Introduction to Near-Field Reactor Neutrino Applications and the Mobile Antineutrino Demonstrator

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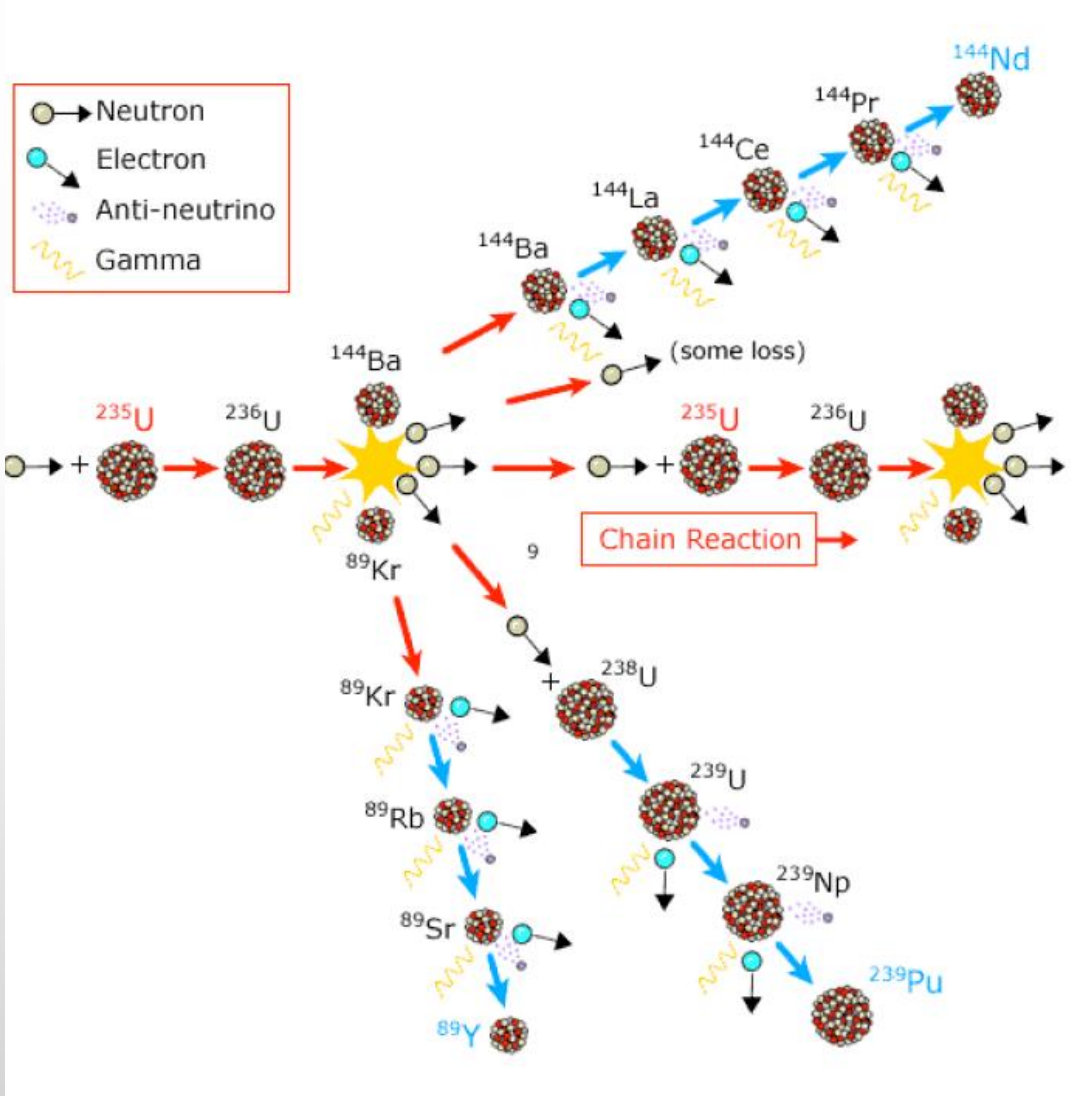
FOR THE MOBILE ANTINEUTRINO DEMONSTRATOR PROJECT

Antineutrinos from the Reactors

- 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 ($\theta_{12},\ \Delta m^2_{21},\ \theta_{13},\ \Delta m^2_{31}$)
- Fissions produce neutron-rich daughters, and they produce $\bar{\nu}_e$ through beta decays:

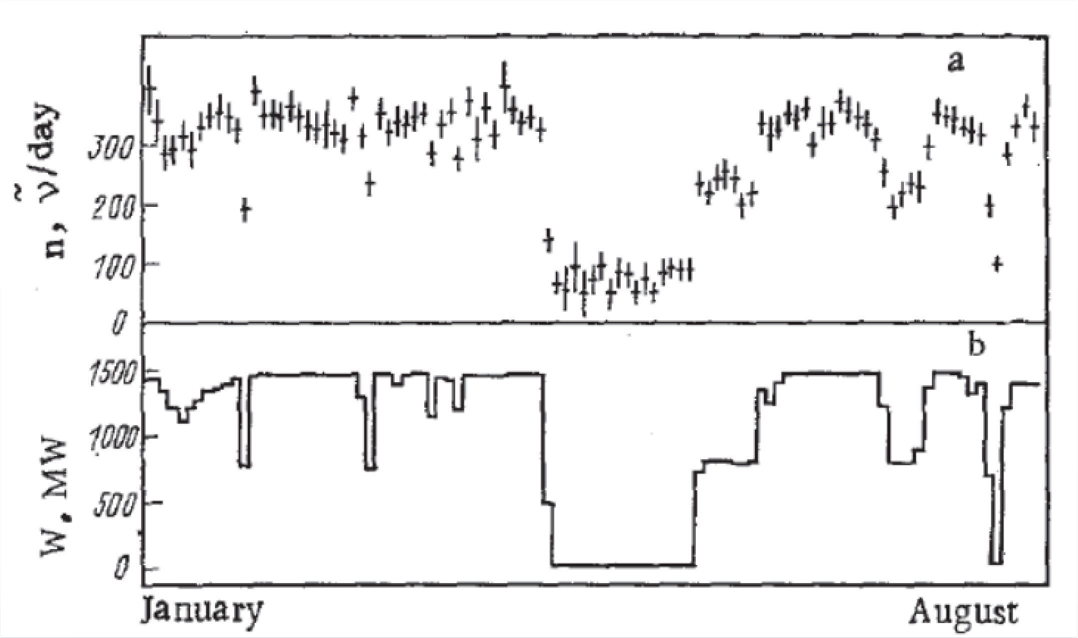
$$^{A}_{Z}\mathrm{X} \rightarrow {}^{A}_{Z+1}\mathrm{Y} + e^- + \bar{\nu}_e$$

- 1 $\mathrm{GW_{th}}$ reactor produces about $2 \cdot 10^{20}\ \bar{\nu}_e/sec$
- Most nuclear reactors have 4 isotopes in the fuel: $^{235}U, ^{239}Pu, ^{241}Pu, ^{238}U$



