High-precision Absolute Reactor Antineutrino Flux Measurement using PROSPECT-I Data

2023 MTV Workshop

March 21, 2023

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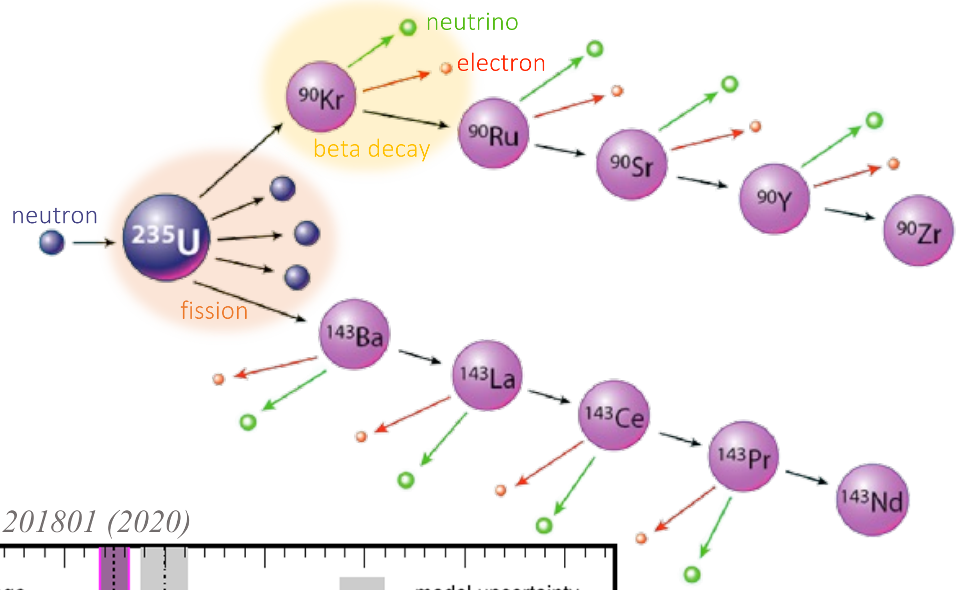
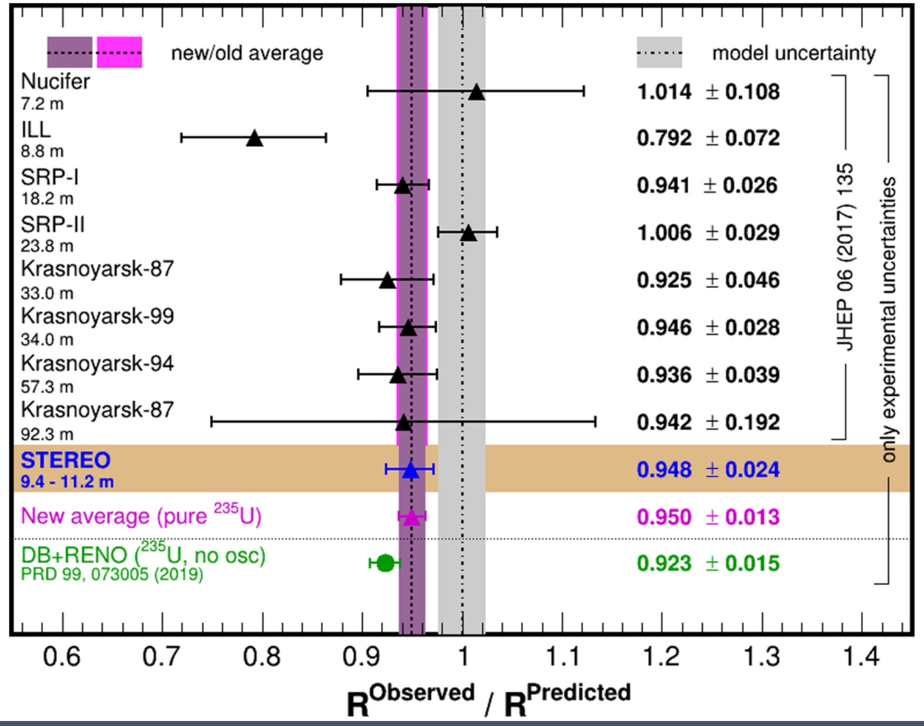
Introduction and Motivation



- Neutrinos are produced from beta decay of fission fragments inside reactor core
- They interact extremely weakly with matter
  - Cannot be shielded or spoofed
  - Can be used to monitor nuclear reactor status, thermal power, and fissile inventory in real time with a suitable detector
- We need precise information about neutrino flux
  - Measured flux and predicted flux do not agree
  - Are flux predictions overestimated?

"Reactor Antineutrino Anomaly"

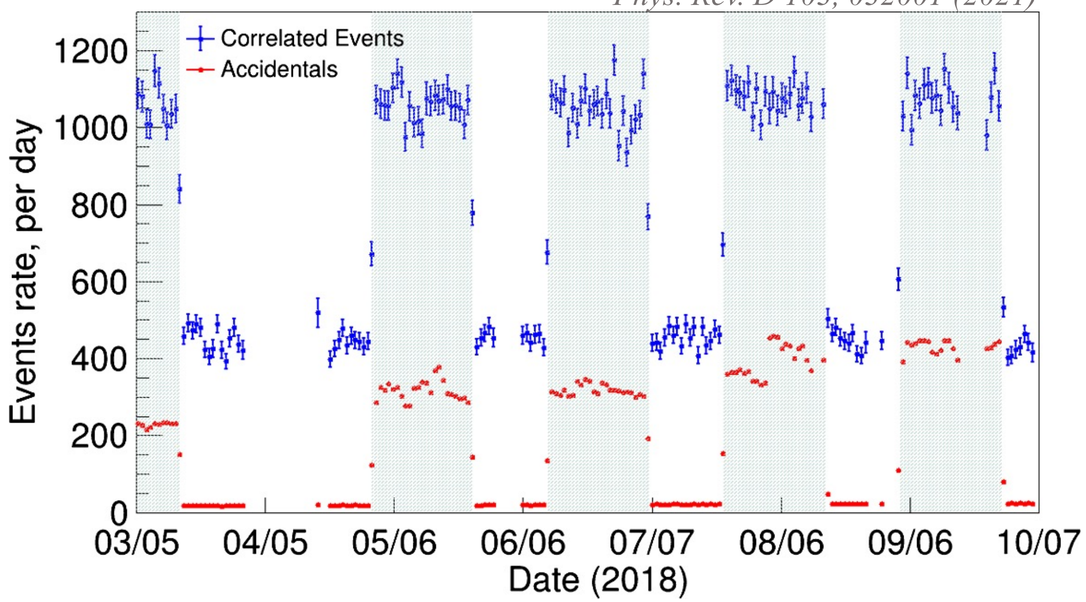
Phys. Rev. Lett. 125, 201801 (2020)

