VIRGINIA TECH

The Center for Neutrino Physics

Near-Field Reactor Neutrino Applications

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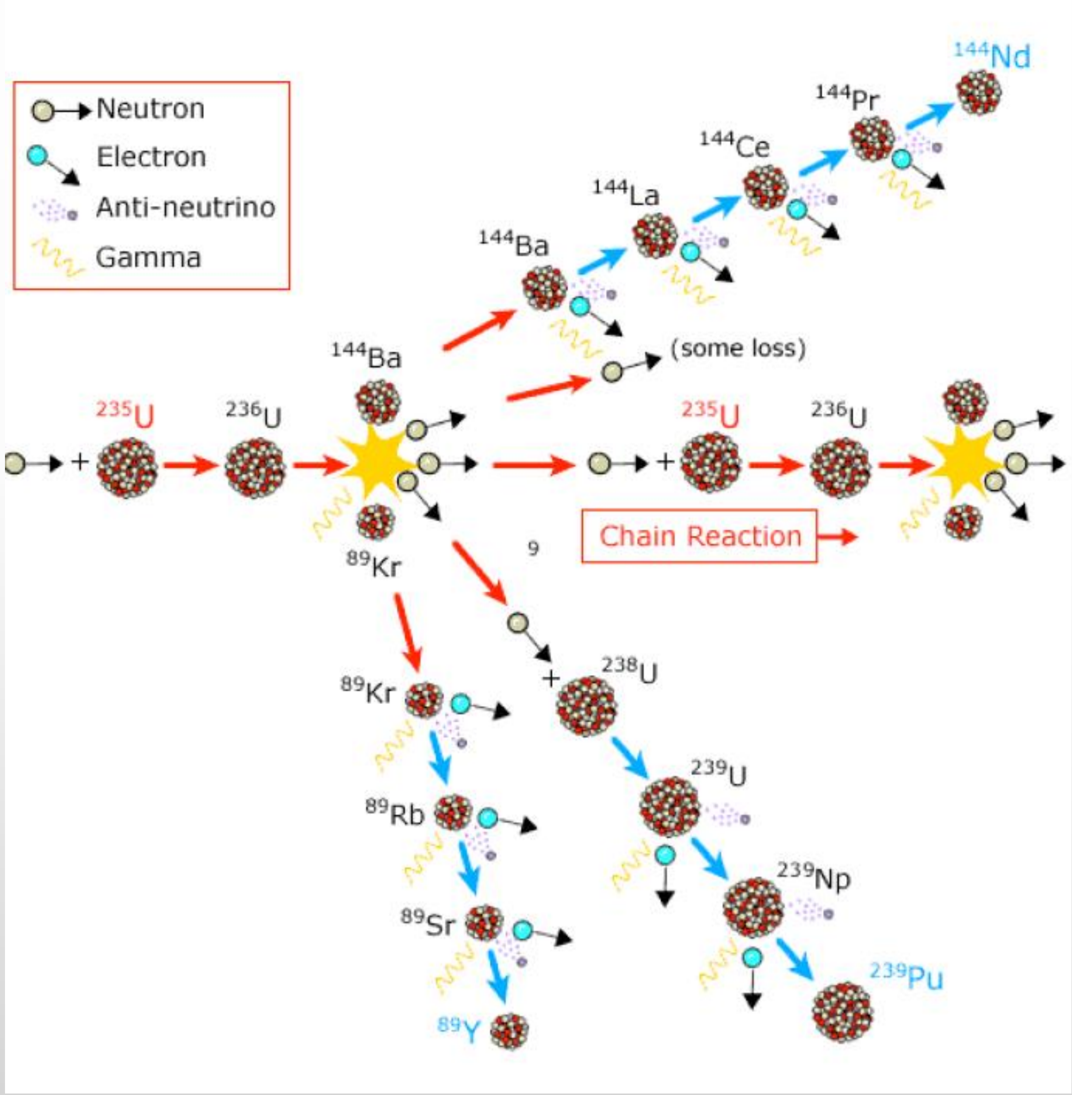
CNP Research Day, December 13th, 2024

Antineutrinos from the Reactors

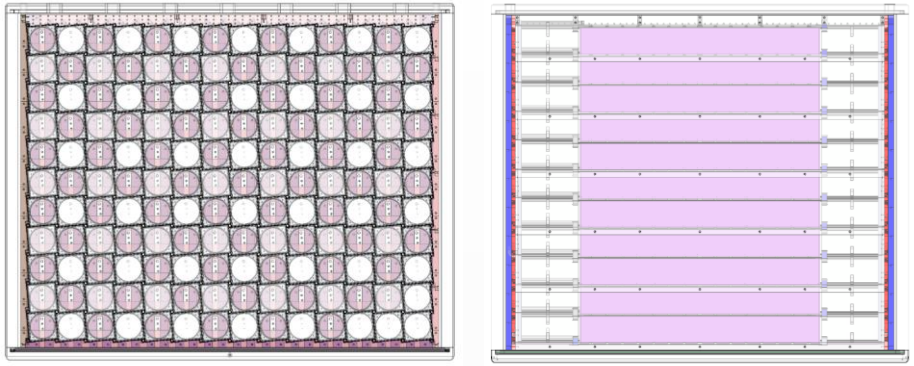
- 1 GW$_{\text{th}}$ reactor produces about $2 \cdot 10^{20}\, \bar{\nu}_e/sec$
- The first neutrino was discovered in reactor experiment at Savannah River (1956)
- Reactor experiments led neutrino physics to a precision era and enable accurate measurements of neutrino oscillations parameters ($\theta_{12},\ \Delta m^2_{21},\ \theta_{13},\ \Delta m^2_{31}$)
- Most nuclear reactors have 4 isotopes in the fuel: $^{235}U, ^{239}Pu, ^{241}Pu, ^{238}U$