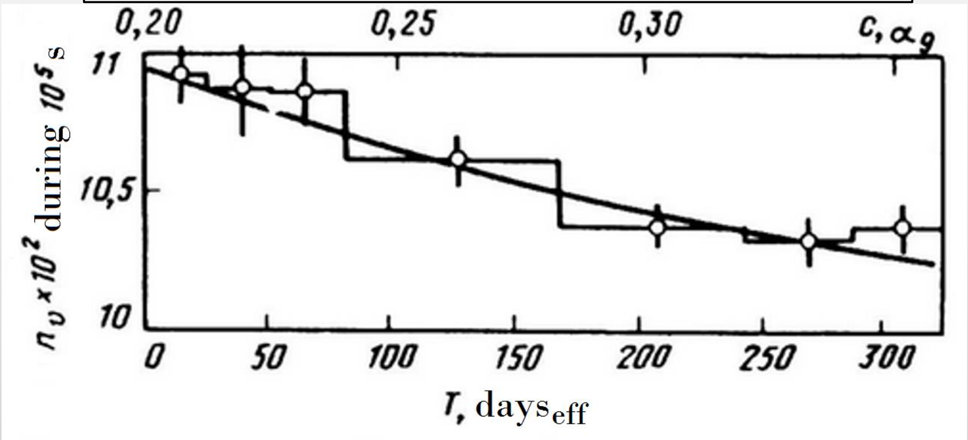
Neutrinos for Reactor Safeguards: History

- First suggested in the 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

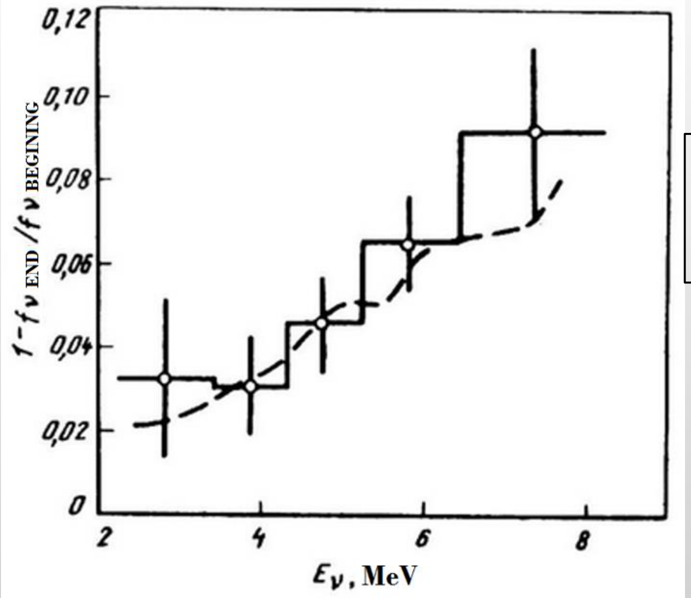


V.A. Korovkin et al., Atomic Energy, 65, No. 3, 712-718 (1988)

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



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

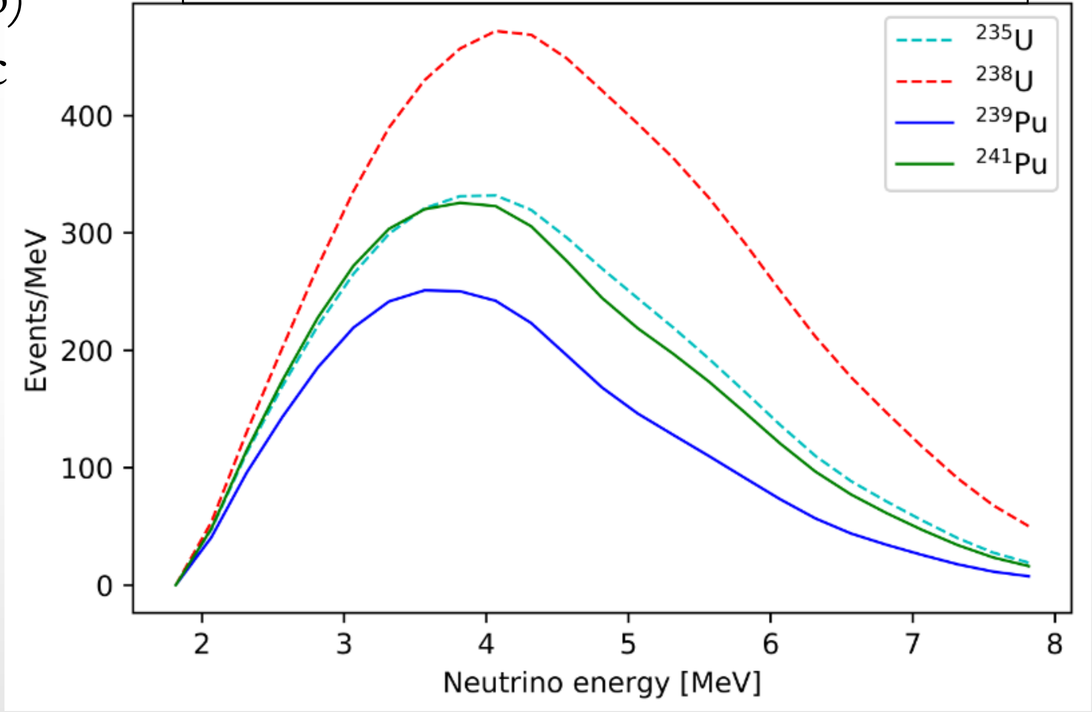


Ratio of $\bar{\nu}_e$ spectra in the beginning and in the end of cycle

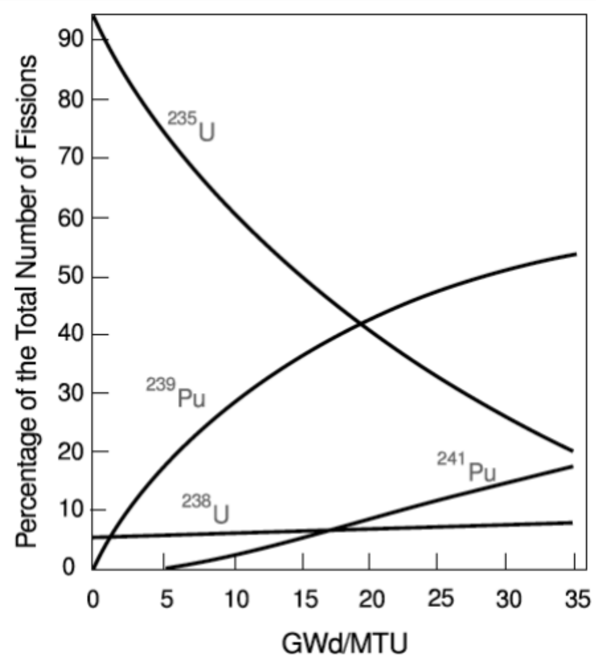
Neutrinos for Reactor Safeguards: Method