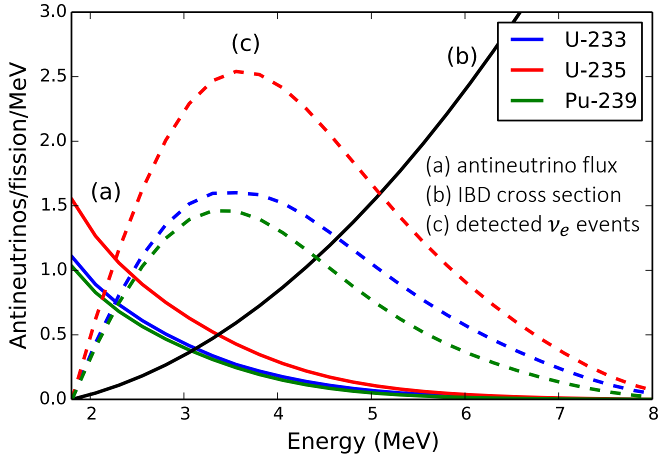


Mission Relevance

- IAEA reactor safeguards are limited in scope and depth
- Short-baseline neutrino detectors offer:
  - Less intrusive option to verify reactor operations
  - Reliable + constant monitoring technology
- We can accomplish this by precisely measuring neutrino flux from a research reactor
  - Pure ^{235}U core enables exploration of measured flux deficit
  - Directly translates to monitoring commercial reactors
- Uncertainties in existing neutrino flux production models may be improved based on high precision measurement of ^{235}U flux

Phys. Rev. D 103, 032001 (2021)





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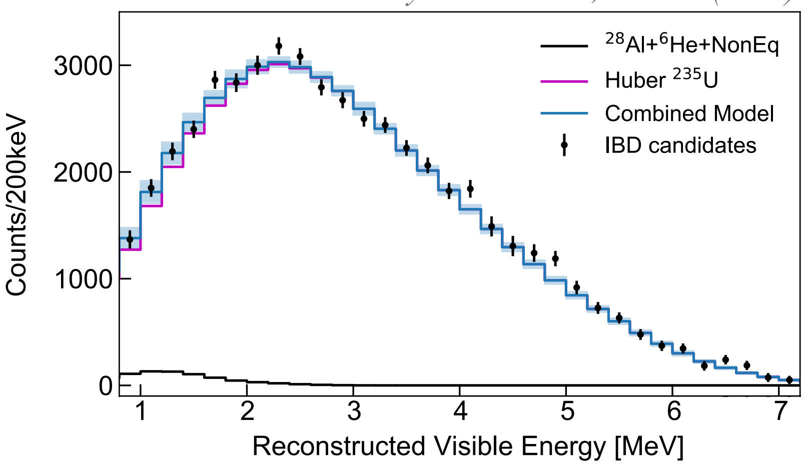
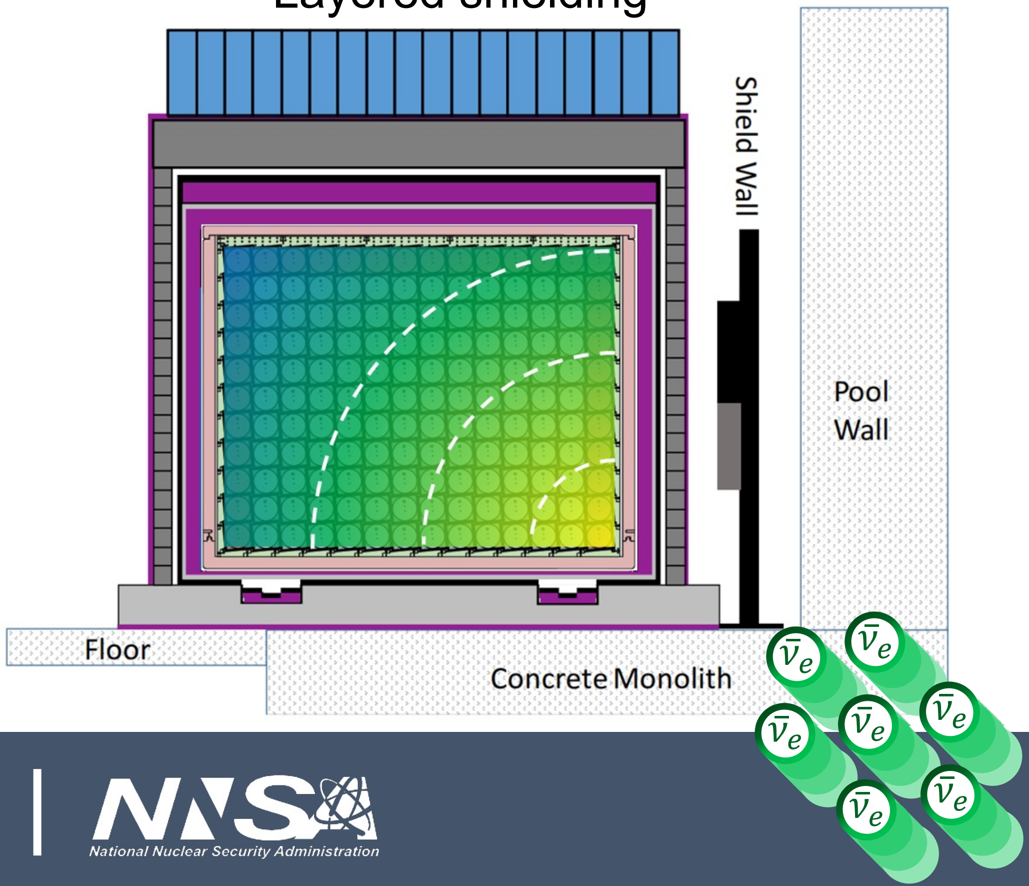