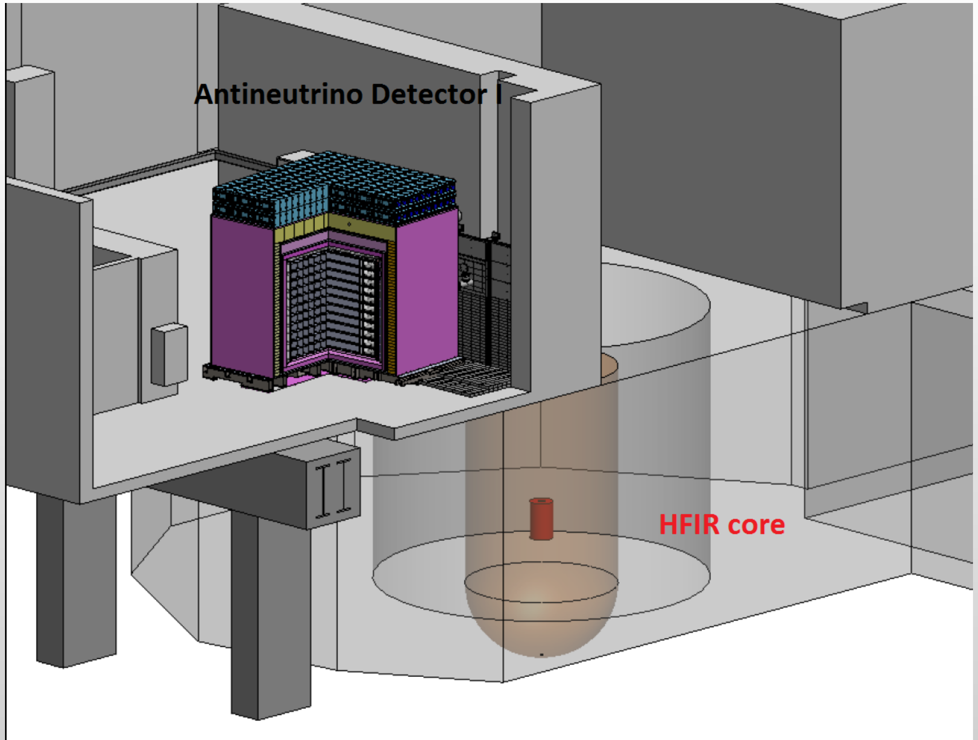


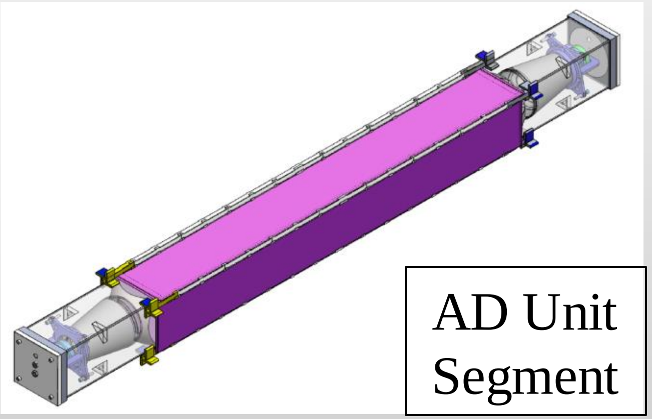
US Near-Field Surface Reactor Antineutrino Experiments: PROSPECT and CHANDLER

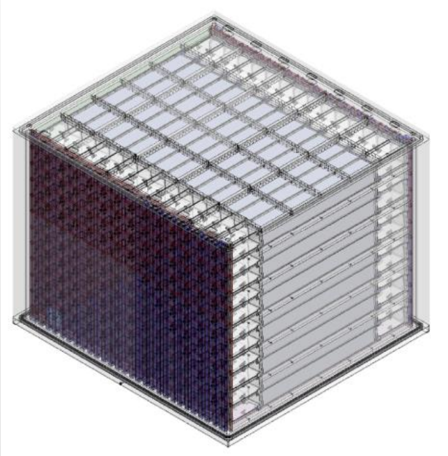
PROSPECT: Detector Design

- PROSPECT – **P**recision **R**eactor **O**scillation and **SPECT**rum Experiment
- 8 m from the reactor core: high background from the reactor
- 11 x 14 (154) array of optical segments of liquid scintillator, size - 119x15x15 cm^3, double-ended PMT readout
- 3.8 tons of ^{6}Li-loaded EJ-309 liquid scintillator developed by PROSPECT collaboration
- Pulse-shape discrimination, high light yield and high energy resolution
- Was deployed at High Flux Isotope Reactor (HFIR) – highly enriched ^{235}U reactor at Oak Ridge National Lab









J. Ashenfelter et al., arXiv:1512.02202v1

Antineutrino Detection

- Search for $\bar{\nu}_e$ through inverse beta decay (IBD) mechanism:

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

- 1-10 MeV prompt signal – annihilation of positron:

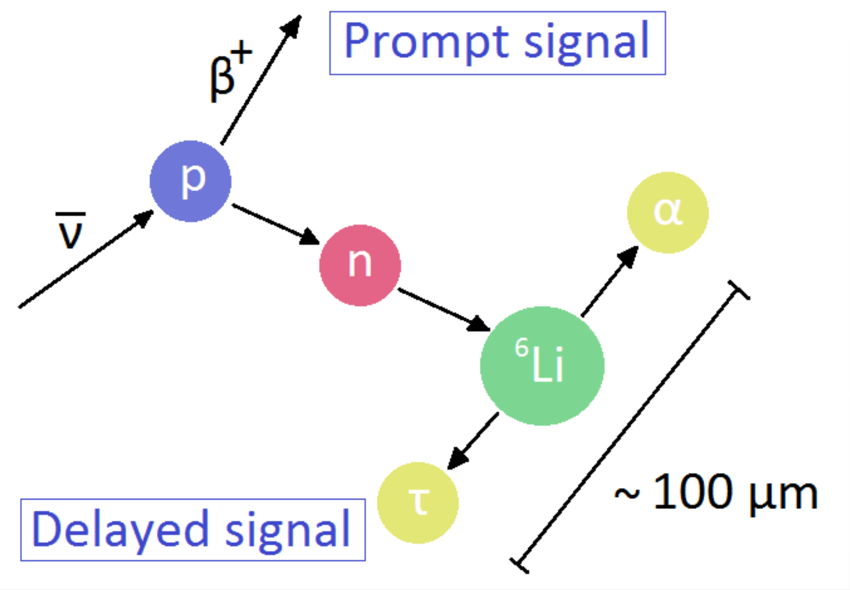
$$e^+ + e^- \rightarrow \gamma + \gamma$$

- ~0.5 MeV delayed signal – from neutron capture on ^{6}Li:

$$n + {}^6Li \rightarrow \alpha + {}^3_1H$$

- Distinctive tag: $t < 100\mu s$ delay in neutron capture
- Strong background rejection due to coincident signature, topological cuts and pulse shape discrimination (PSD) ability of liquid scintillator

