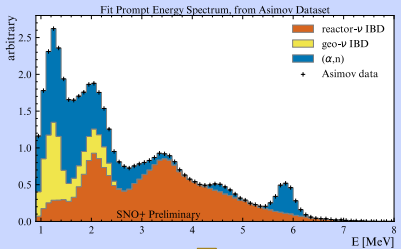


Practically eliminates the impact of (α, n) on Δm^2_{21} measurements.

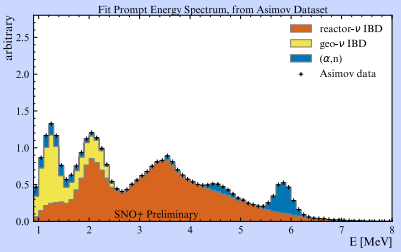
Work still preliminary, simulation-based.

See Sofia Andringa's poster on Friday for SNO+ oscillation analysis results!

Impact on prompt energy spectrum:



apply classifier



Results

[1] SNO+ collaboration. *The SNO+ experiment*. Journal of Instrumentation, 16(08):P08059, 2021.
[2] SNO+ Collaboration. *Observation of antineutrinos from distant reactors using pure water at SNO+*. arXiv preprint arXiv:2210.14154, 2022.
[3] SNO+ Collaboration. *Initial measurement of reactor antineutrino oscillation at SNO+*. arXiv preprint arXiv:2405.19700, 2024.
[4] C. Mills, *Improved sensitivity to Δm_{21}^2 by classification of the $^{13}C(\alpha, n)^{16}O$ background in the SNO+ antineutrino analysis*, Ph.D. thesis, U. Sussex (2022).
[5] A. Zummo, *Measurement of reactor antineutrino oscillation with SNO+*, Ph.D. thesis, U. Pennsylvania (2024).
[6] Glen Cowan. Statistical data analysis. Oxford university press, 1998.