- 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



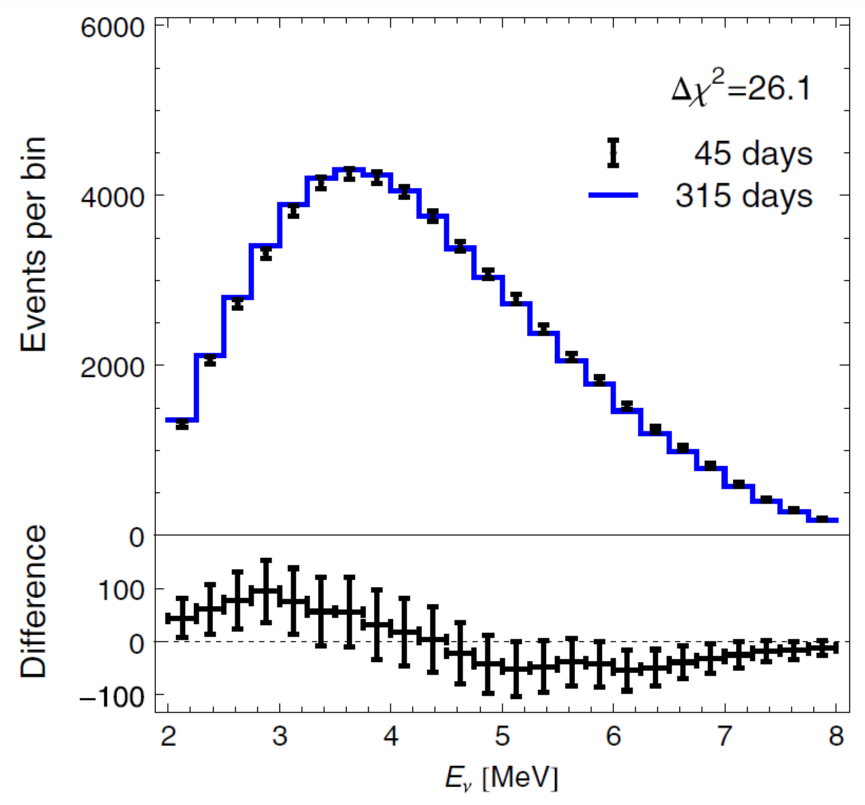
M. Bowen, P. Huber, "Inverse beta decay and coherent elastic neutrino nucleus scattering – a comparison" (2019)



Evolution of the fuel composition for a pressurized water reactor

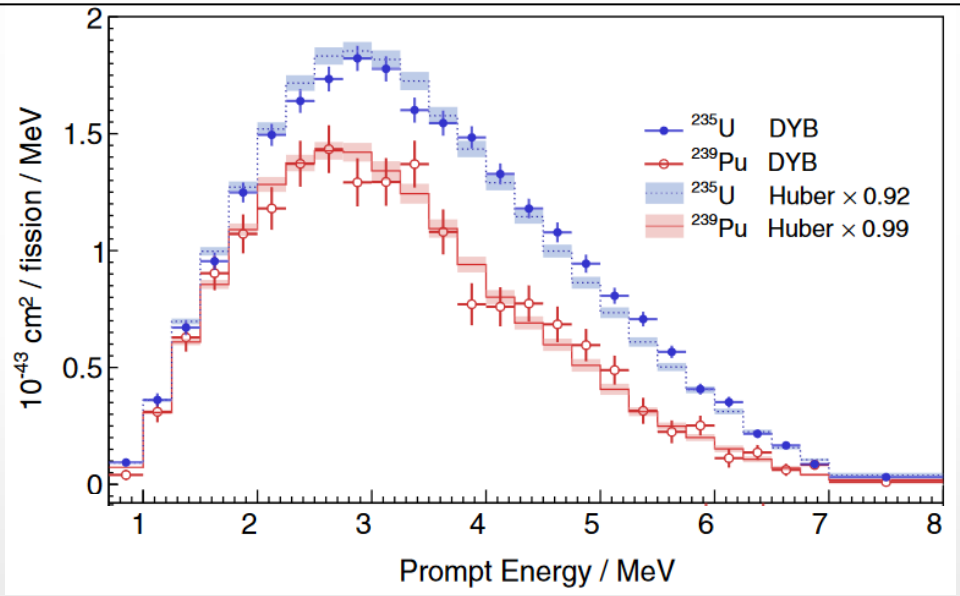
M. M. Nieto et al., Nuclear Science and Engineering, 149:3, 270-276 (2005)

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

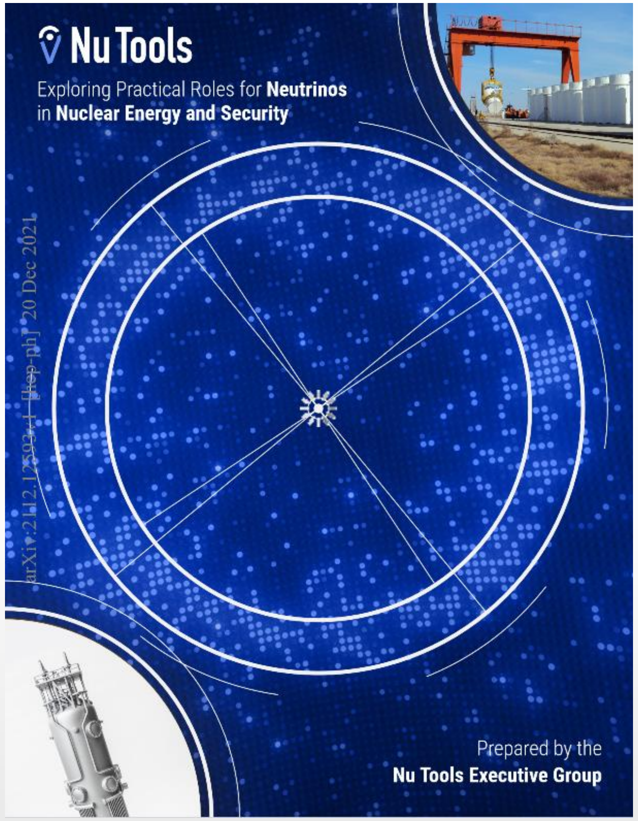


D. Adey et al., Phys. Rev. Lett. 123, 111801

- Simulation for 40 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

NuTools: The Goals of the Study

- Study was commissioned by the DOE National Nuclear Security Administration (NNSA) Office of Defense Nuclear Nonproliferation Research and Development (DNN R&D)
- This 2-year study was conducted by a group of neutrino physicists and nuclear engineers from US universities and government laboratories
- Central theme of the study – **Potential utility** of antineutrino detection technologies. Useful application of neutrinos will depend not only on advancing physics and technology but also on ***understanding the needs and constraints of potential end-users***.