IBD reaction in LiLS

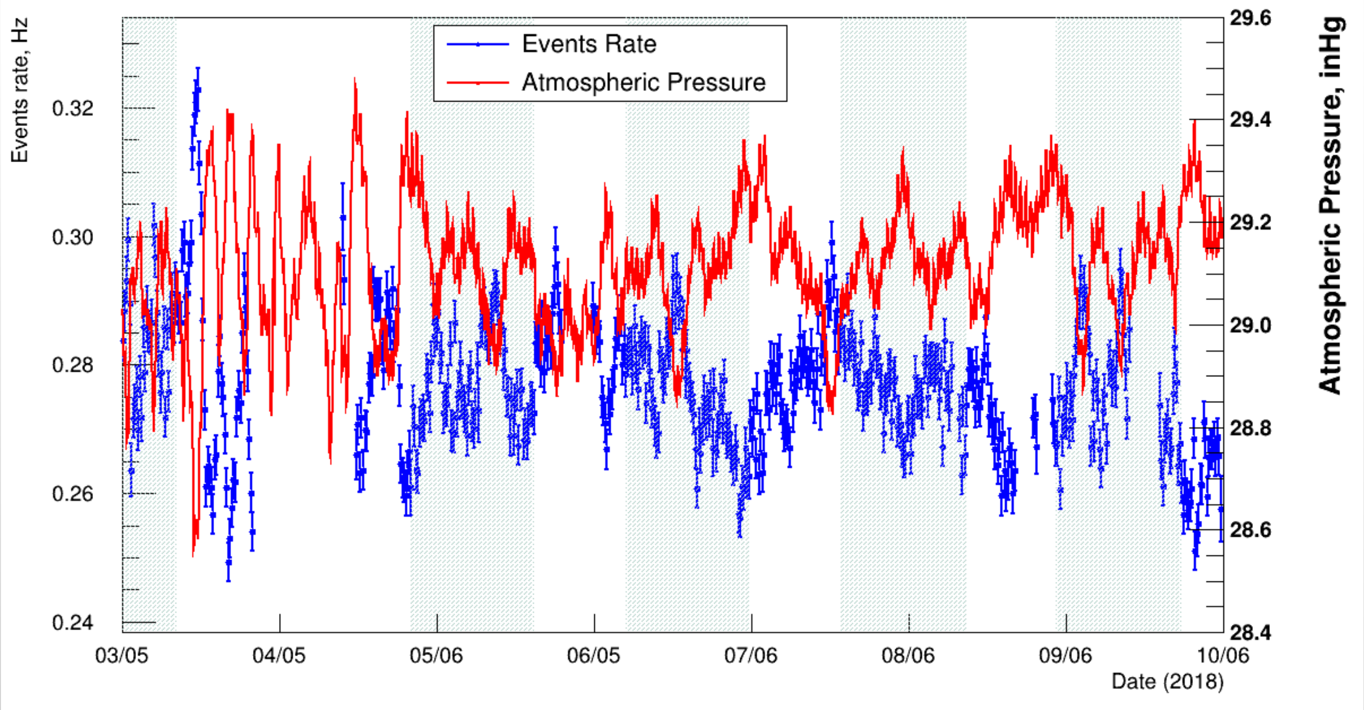


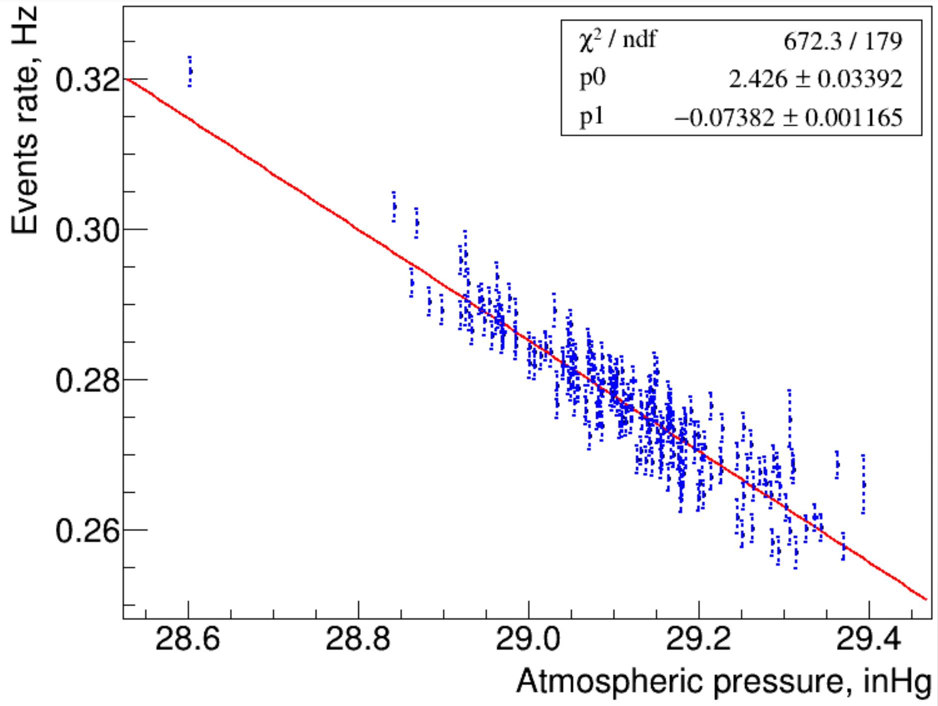
One triggered event – <u>pulse</u>; pulses are combined into <u>clusters</u> of events within 20 ns of time of arrival

<u>Single events</u>: prompt single event, delayed single event
<u>Coincidence events</u>: prompt single event + time period/distance condition + delayed single event

PROSPECT: Background

- Neutron recoil (cuts the same as for recoil-like event) that subsequently follows by capture on ^{6}Li.
- Neutron capture cut is the same as for delayed-like neutron candidates. Coincidence cuts are the same as for IBD
- Shows great dependence with atmospheric pressure and no different between reactor on and reactor off periods. Pure cosmogenic background