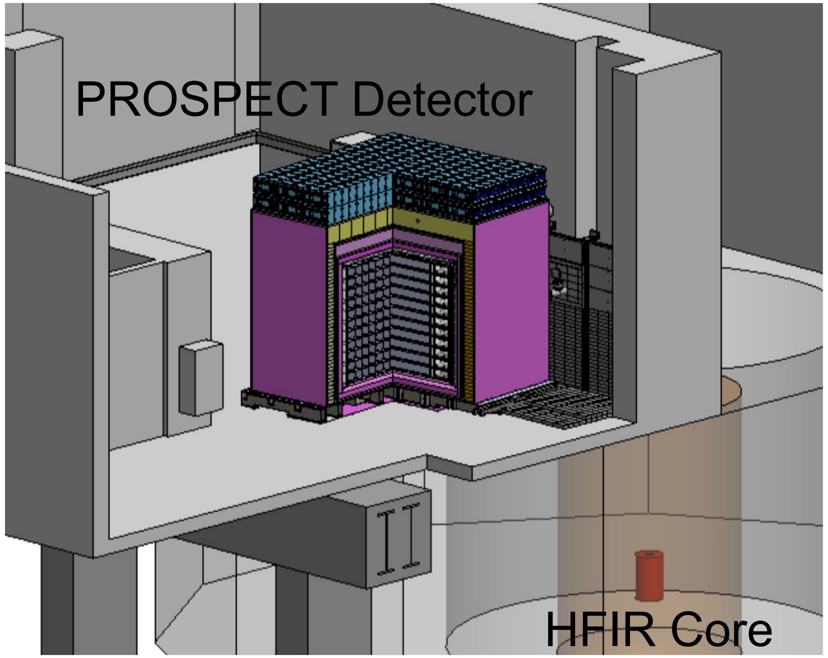
Technical Approach

- Precision Reactor Oscillation and Spectrum Experiment

Segmented liquid scintillator target

- Inverse beta decay (IBD) interactions
- Double PMT readout
- Layered shielding





High Flux Isotope Reactor (HFIR)

- 93% ^{235}U fuel
- 85 MW thermal power
- Compact core
- High flux in the few MeV range

Defining Absolute Flux

- We will compute the observed IBD cross section per fission:

$$\sigma_f^{obs} = \frac{N^{obs}}{\frac{P_{th}}{\langle E_f \rangle} \frac{N_p}{4\pi L^2} \epsilon}$$

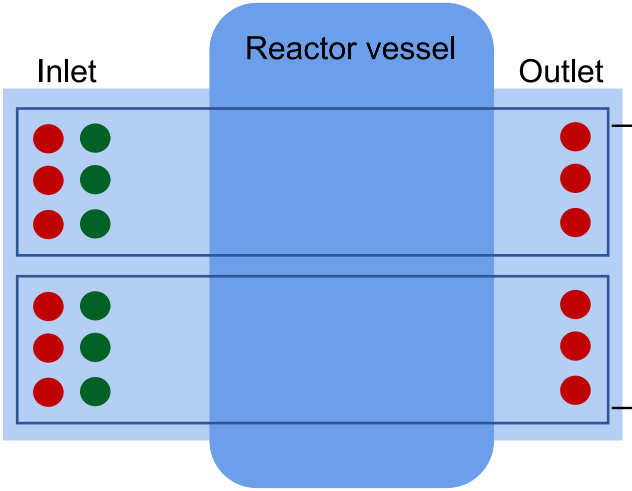
  - Total uncertainty on the flux measurement (σ_f^{obs}) is determined by propagating the uncertainties of the factors in the expression

	Parameter	Value	Uncertainty (%)
Statistical	Number of observed IBD candidates (N^{obs})		
Background systematics	Background subtraction		
Reactor systematics	Reactor thermal power (P_{th})		
	Energy released per fission (E_f)		
Signal detection systematics	Number of protons in fiducial volume (N_p)		
	Baseline (L)		
	Signal detection efficiency (ϵ)		
	Total ($\boldsymbol{\sigma_f^{obs}}$)		<2.5%

Determining number of fissions and targets

$$\sigma_f^{obs} = \frac{N^{obs}}{\frac{P_{th}}{\langle E_f \rangle} \frac{N_p}{4\pi L^2} \epsilon}$$

- Reactor thermal power: 2.14% uncertainty
  - Sensors in the primary coolant loop monitor the temperature and flow rate of coolant as it transports heat out of the core.



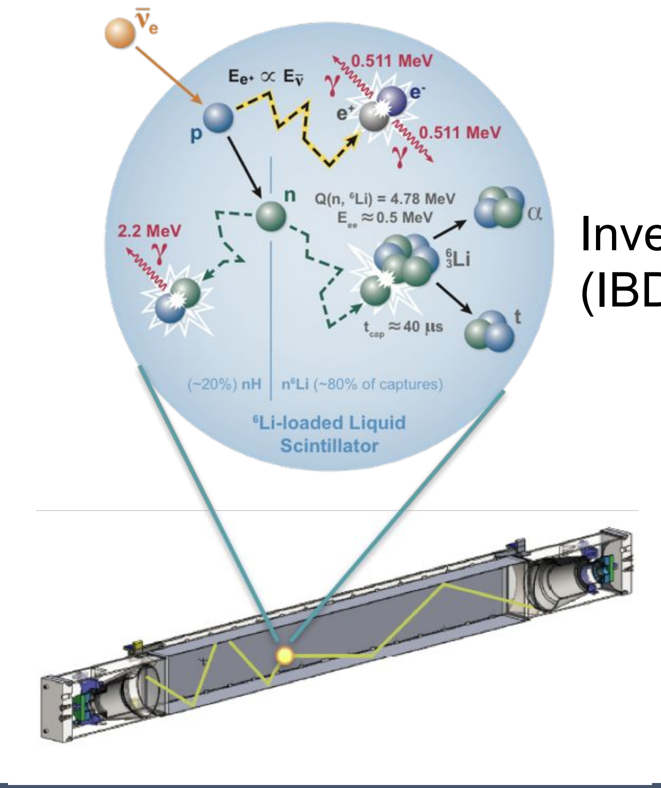
→ **Servo system**
Combine 3 uncorrelated channels → **2.14% unc.**

→ **Safety system**
Combine 3 uncorrelated channels → **1.84% unc.**

3 inlet + 3 outlet temperature sensors (RTDs) for each system
3 flow rate sensors (Venturi tubes) for each system

→ Could improve to 1.4% uncertainty.