O. Akindele et al., arXiv:2112.12593v1

The goals of the report:

- To provide strategic input to guide possible future R&D investments in the DNN R&D portfolio
- To inform the R&D efforts of scientists and engineers interested in neutrino applications
- To offer members of the nuclear energy and nuclear security communities a perspective on where neutrino technology could eventually have practical value

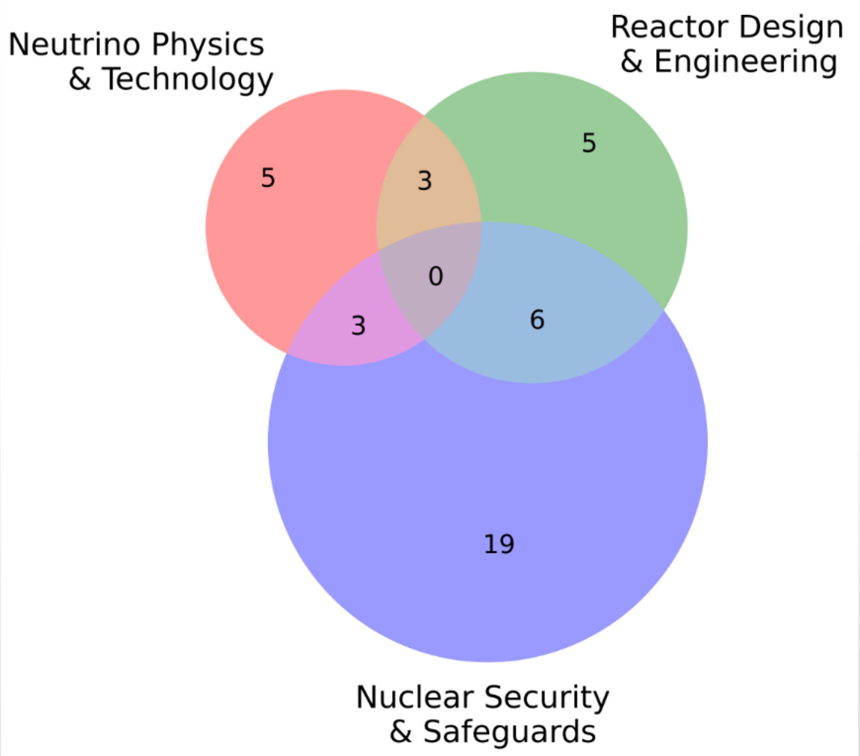
NuTools: Method of the Study

- The utility of the technology depends on the **needs and constraints** of end-users: reactor designers, inspectors, diplomats, and other specialists.
- Community assessment was performed through semi-structured interviews and a mini-workshop in July 2020
- Interviewees were selected with an emphasis on experts outside the physics research community, including:
  - international and domestic safeguards practitioners,
  - nuclear reactor vendors and operators, and
  - nuclear policy experts with experience in government agencies and non-governmental organizations
- Use cases considered as starters:

Reactor power monitoring
Fissile content tracking
Non-fissile material transmutation
Irradiated fuel monitoring

Post-incident monitoring
Regional reactor observation
Scientific engagement

The fields of the specialization of the 41 experts engaged for the study



O. Akindele et al., arXiv:2112.12593v1

NuTools: Cross Cutting Findings

The study identified three findings that apply across all potential applications of neutrino technology:

End-user Engagement: The neutrino technology R&D community is only beginning to engage attentively with end-users, and further coordinated exchange is necessary to explore and develop potential use cases.

Technical Readiness: The incorporation of new technologies into the nuclear energy or security toolbox is a methodical process, requiring a novel system such as a neutrino detector to demonstrate sufficient technical readiness.

Neutrino System Siting: Siting of a neutrino-based system requires a balance between intrusiveness concerns and technical considerations and sitting as close as possible is the most beneficial.

NuTools: Use Case Findings

- **Current International Atomic Energy Agency (IAEA) Safeguards**: The safeguards community is satisfied with the existing toolset and does not see a specific role for neutrinos
- **Advanced Reactors**: However, advanced reactors impose new safeguards challenges which can become possible use cases for neutrino monitoring
- **Future Nuclear Deals**: The policy community is interested in neutrino detection as a possible element of future nuclear deals involving cooperative reactor monitoring or verifying the absence of reactor operations
- **Reactor Operations**: Utility of neutrino detectors as a component of instrumentation and control systems at existing reactors would be limited
- **Non-Cooperative Reactor Monitoring or Discovery**: Implementation constraints related to required detector size, dwell time, distance, and backgrounds preclude consideration of neutrino detectors for non-cooperative reactor monitoring or discovery
- **Spent Nuclear Fuel**: Non-destructive assay of dry casks is a capability need which could potentially be met my neutrino technology, whereas long-term geological repositories are unlikely to present a use case
- **Post-Accident Response**: Determining the status of core assemblies and spent fuel is a capability need for post-accident response, but the applicability of neutrino detectors to these applications requires further study

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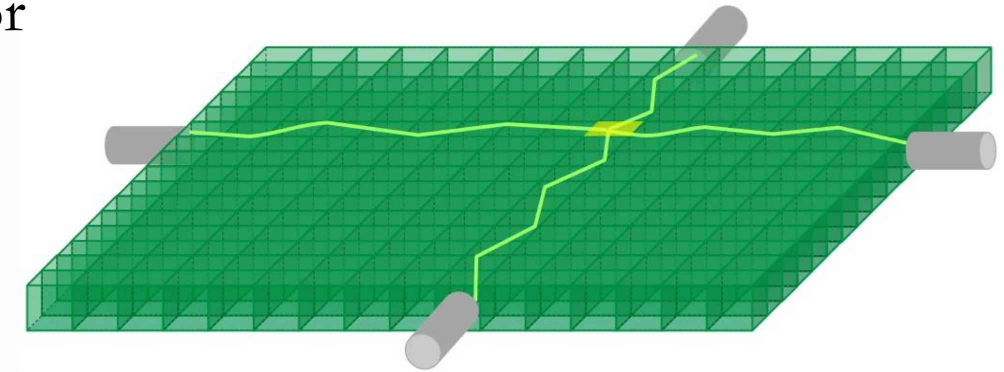
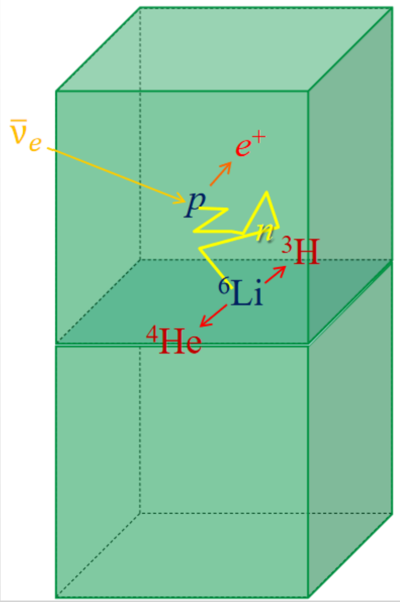
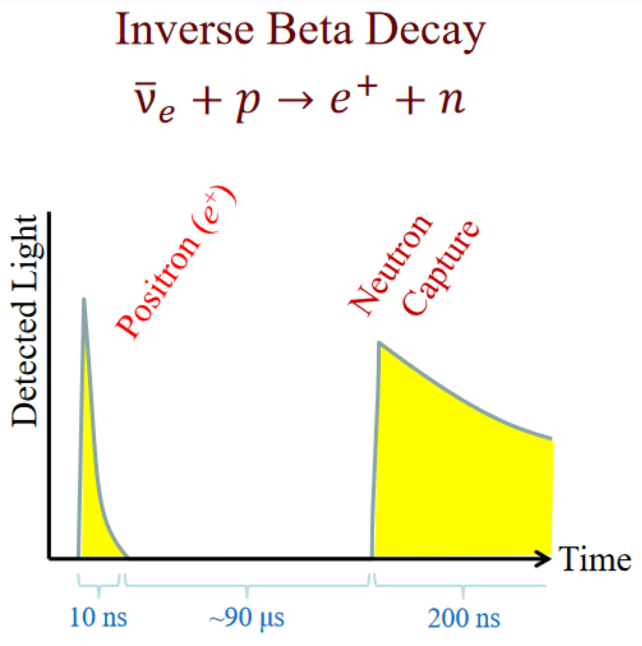
US Near-Field Surface Reactor Antineutrino Experiments