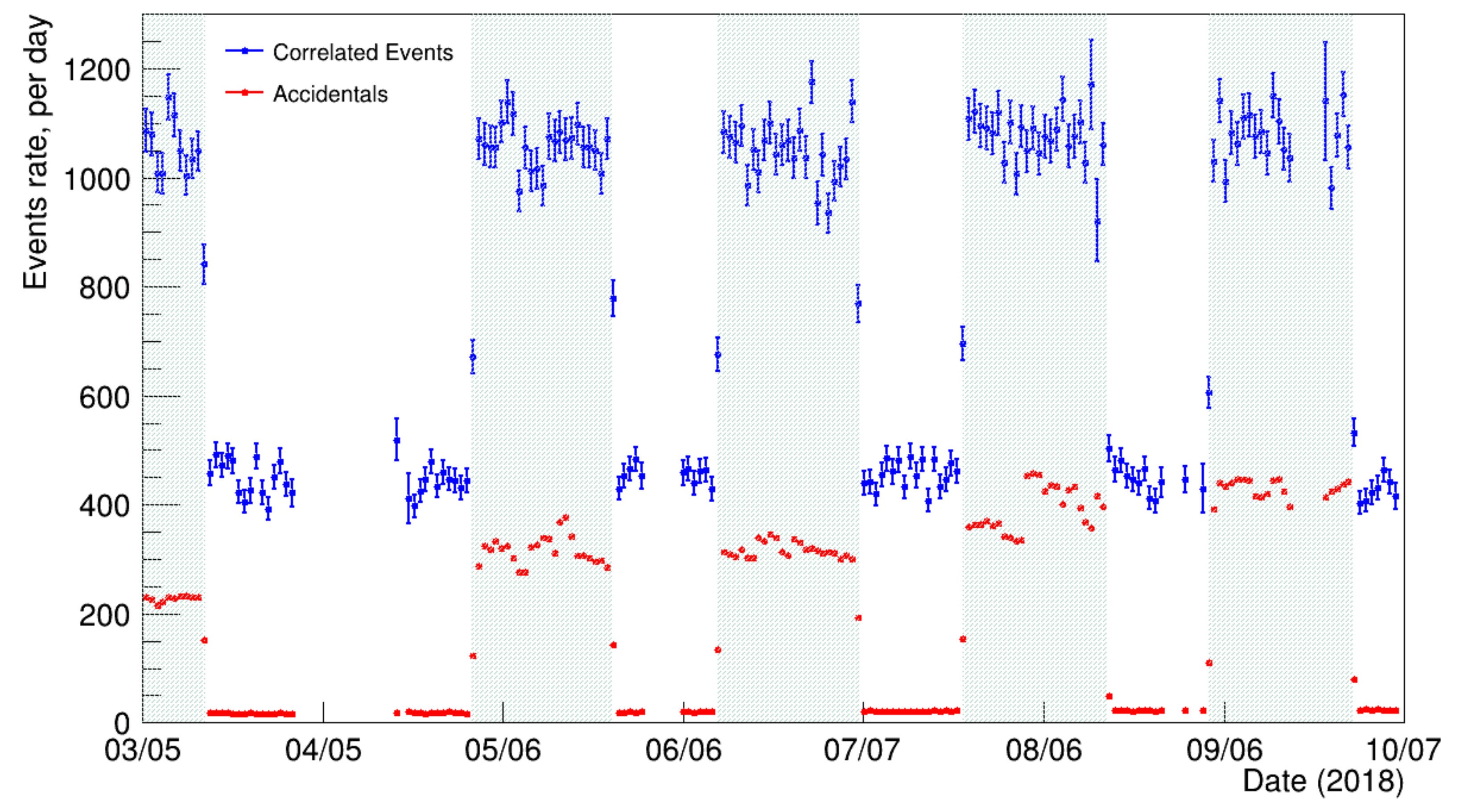




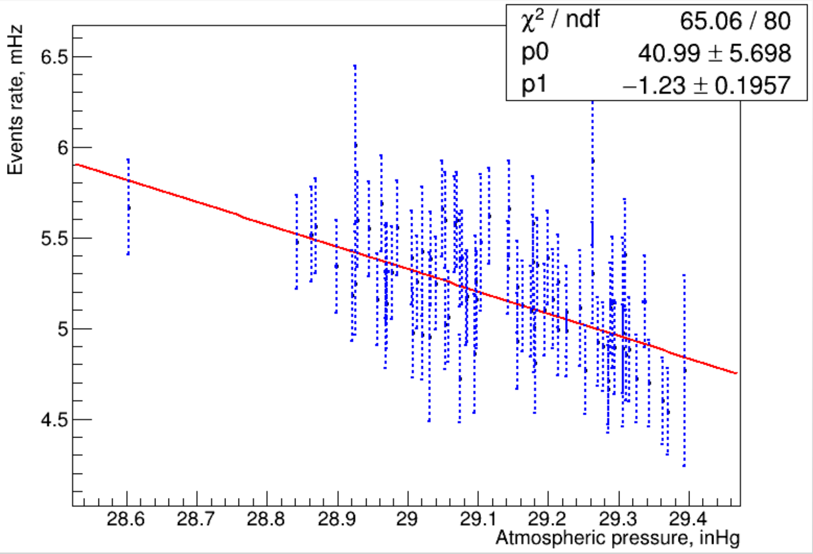
PROSPECT: Results

- Accidental coincidences rates are calculated by the reversal delayed-like event + prompt-like event and the accidental rate is subtracted from IBD rate

The ratio of IBD to accidentals is 1.78. The ratio of IBD to cosmogenic background is 1.37

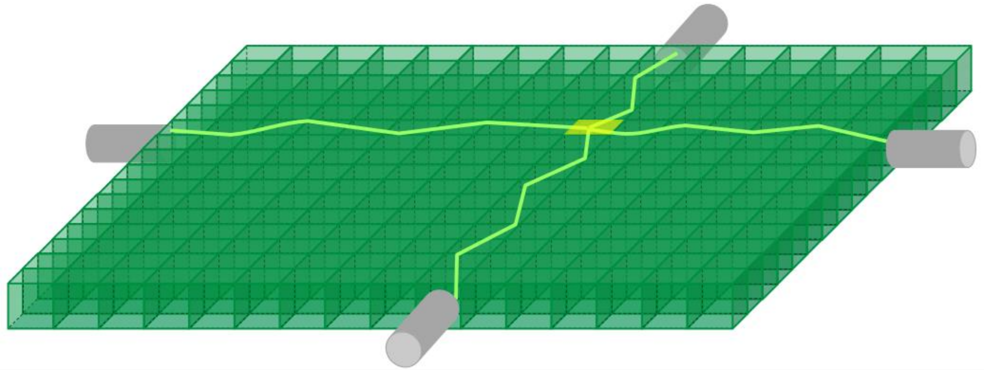


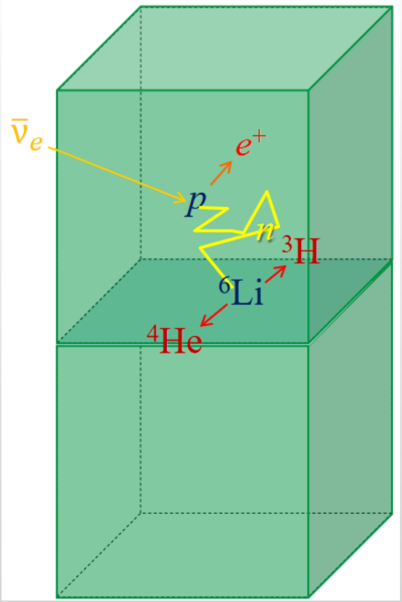
$$BG^{subtr}_{RxOff} = \frac{t_{On}}{t_{Off}} \cdot BG^{initial}_{RxOff} \cdot \frac{a\bar{P}_{On} + b}{a\bar{P}_{Off} + b}$$