- Target density: ~1% uncertainty
  - Average number of protons in some volume within which we know the IBD detection efficiency well.

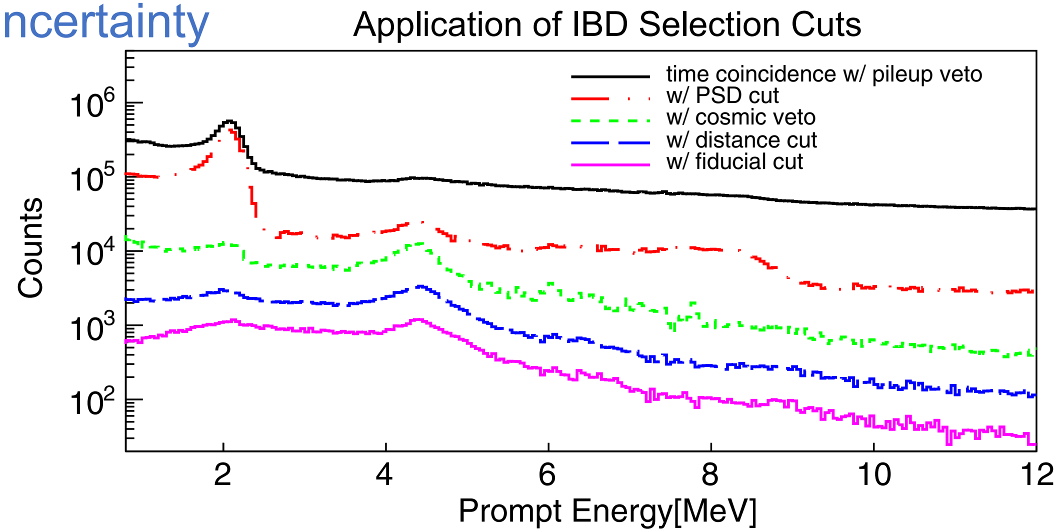


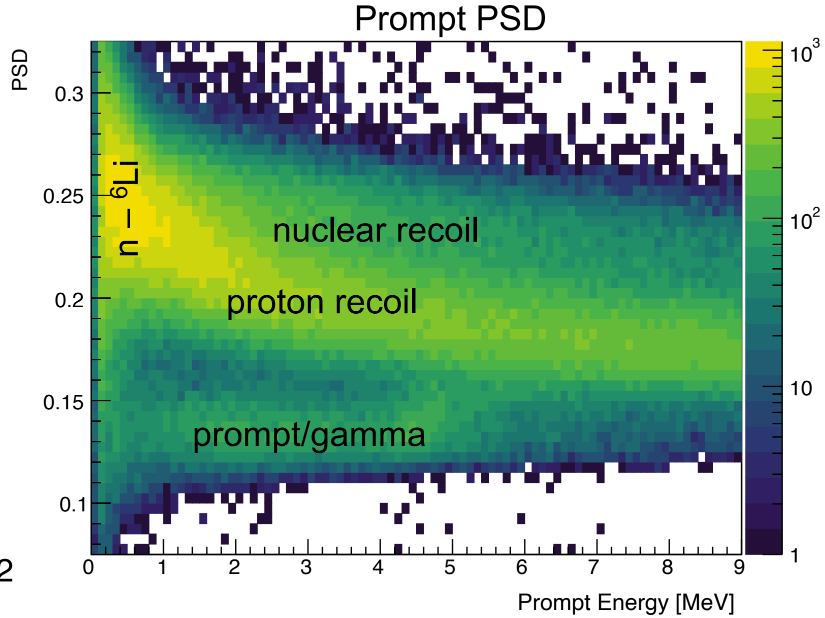
Inverse beta decay (IBD)

Signal detection efficiency: <2% uncertainty

$$\sigma_f^{obs} = \frac{N^{obs}}{\frac{P_{th}}{\langle E_f \rangle} \frac{N_p}{4\pi L^2} \epsilon}$$

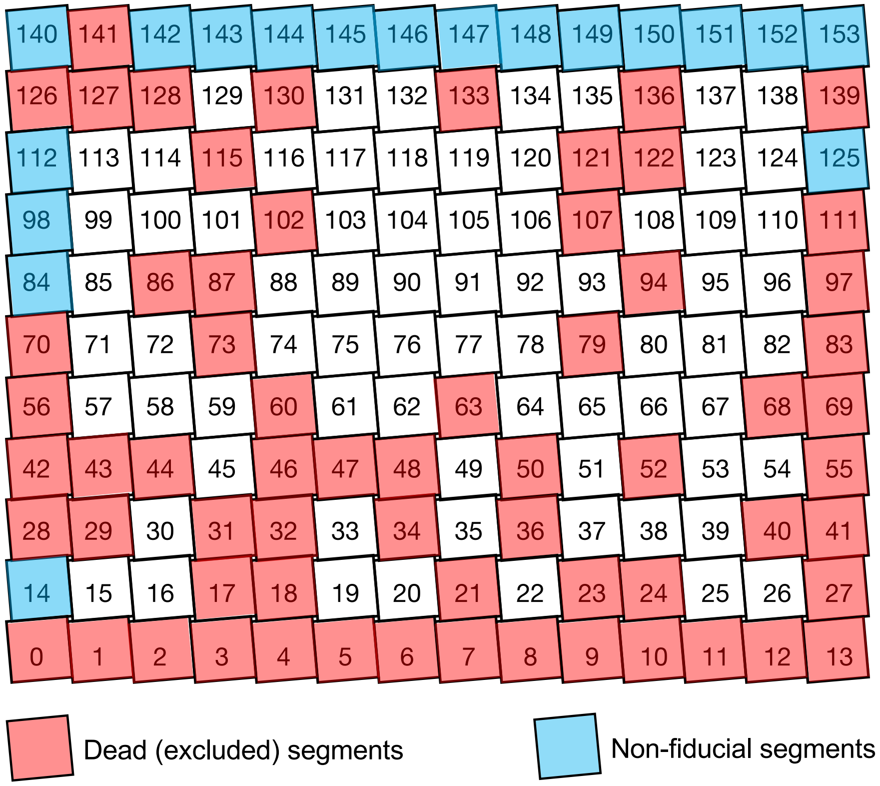
- PROSPECT detects neutrinos via inverse beta decay (IBD)
  - Prompt signal (e^+) provides good energy estimate of incident neutrino
  - Delayed localized neutron capture signal (n – ^{6}Li)
- Event selection achieved using selection cuts
  - Event timing, energy, distance, fiducial volume, pulse shape discrimination (PSD)
  - Compare data to simulation to calculate efficiency of each cut
- Optimize the cuts in order to:
  - Maximize effective statistics
  - Minimize associated uncertainty in the efficiency