CHANDLER

- 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

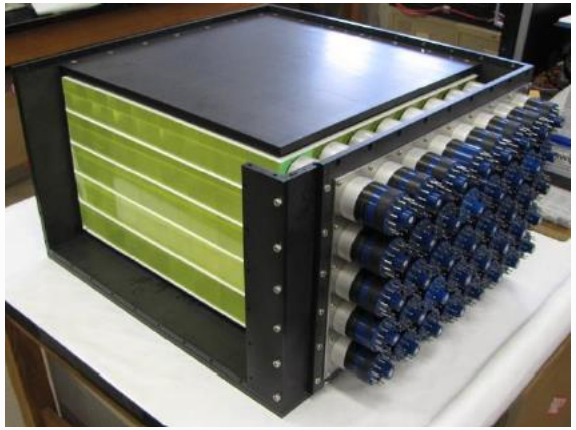


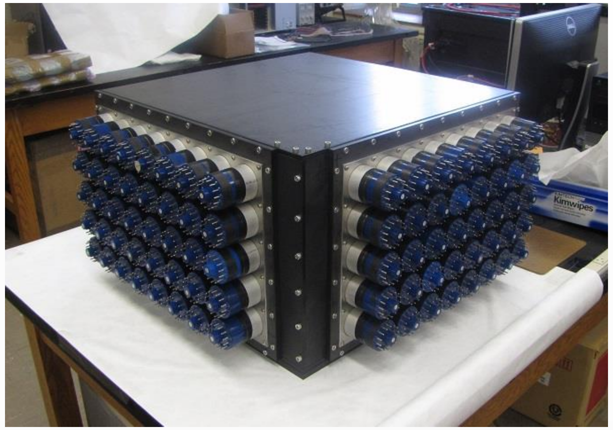




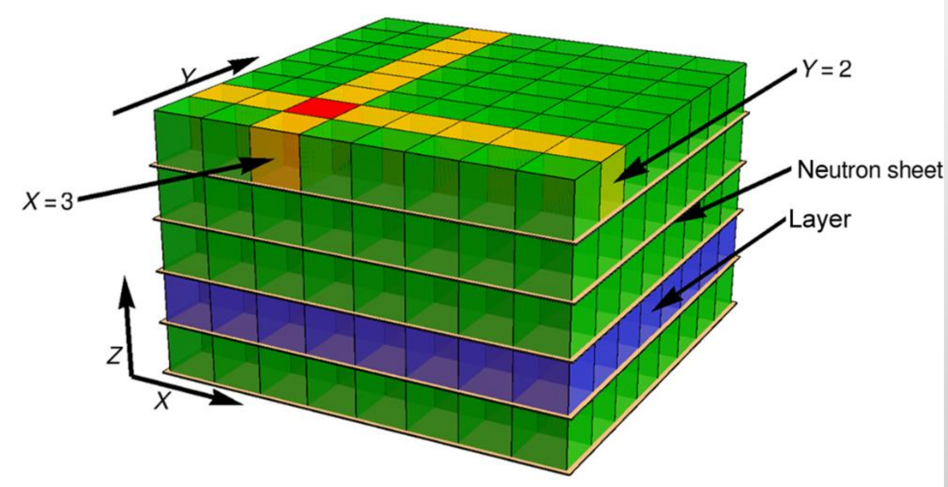
MiniCHANDLER

- 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



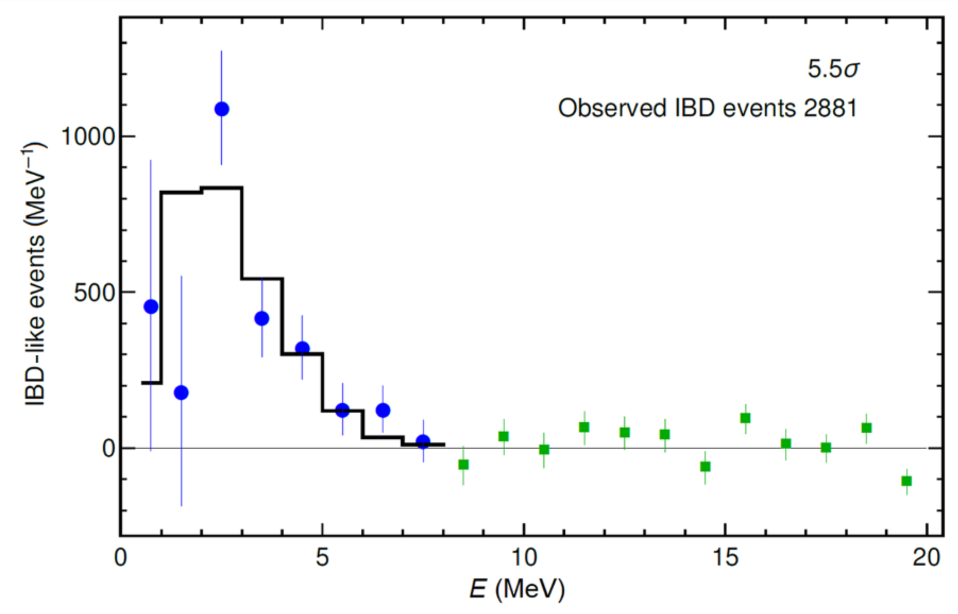


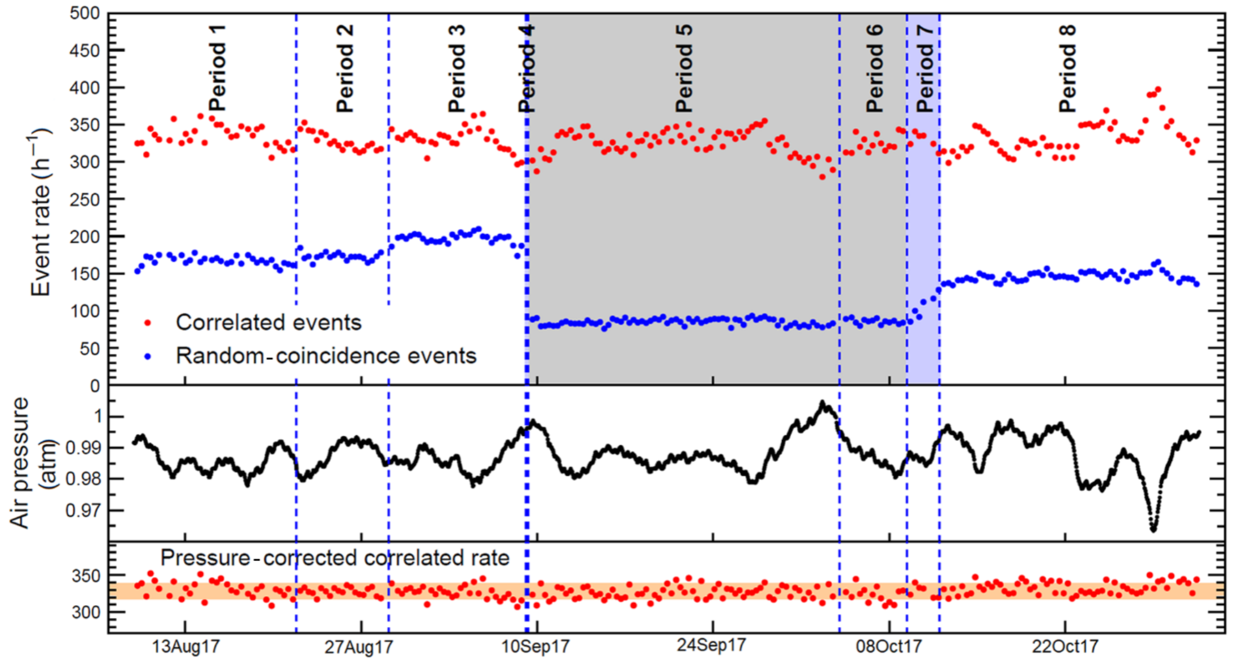
A. Haghighat et al., Phys. Rev. Applied 13, 034028 (2020)