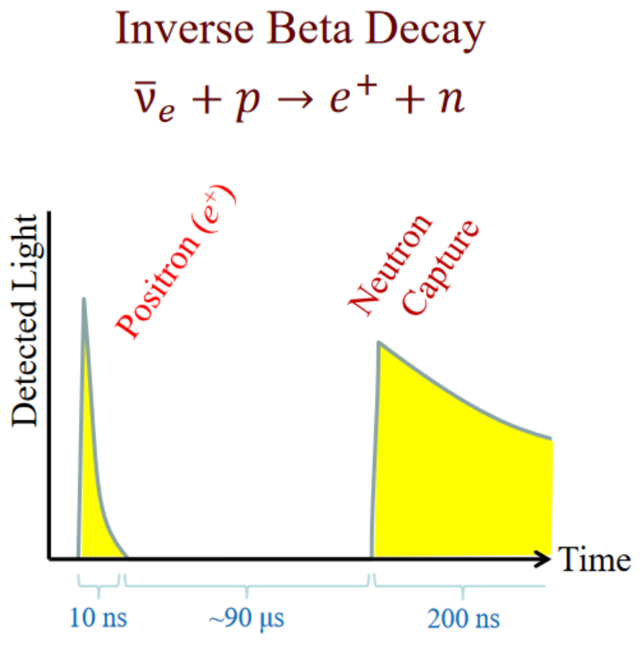


CHANDLER: Technology Design

- CHANDLER – **C**arbon **H**ydrogen **A**nti**N**eutrino **D**etector with a **L**ithium **E**nhanced **R**aghavan-optical-lattice
- **Raghavan Optical Lattice** (ROL) – detector technology that transports light by total internal reflection along columns and rows of cubic cells
- 3D segmentation: solid plastic cubes of wavelength-shifting scintillator with a size of 6.2 cm; no liquid scintillator
- Between the layers of cubes – thin sheets of ^{6}LiF and ZnS:Ag scintillator to detect thermal neutrons
- Prompt signals are produced in the cubes; delayed neutron captures – in the sheets
- Decay constant of plastic scintillator: ~10 ns; decay constant of ZnS:Ag scintillator: ~200 ns
- This difference enables identification of positrons and neutrons

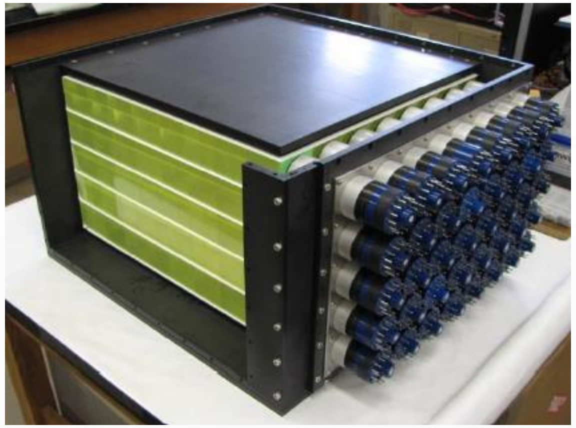


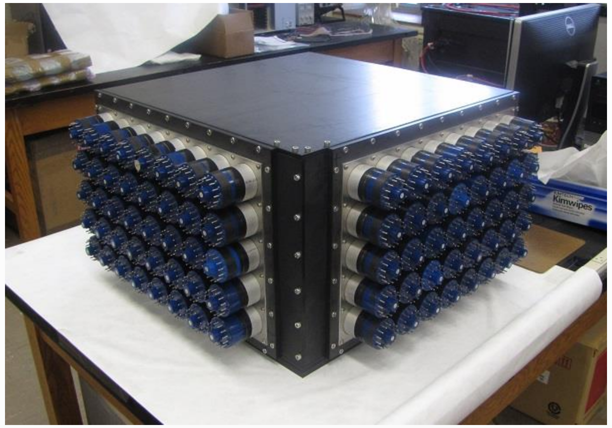




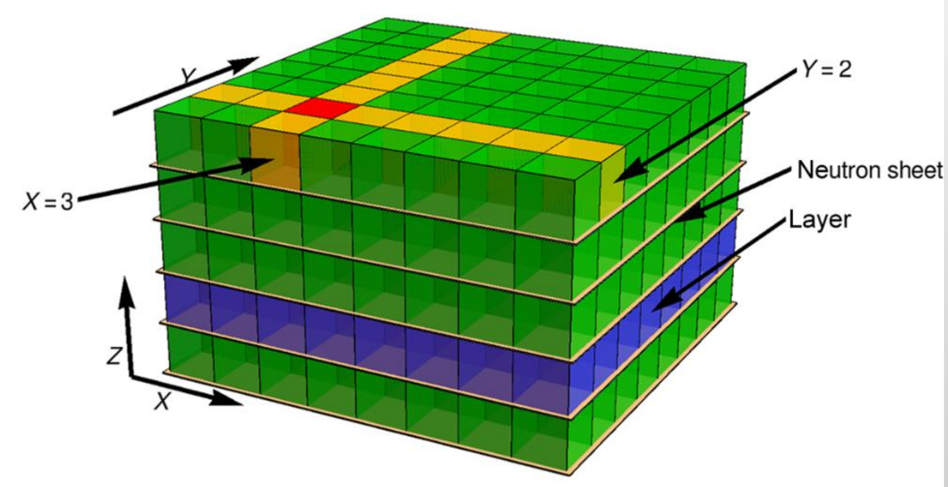
MiniCHANDLER

- 80 kg prototype of CHANDLER
- 8 × 8 × 5 array of cubes and 6 neutron sheets
- PMTs on one end of each column and row of cubes
- 14 ft trailer that has quiet power supply, Wi-Fi, AC
- Deployed at 25 m from the center of reactor core number 2 at North Anna Nuclear Power Plant, taking data from June to November 2017