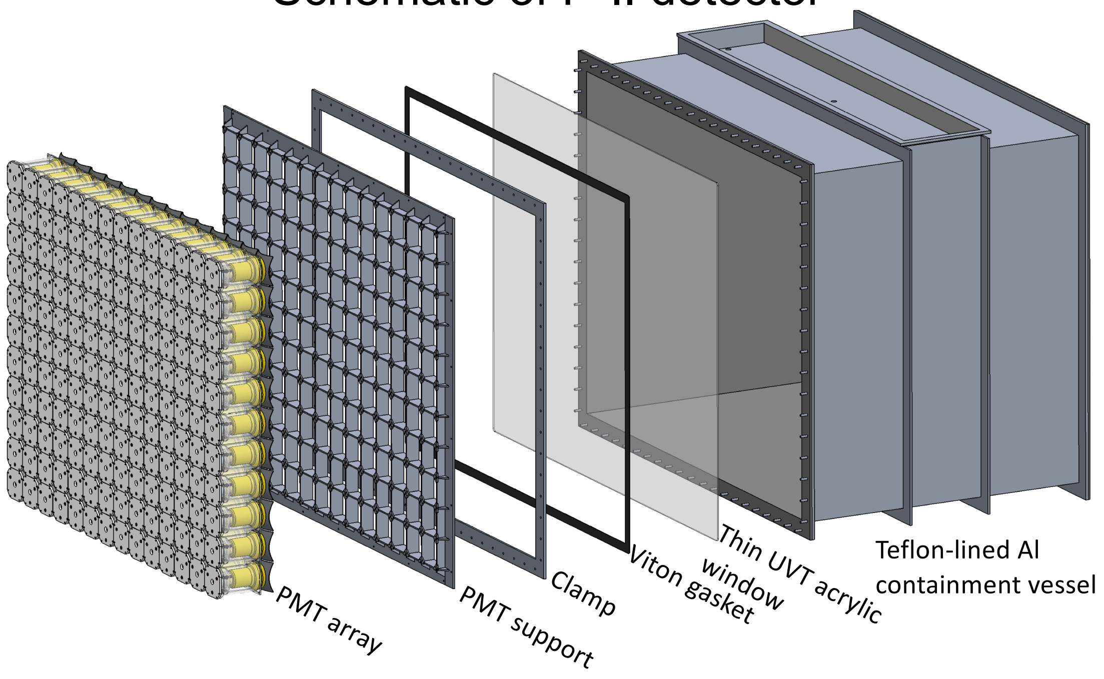


Next Steps

- Quantify impact of dead material on detection efficiency
  - Calculate uncertainty on ^{6}Li capture fraction