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

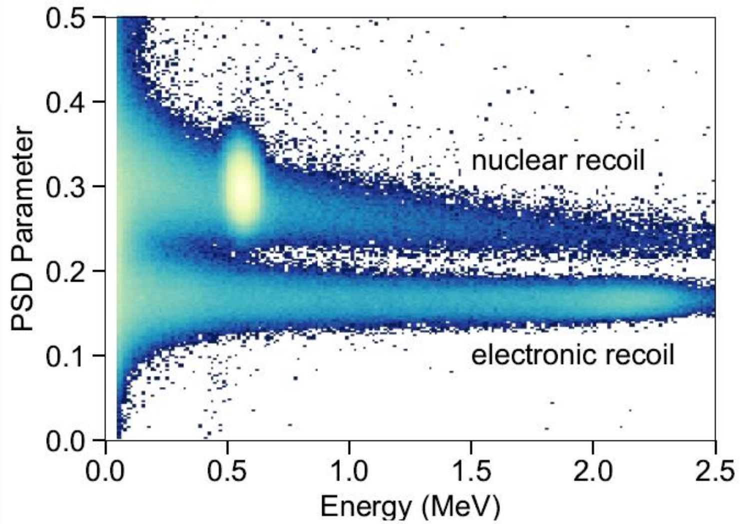


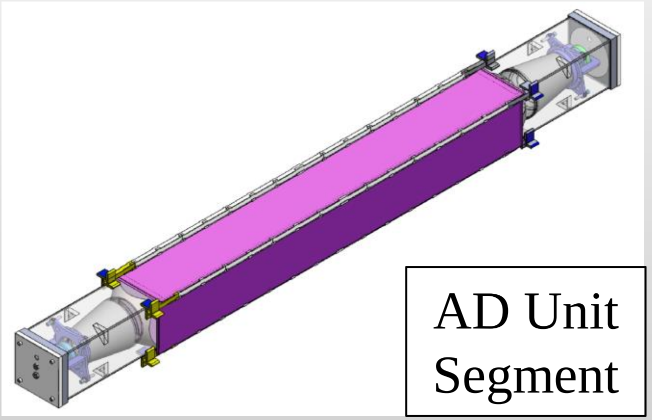


A. Haghighat et al., Phys. Rev. Applied 13, 034028 (2020)

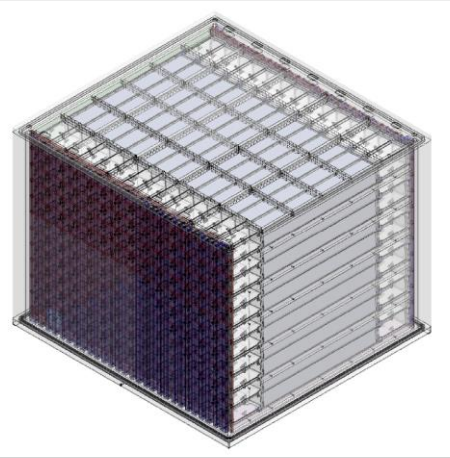
PROSPECT

- PROSPECT – **Precision Reactor Oscillation and SPECTrum** 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