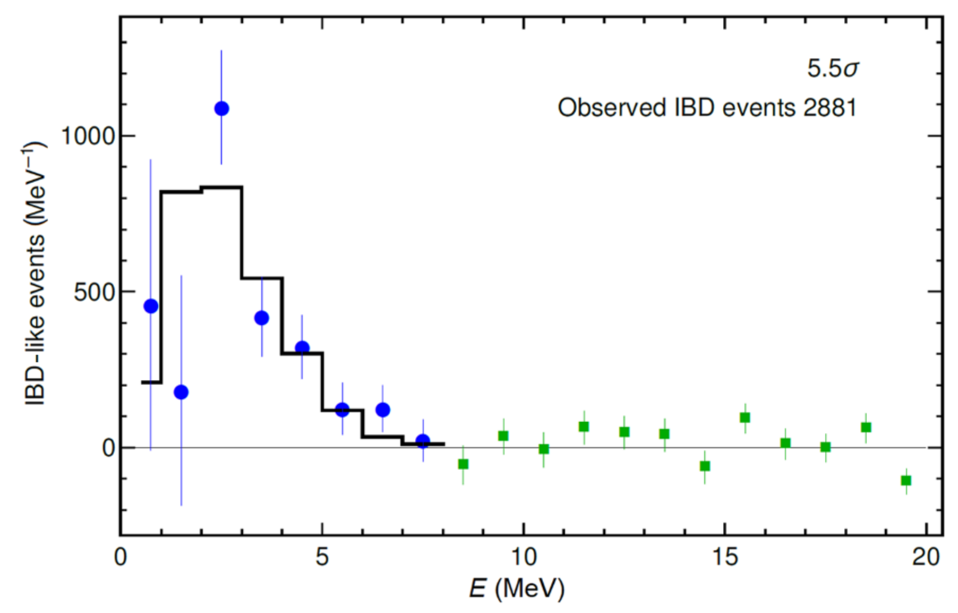


A. Haghighat et al., Phys. Rev. Applied 13, 034028 (2020)



MiniCHANDLER Results

- 2 reactor-on periods + 1 reactor-off period
- Observed 5.5 σ excess of IBD-like events in reactor-on with respect to reactor-off
- The first observation of neutrinos with a mobile detector
- The first observation of reactor neutrinos with an essentially unshielded detector
- The first successful use of a Raghavan Optical Lattice



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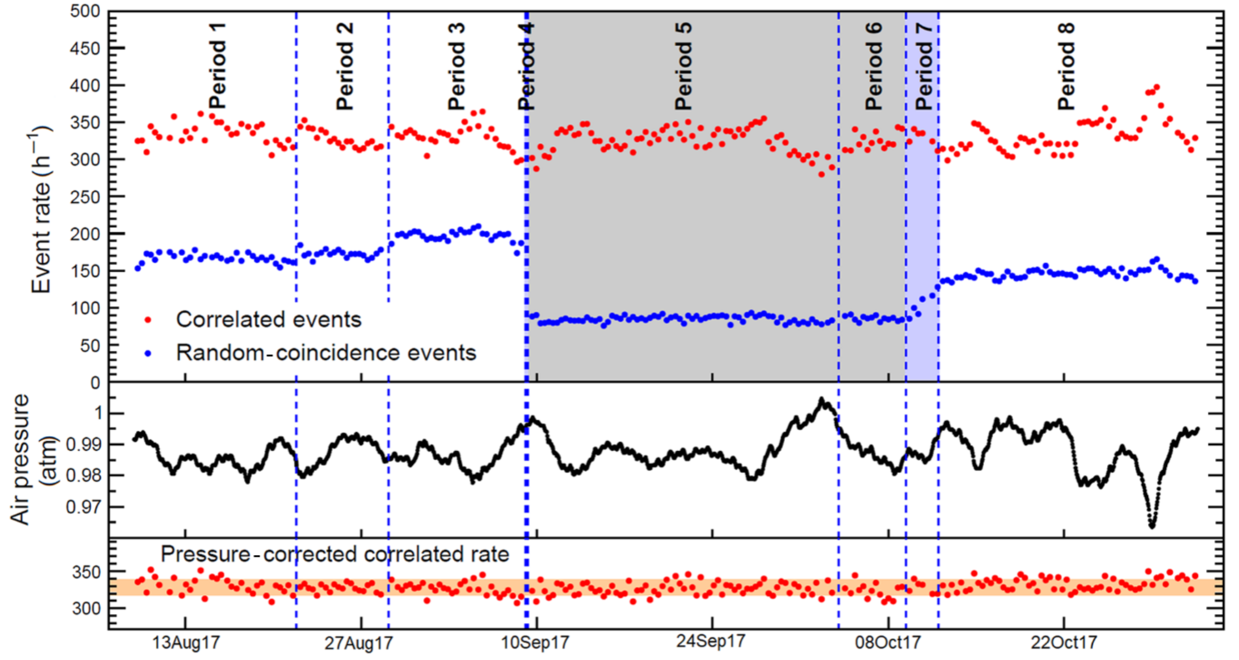
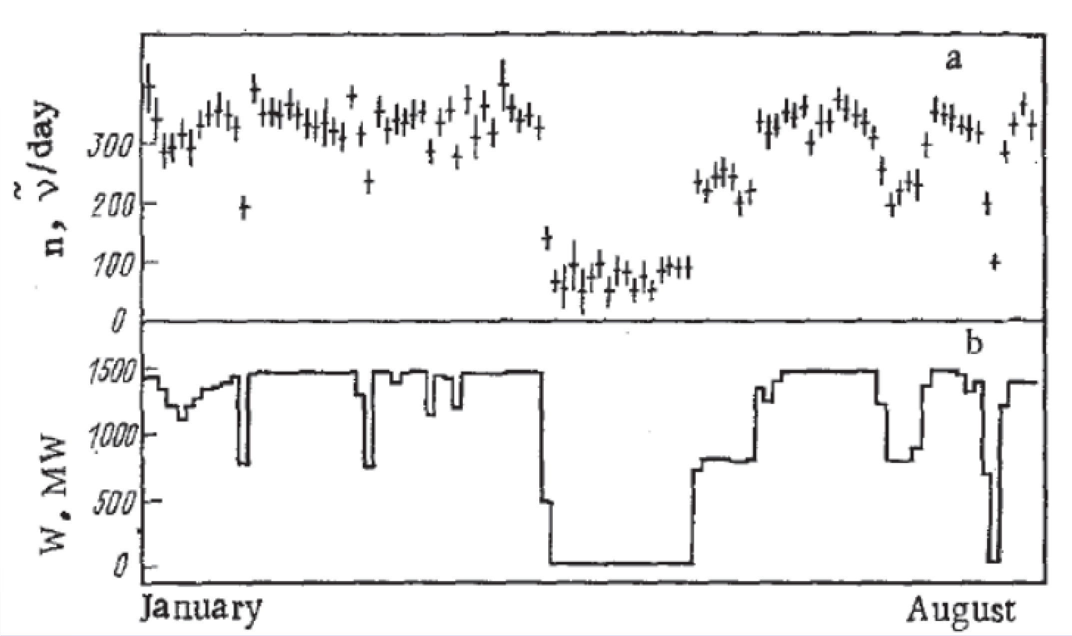