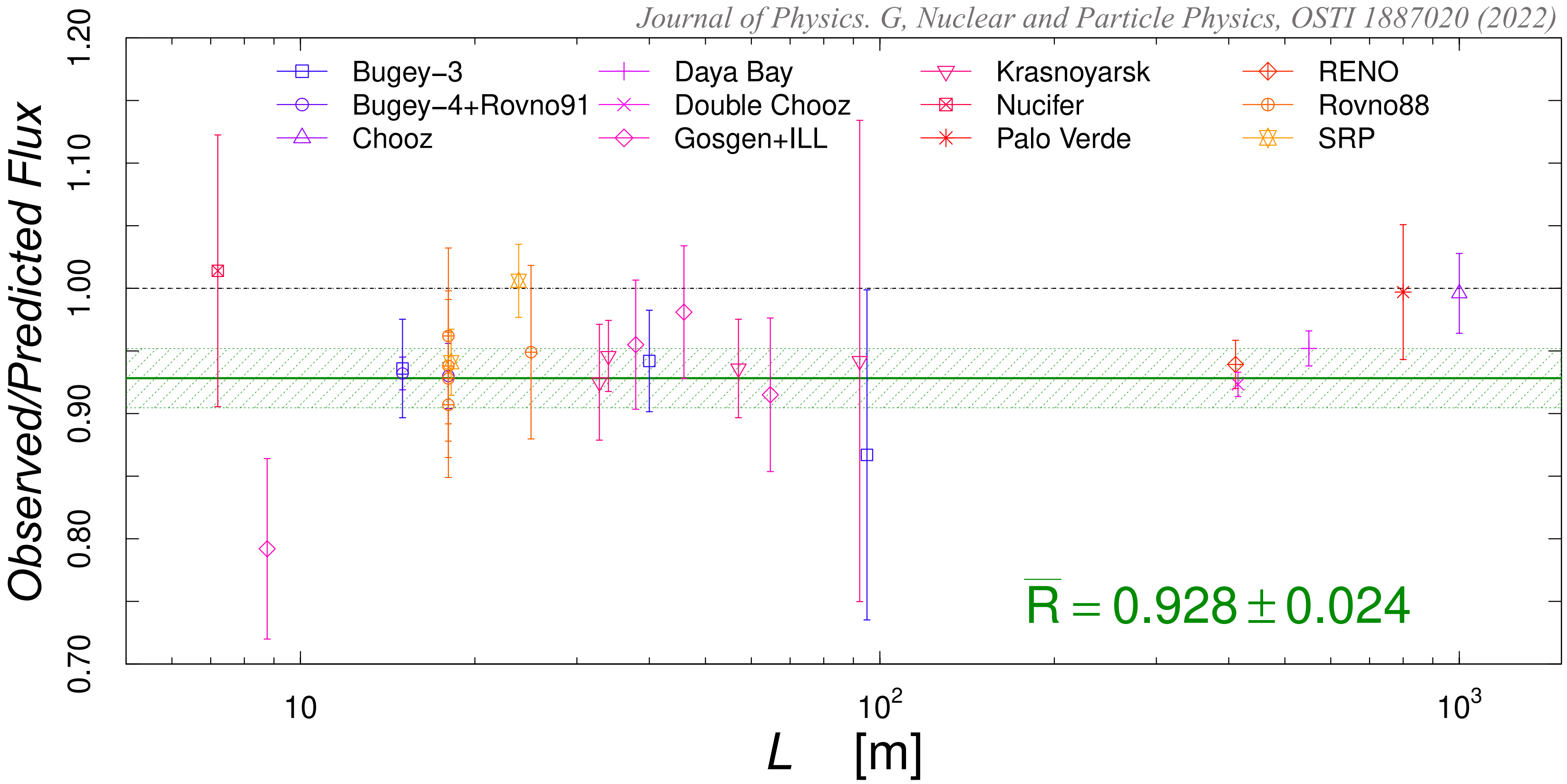
Schematic of P-II detector



- Optimize PROSPECT-II design and external calibration strategy for flux measurement
  - Apply measurement procedure to P-II data
  - Compare to applications-oriented neutrino detectors

Expected Impact

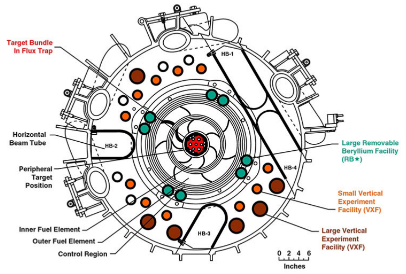
- Goal: Make a world-leading precision measurement of ^{235}U neutrino flux with <2.5% uncertainty
- Contribute to the global reactor flux picture and reactor neutrino literature



MTV Impact

- Current collaborations with national labs:
    - ORNL, LLNL, BNL, NIST
- Site visits:
    - HFIR complex at ORNL
- Past conferences:
    - INMM & ESARDA Joint Annual Meeting
    - Science, Peace, Security
    - Neutrino
    - APS DNP + DPF
- Upcoming publications:
    - The Potential of Antineutrino Detectors for Remote Reactor Monitoring, Discovery and Exclusion Applications. *The Nonproliferation Review*, 2023. A. Bernstein, F. Dalnoki-Veress, J. Hecla, P. Kunkle, J. Learned. *(under review).*
- Technology collaborations:
    - Drexel, GIT, University of Hawaii, IIT, Susquehanna, Temple, University of Tennessee, University of Waterloo, University of Wisconsin, Yale University

OAK RIDGE National Laboratory | HIGH FLUX ISOTOPE REACTOR



Conclusion

- These updates demonstrate a path toward significant improvements in decreasing piecewise uncertainty of the absolute flux measurement
- Calculate and optimize signal detection efficiency according to required event selection cuts
- Final measurement will demonstrate how well an above-ground detector can monitor the power of a research reactor
- Supports NNSA mission by using precision monitoring technology to prevent diversion of weapons-usable material from nuclear reactors

Acknowledgements

The Consortium for Monitoring, Technology, and Verification would like to thank the DOE-NNSA for the continued support of these research activities.

This work was funded by the Consortium for Monitoring, Technology, and Verification under Department of Energy National Nuclear Security Administration award number DE-NA0003920

Backup

What does an absolute flux measurement report?

- Can we look at a single isotope (^{235}U) and report the **number of antineutrinos released per fission**?
  - No → IBD experiments only detect antineutrinos above the IBD threshold ($\frac{1}{3}$ of total neutrino flux)
- Instead we can report **IBD cross section per fission $\boldsymbol{\sigma_f}$**:

$$\underbrace{\sigma_f}_{\text{IBD cross section per fission}} = \int \underbrace{S(E_\nu)}_{\bar{\nu}_e \text{ spectrum from reactor}} \underbrace{\sigma(E_\nu)}_{\text{IBD cross section}} dE_\nu$$

- We can also report the **ratio** of **observed IBD rate $\boldsymbol{\sigma_f^{obs}}$** to the **predicted IBD rate $\boldsymbol{\sigma_f^{pred}}$** using the most recent ^{235}U absolute reactor neutrino flux prediction:

$$R = \frac{\sigma_f^{obs}}{\sigma_f^{pred}}$$

→ Predicted reactor $\bar{\nu}_e$ energy spectra based on new measurements of β spectra from ^{235}U performed at a research reactor at Kurchatov Institute in Russia

- Expectation: Observed flux and predicted flux be consistent within error bars

Deriving σ_f^{obs}

Given $\bar{\nu}_e$'s emitted isotropically from fission products of ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu. The number of $\bar{\nu}_e$ with energy E_ν emitted from a reactor at time t can be predicted using:

$$\frac{d^2\phi(E_\nu,t)}{dE_\nu dt} = \frac{P_{th}(t)}{\sum_i f_i(t)\langle E_f\rangle_i}\sum_i f_i(t)S_i(E_\nu)c_i^{NE}(E_\nu,t) + S_{SNF}(E_\nu,t) \quad (1)$$

Where the sums are over ^{235}U, ^{238}U, ^{239}Pu, ^{241}Pu.