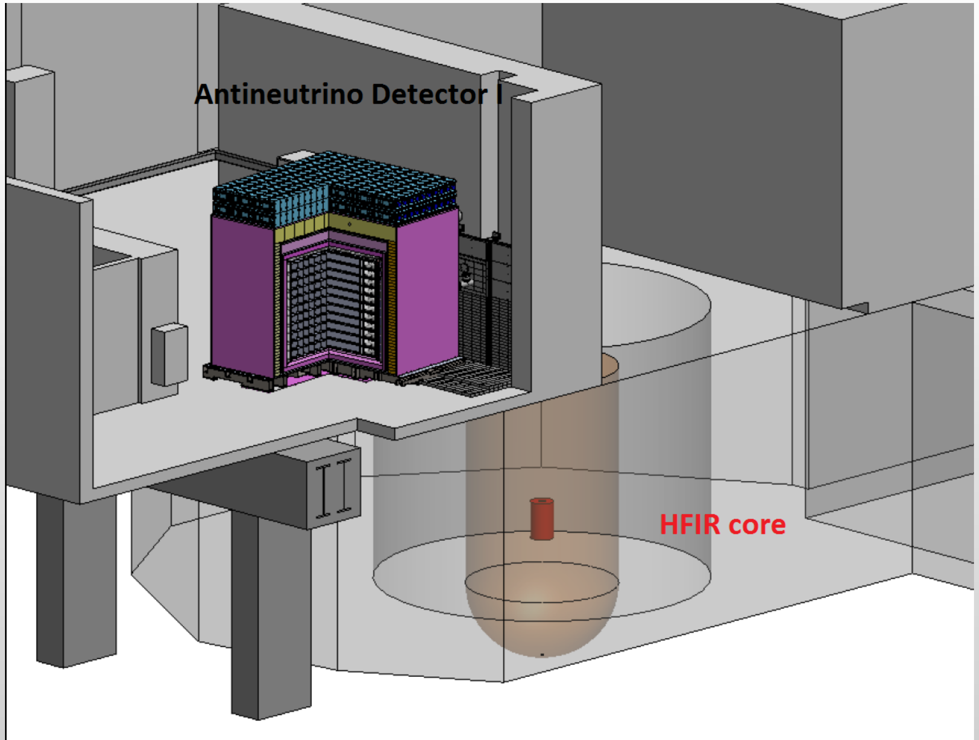




AD Unit Segment



J. Ashenfelter et al., arXiv:1512.02202v1



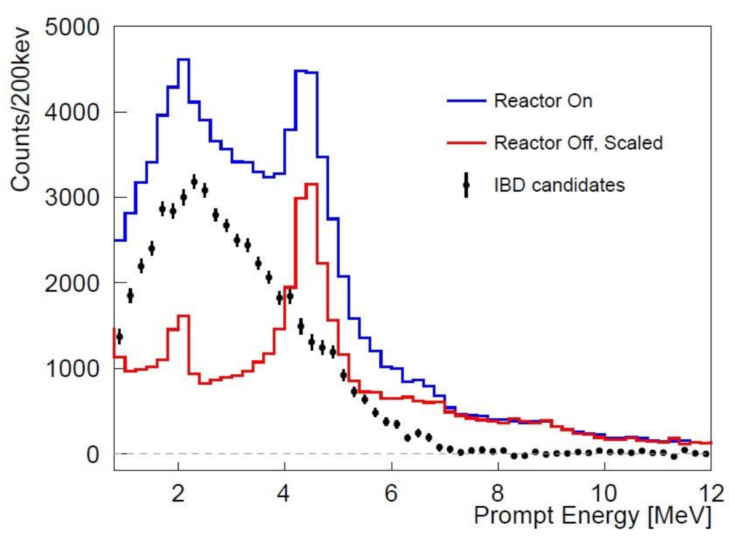
PROSPECT Results

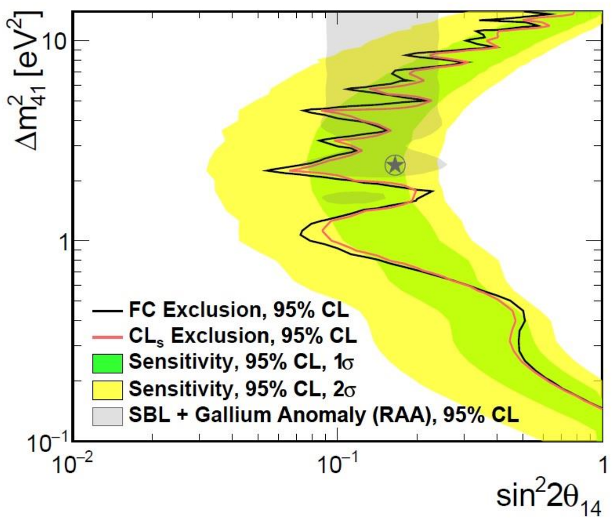
- Was deployed at HFIR and taking data in February – November 2018
- Ratio of IBD/accidentals: 1.78. Ratio of IBD/cosmogenic background: 1.37
- Total number of detected IBDs: 50560 ± 406
- PROSPECT disfavored RAA best-fit point at 2.5σ CL, and other regions in the ~0.1-15 eV^2 at more than 95% CL
- ^{235}U results shows good result with Huber reactor model with a χ^2/DOF of 30.79/31.

Goals:

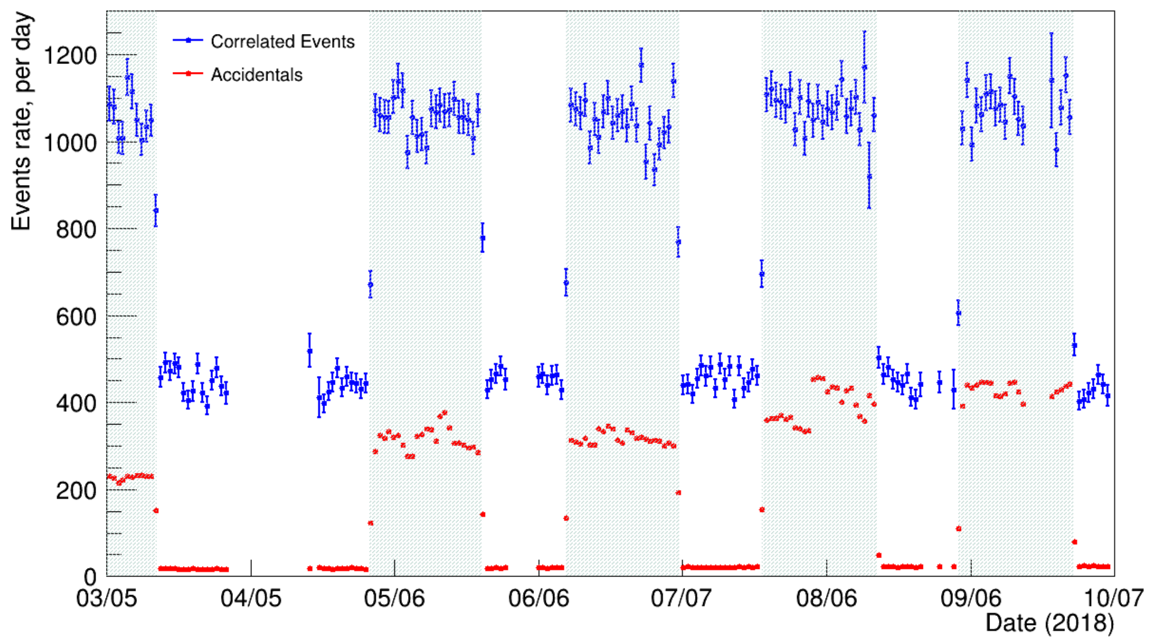
1. Search for short-baseline sterile neutrino oscillations
2. Measurement of $\bar{\nu}_e$ energy spectrum from highly-enriched uranium reactor core