Applied Antineutrino Physics

For nuclear safeguards and nonproliferation

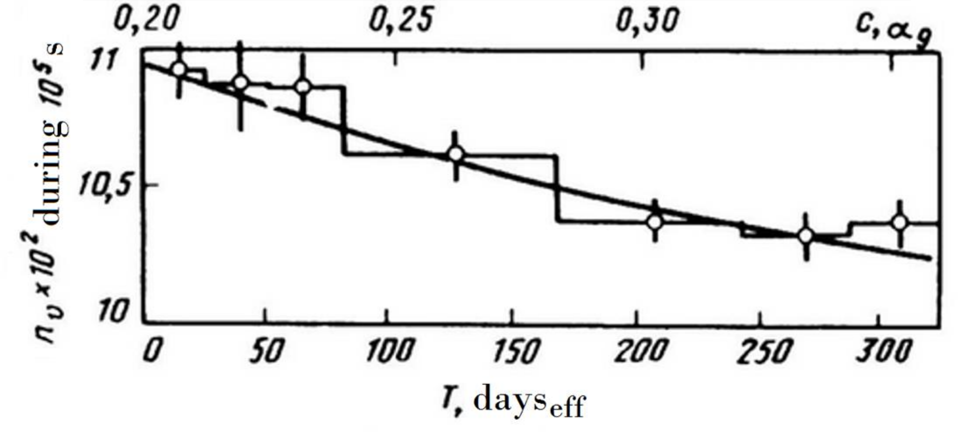
Neutrinos for Reactor Safeguards: History

- First suggested in mid-70s
- **Rovno experiment**: 18 m from the reactor core; USSR; 1986
- Neutrino flux is proportional to reactor power if the fuel composition does not change
- However, the fuel composition changes with time – ^{235}U decreases, and ^{239}Pu increases
- Antineutrino spectrum also changes

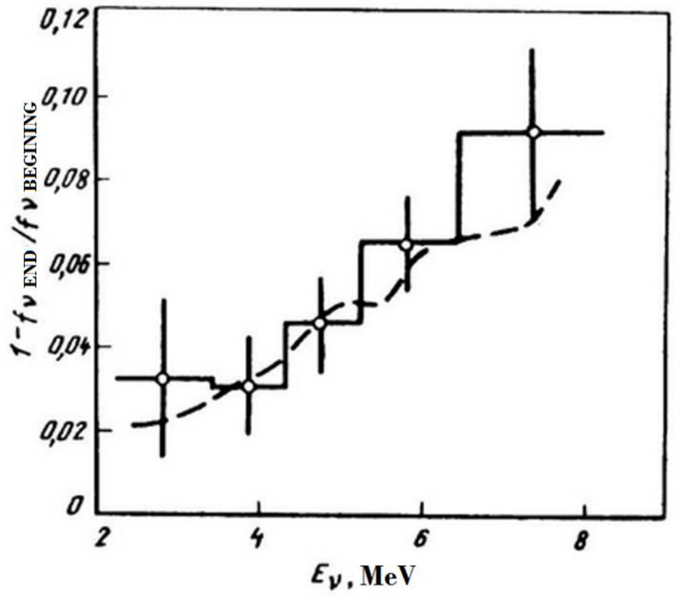


V.A. Korovkin et al., Atomic Energy, 65, No. 3, 712-718 (1988)

Change of $\bar{\nu}_e$ flux due to fuel burnup



Yu.V. Klimov et al., Atomic Energy, v.76-2, 123 (1994)

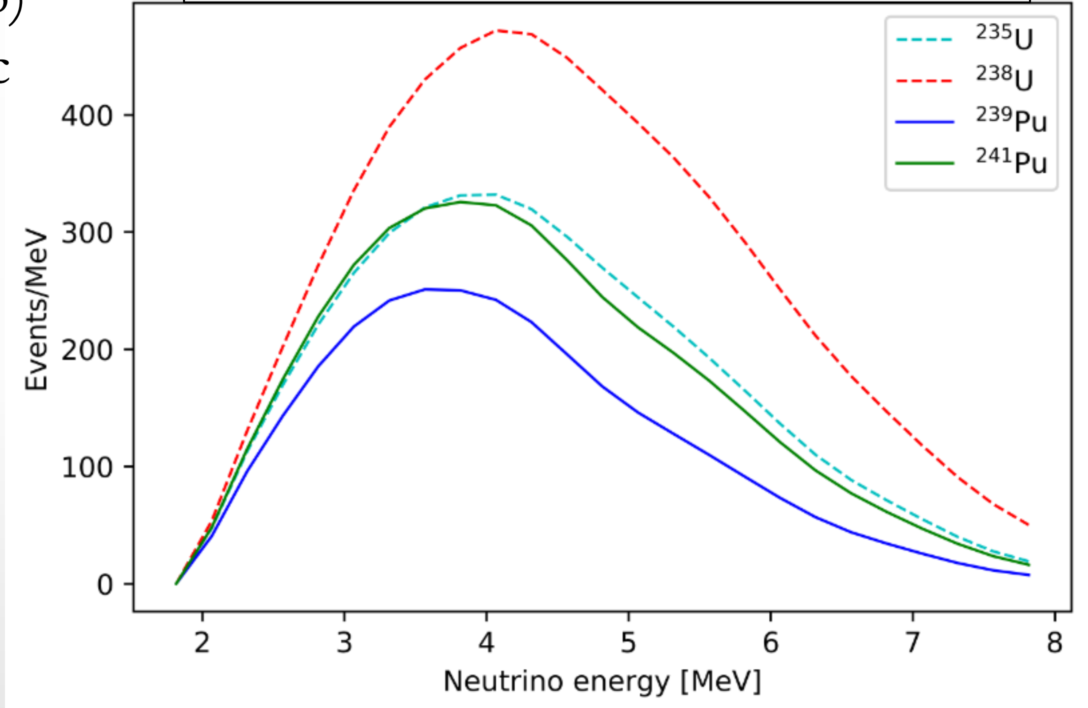


Ratio of $\bar{\nu}_e$ spectra in the beginning and in the end of cycle

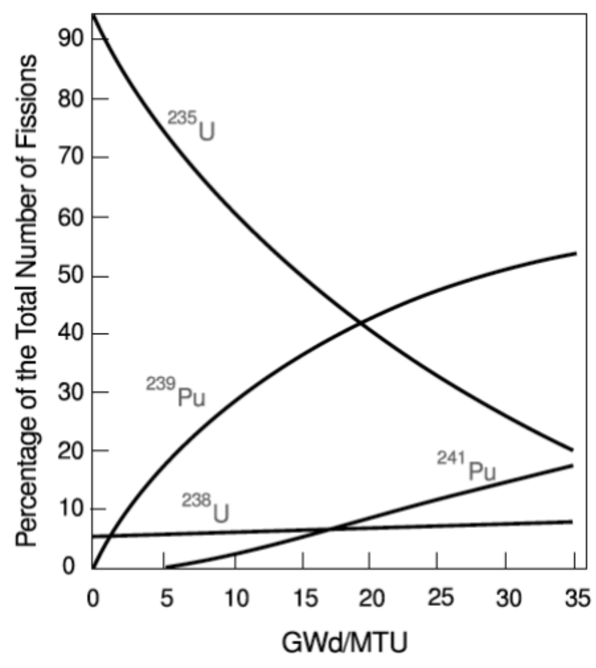
Neutrinos for Reactor Safeguards: Method