- P_{th}: Reactor thermal power
- f_i: Fission fraction due to isotope i
- $\langle E_f\rangle_i$: Average thermal energy released per fission
- $S_i(E_\nu)$: $\bar{\nu}_e$ energy spectrum per fission
- c_i^{NE}: Correction to the energy spectrum due to reactor non-equilibrium effects using long-lived fission fragments
- S_{SNF}: Contribution from spent nuclear fuel (SNF)

Simplifying for PROSPECT with only ^{235}U fission over a specific runtime t and negligible SNF contribution gives the differential $\bar{\nu}_e$ rate to be

$$\frac{d\phi(E_\nu)}{dE_\nu} = \frac{P_{th}}{\langle E_f\rangle}S(E_\nu)c^{NE}(E_\nu) \quad (2)$$

The total number of detected IBD events N^{obs} can be estimated as

$$N^{obs} = \frac{N_p}{4\pi L^2}\epsilon\int P_{sur}(E_\nu,L)\sigma_{IBD}(E_\nu)\frac{d\phi(E_\nu)}{dE_\nu}dE_\nu \quad (3)$$

- $\sigma_{IBD}(E_\nu)$: IBD cross section
- L: Distance between detector center and reactor core
- $P_{sur}(E_\nu,L)$: Survival probability due to neutrino oscillation
- N_p: Number of target protons
- ϵ: IBD signal detection efficiency

Plugging in (2) to (3) gives

$$N^{obs} = \frac{P_{th}}{\langle E_f\rangle}\frac{N_p}{4\pi L^2}\epsilon\int S(E_\nu)\, c^{NE}(E_\nu)\, P_{sur}(E_\nu,L)\, \sigma_{IBD}(E_\nu)\, dE_\nu \quad (4)$$

Redefining $S(E_\nu)$ to absorb $P_{sur}(E_\nu,L)$ and $c^{NE}(E_\nu)$ terms and dividing on both sides by the prefactor gives

$$\boxed{\frac{N^{obs}}{\frac{P_{th}}{\langle E_f\rangle}\frac{N_p}{4\pi L^2}\epsilon} = \int S(E_\nu)\sigma_{IBD}(E_\nu)dE_\nu = \sigma_f^{obs}}$$

which is the **observed IBD cross section per fission** we will report.

National Nuclear Security Administration

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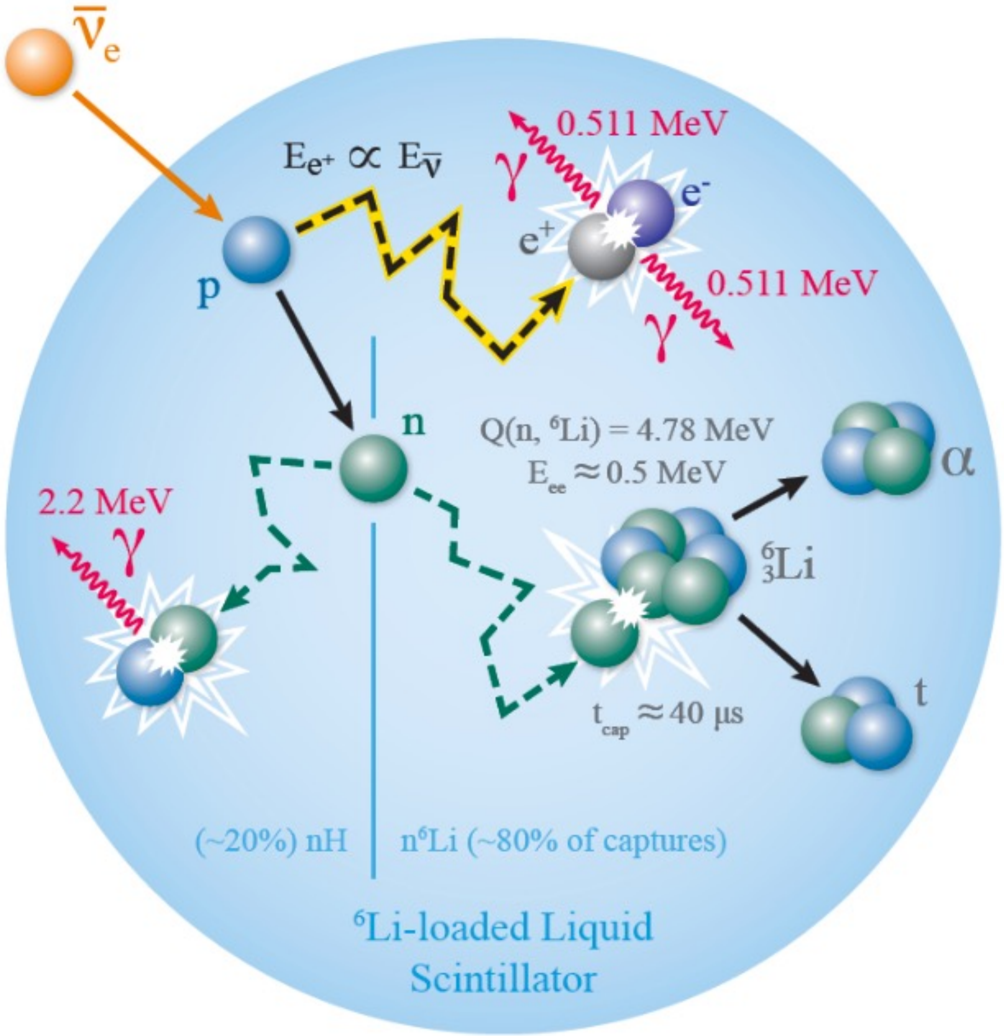
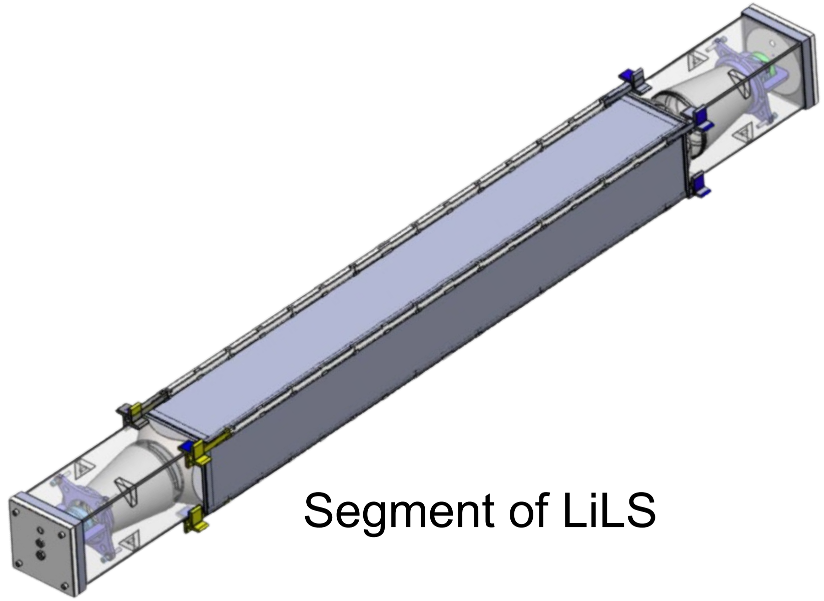
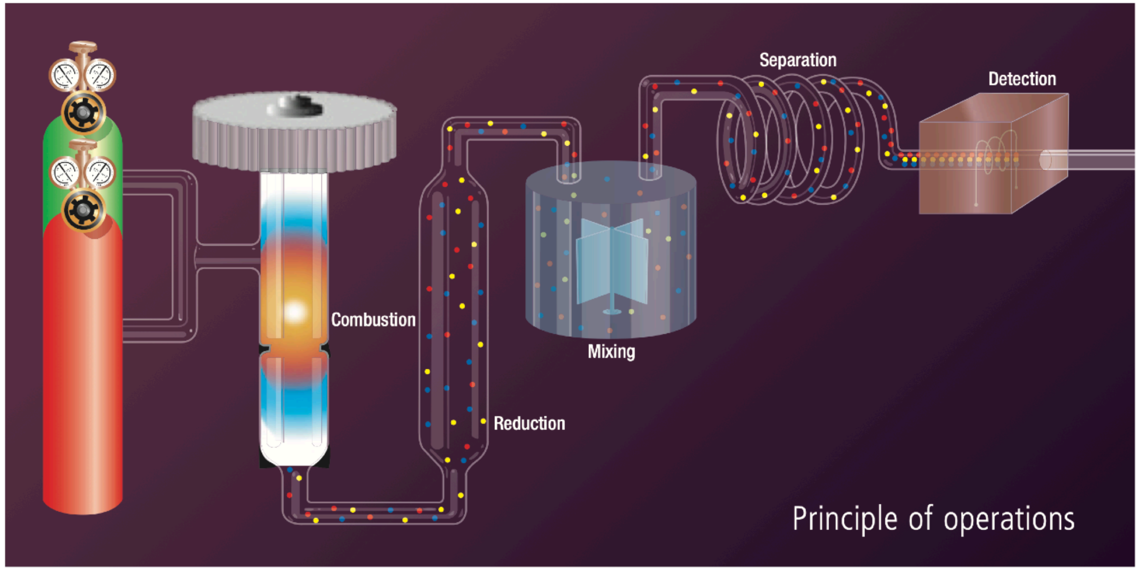
Inverse Beta Decay (IBD)