Yesterday's talks by D. V. Vargas and F. Sutanto on PROSPECT



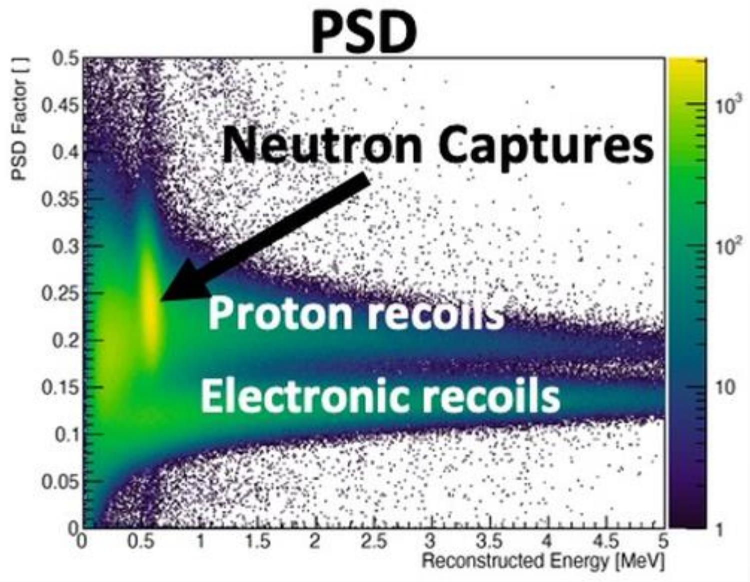


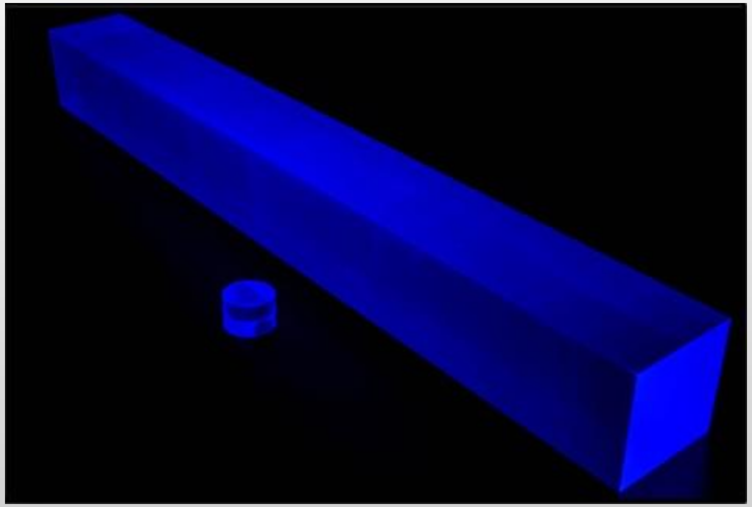
M. Andriamirado et al., Phys. Rev. D 103, 032001 (2021)



ROADSTR

- ROADSTR – **R**eactor **O**perations **A**ntineutrino **D**etection **S**urface **T**estbed **R**over
- Similar to PROSPECT 2D-segmented detector design but mobile and utilizing plastic instead of liquid scintillator
- 0.1% ^{6}Li-doped **plastic** scintillator with PSD capability – a product of technology sharing agreement between LLNL and Eljen Technology
- 5.5 cm x 5.5 cm x 50 cm plastic bars
- Double-ended PMT readout





See next talk by Christian Roca

S. Dazeley et al., Neutrino 2022 Poster P0422

Mobile Antineutrino Demonstrator Project

Mobile Antineutrino Demonstrator Collaboration

- Neutrino physicists, nuclear engineers, and students from US universities and government laboratories – the majority has been working with reactor antineutrino detectors in the past and currently (CHANDLER, PROSPECT, ROADSTR)

- Sponsor: National Nuclear Security Administration Office of Defense Nuclear Nonproliferation R&D.

Lawrence Livermore National Laboratory

VIRGINIA TECH

OAK RIDGE National Laboratory

NIST

ILLINOIS INSTITUTE OF TECHNOLOGY

Georgia Tech

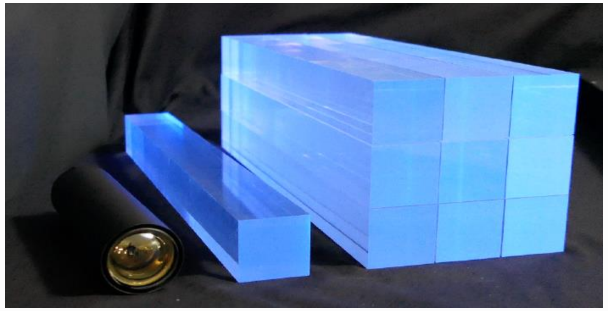
YALE

U. S. NAVAL ACADEMY

DEPARTMENT OF ENERGY · UNITED STATES OF AMERICA

NNSA National Nuclear Security Administration

Project R&D Goal and Timeline



Concept: Ton-scale detector in moveable platform

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

Projected Timeline:

- 2022: Conduct detector R&D in coordination with potential end-users
- 2023: Finalize system design and begin construction
- 2024: Complete system construction and deliver system to first demonstration site

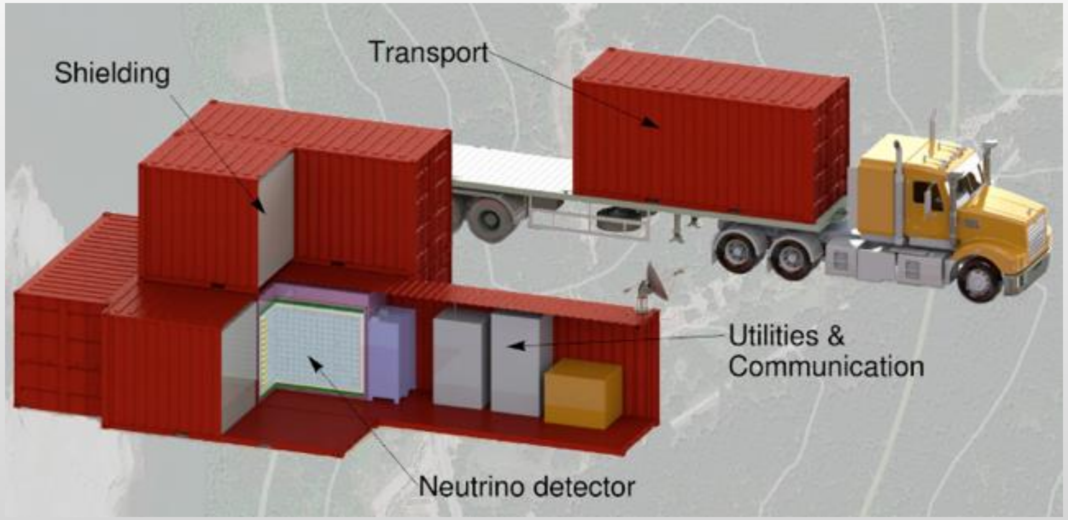
Project Concept and Design

Conceptual system design: The project will observe $\bar{\nu}_e$ from outside the reactor containment building using a

- 1-ton segmented scintillator detector, designed to operate unattended for months,
- Housed in a standard shipping container or enclosed trailer, with
- Option of supplemental cosmic ray shielding in additional stacked containers.

The system will require electrical power, in addition to a deployment location in proximity to the reactor containment.

Project aims to demonstrate a **realistically deployable system** that **addresses areas of real need** for reactor verification or advanced reactor safeguards.



Summary

- Success of particle physics in above-ground detection of reactor antineutrinos led to considerations of use of these advanced technologies to monitor reactors for safeguards and nuclear nonproliferation purposes.

- Advancing these technologies even further and implementing them in practice as a nuclear monitoring tool will improve particle physics studies, including sterile neutrino oscillations searches and measurements of reactor flux and spectrum.

- Therefore, synergy of fundamental physics and real-world applications will benefit and provide better results for both areas.

Thank you!

Backup

NuTools: Final Recommendations

The report makes two recommendations to the sponsor of the technology:

- **Recommendation for End-User Engagement**: DNN should support engagement between neutrino technology developers and end-users in areas where potential utility has been identified

- **Recommendation for Technology Development**: DNN should lead a coordinated effort among agencies to support a portfolio of neutrino detector system development for areas of potential utility, principally in future nuclear deals and advanced reactors.