- We can measure the reactor power
- Both flux and spectra change with fuel evolution (burnup)
- Using those differences, we can infer reactor fuel isotopic composition, and we can see if there is an undeclared production of fissile materials
- Simultaneously, we can measure flux and spectra of the reactor for scientific purposes

Energy spectra for uranium-235, uranium-238, plutonium-239, and plutonium-241



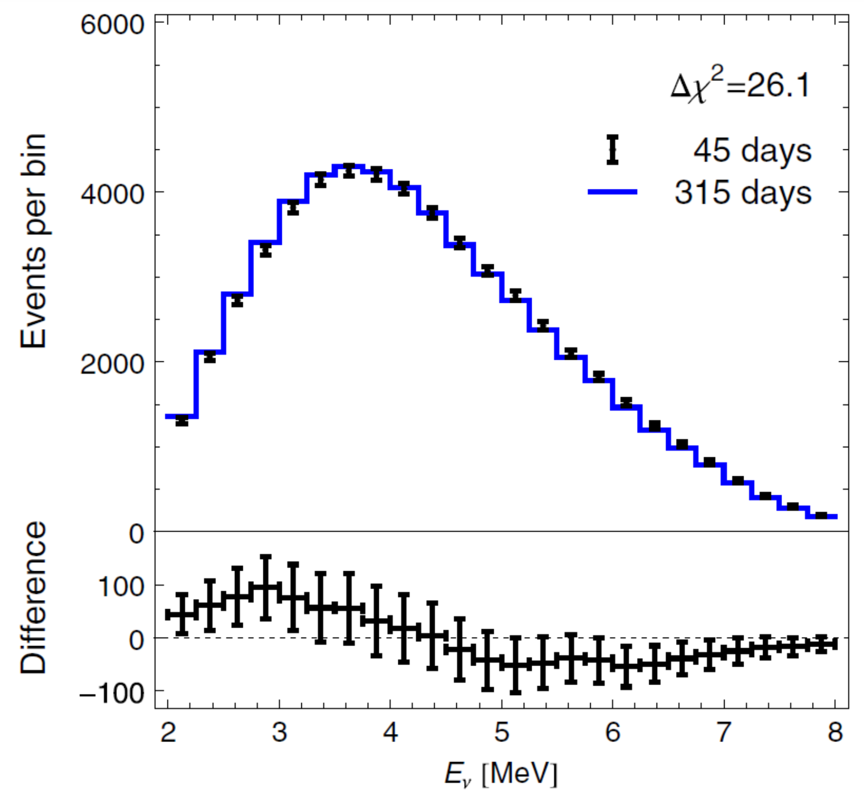
M. Bowen, P. Huber, “Inverse beta decay and coherent elastic neutrino nucleus scattering – a comparison” (2019)



Evolution of the fuel composition for a pressurized water reactor

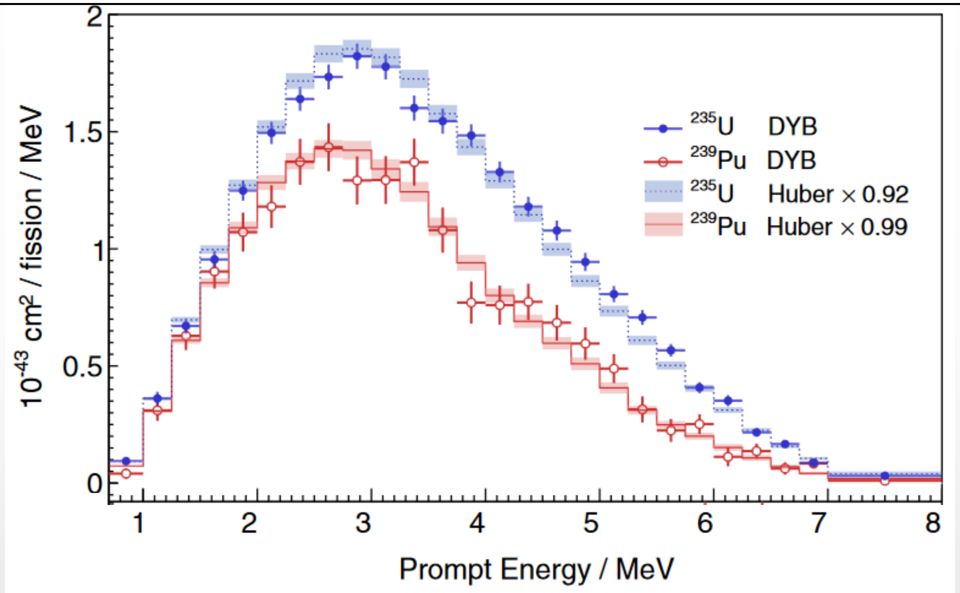
M. M. Nieto et al., Nuclear Science and Engineering, 149:3, 270-276 (2005)

Neutrinos for Reactor Safeguards: Examples



E. Christensen et al., Phys. Rev. Lett. 113, 042503

Experimentally extracted ^{235}U and ^{239}Pu spectra from Daya Bay experiment and the corresponding Huber-Mueller model predictions with the normalization factors 0.92 and 0.99



D. Adey et al., Phys. Rev. Lett. 123, 111801

- Simulation for 40 $\mathrm{MW_{th}}$ heavy water reactor, 19 m from the reactor core
- Comparison of $\bar{\nu}_e$ spectra of the core of age of 45 days vs of 315 days
- The older core has a “softer” antineutrino spectrum – due to higher plutonium content in the fuel (which produces this “softer” spectrum)
- χ^2-difference of 26.1 between two spectra corresponds to 7 kg difference in Pu content

Mobile Antineutrino Demonstrator

Mobile Antineutrino Demonstrator Collaboration

Concept:

- Ton-scale detector in moveable platform
- 2 Technologies are tested: 2D (ROADSTR) and 3D (CHANDLER)

Project Goal:

- Use recent advances in $\bar{\nu}_e$ detection to build a mobile system capable of measuring the $\bar{\nu}_e$ signal from a reactor, providing new options to meet future nuclear safeguards and verification needs.

Anticipated capabilities:

- Reactor power monitoring, such as for verification of a reactor shutdown agreement
- Fuel content monitoring, as a component of safeguarding advanced reactor designs

Lawrence Livermore National Laboratory

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Thank you!