Segment of LiLS

Proton density: Combustion measurements



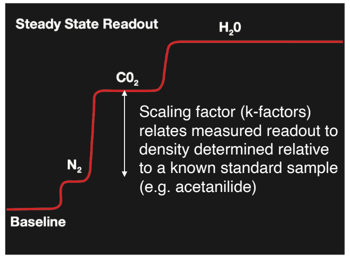
1) Sample is combusted completely in pure Oxygen and reduced to the elemental gases CO_2, H_2O, N_2 and SO_2. Various catalysts aid the process

2) Gases are rapidly mixed and precisely maintained at controlled conditions of pressure, temperature and volume. Gases are mechanically homogenized

3) Separation via Frontal Gas Chromatography

4) Gas measured by a thermal conductivity detector

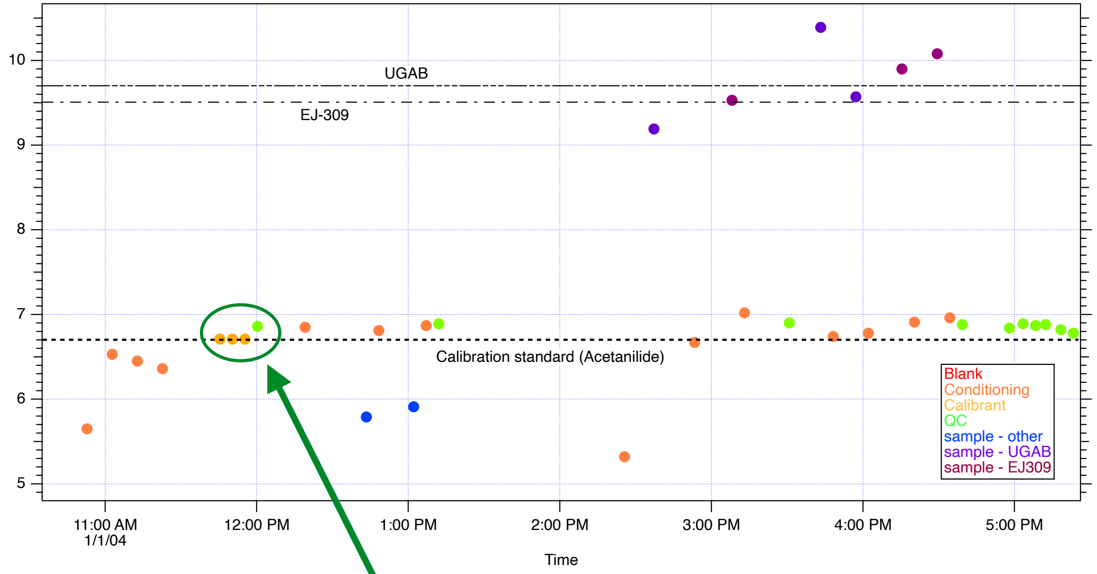
The PerkinElmer
2400 CHN Elemental Analyzer



To obtain a wt %, need to know: baseline and ‘K-factors’

Measurement sequence

- ‘Blanks’ to determine baseline
- Reference samples to determine calibration
- 2nd reference sample to validate calibration
- Samples interspersed w/ conditioning runs



Discrepancy between standard and reference (both acetanilide)
Suggests problem with calibration curve - standard practice is to adjust normalization not shape
Possible systematic at the % level