PROSPECT (Precision Oscillation and Spectrum Experiment)

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For the PROSPECT Collaboration
Reactor antineutrinos

Rich history of impactful results:

First detection
Multiple mixing angles

Nuclear reactors are beautiful antineutrino sources:
Typical GW commercial reactor $\sim 10^{21} \nu_e$/sec

Rule of thumb: $\sim 1$ event per day per ton of LS per GW$_{th}$ at 1km
(or 10 per ton per day per MW$_{th}$ at 10 m)
Reactor antineutrinos

**Source**

Reactors generate energy from the fission of Uranium and Plutonium isotopes:
- Each fission yields a pair of neutron rich daughters
- On average 6 beta decays for both to reach stability

Beta decays are a pure $\bar{\nu}_e$ source where
- > 99.9% of $\bar{\nu}_e$ are produced by fissions in $^{235}$U, $^{238}$U, $^{239}$Pu, $^{241}$Pu

**Detection**

inverse beta decay

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

From Bemporad, Gratta and Vogel

mean energy of $\nu_e$: 3.6 MeV

threshold: neutrinos with $E < 1.8$ MeV are not detected

only ~ 1.5 $\nu_e$/fission are detected
Predicting the antineutrino spectrum

Two(+) approaches:

**ab initio summation from nuclear databases:**

Add 1000s of beta-decays from nuclear databases to calculate spectrum and flux
underestimates rates due to missing data (~85%-90% of total flux)
large uncertainties in some required isotopes

**Beta conversion:**

Measure cumulative beta spectra from $^{235}\text{U}$, $^{238}\text{U}$, $^{239}\text{Pu}$, $^{241}\text{Pu}$
Use virtual beta-branches to convert into neutrino spectra
Do virtual branches capture required physics?
  - e.g. treatment of forbidden transitions, shape corrections

**A hybrid:**

*ab initio* as far as possible, virtual branches afterwards
2011 new $\nu_e$ flux predictions:
- re-analysis of 19 short-baseline expts.
- improved antineutrino spectra: +3%
- neutron lifetime correction: +1%
- off-equilibrium effects: +1%

$3\sigma$ tension with experiment

Error budget dominated by flux prediction

SAGE/Gallex ($^{71}$Ge): see neutrino deficit from calibration sources:

$^{51}$Cr & $^{37}$Ar monoenergetic $\nu_e$ sources

*excited state correction, Haxton '98*

Both reactor and source experiments observe a *deficit* of neutrinos with respect to theoretical predictions.

**Missing nuclear physics or new physics?**
2011 new $\nu_e$ flux predictions:
- re-analysis of 19 short-baseline expts.
- improved antineutrino spectra: +3%
- neutron lifetime correction: +1%
- off-equilibrium effects: +1%

3$\sigma$ tension with experiment

Error budget dominated by flux prediction

SAGE/Gallex ($^7$Ge): see neutrino deficit from calibration sources:

A possible explanation: the existence of additional neutrino states

Sterile neutrinos could mix with Standard Model neutrinos leading to an oscillation in both distance and energy

With a large enough mass splitting, meter scale oscillations.
Neutrino Disappearance (reactor)

Allowed regions for antineutrino oscillation (3+1 model)

- Note that best fit lies within a shallow chi-squared space
- New experiments needed.
- Implied oscillation length is a few meters, and thus *unobservable* at large distances or at reactors with large cores
- Motivates spatial resolution, compact core

Non-trivial signal:
Figure above as seen by a modest multi-ton scale detector at ~10 m in 3 years

['s correspond to oscillations in upper left
Spectral Anomaly

Unexpected ‘bump’ in power reactor (LEU) spectrum

All $\theta_{13}$ experiments observe a similar spectral excess of ~10% between 5-7 MeV

*Predictions based on beta-conversion (Huber, Mueller, Haag)*

Matches all characteristics of IBD events

Excess tracks with reactor power (i.e. reactor source), Observed at all baselines

*Motivates additional experiments with other reactor/fuel types, and excellent energy resolution*

Also begs the question, can we predict spectrum well enough to meaningfully study total flux?
Highly complex $\beta$-decays: $\beta$-transitions feed highly excited states
these transitions followed by the $\gamma$-cascades from the daughter
System is difficult to study with low efficiency detectors
Leads to errors in databases

Total Absorption Spectroscopy
Some 80 isotopes re-measured w/ high-efficiency NaI array (e.g. MTAS).

Handful of isotopes contribute to the ‘bump ‘ region
-top three contribute 43% of the flux

from K.P. Rykaczewski
MTAS (Modular Total Absorption Spectroscopy)

- Top three isotopes contributing to the bump region: $^{142}$Cs, $^{92}$Rb, and $^{96}$Y

- Recently remeasured and reported in e.g.: PRL 117, 092501 (2016), PRC 95, 024320 (2017)

- $^{142}$Cs shows substantial difference from ENSDF

- Amounts to about a 2% change in the detected flux from top three contributing nuclei,

- Decreases reactor anomaly slightly to 0.97(2) (-0.011(1))

- However, this also decrease flux in the ‘bump’ region, increasing maximum discrepancy from 10% to 12%

While these measurements may be important to constraining these anomalies, they do not appear likely to eliminate both.

Largely consistent results in PHYSICAL REVIEW C 95, 024320 (2017)
## Focusing on Reactor anomalies

### Considerable international interest:
Diverse techniques (background suppression, detection technology, location) 
Overlapping sensitivities

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Reactor Power/Fuel</th>
<th>Overburden (mwe)</th>
<th>Detection Material</th>
<th>Segmentation</th>
<th>Optical Readout</th>
<th>Particle ID Capability</th>
</tr>
</thead>
<tbody>
<tr>
<td>DANSS (Russia)</td>
<td>3000 MW LEU fuel</td>
<td>~50</td>
<td>Inhomogeneous PS &amp; Gd sheets</td>
<td>2D, ~5mm</td>
<td>WLS fibers.</td>
<td>Topology only</td>
</tr>
<tr>
<td>NEOS (South Korea)</td>
<td>2800 MW LEU fuel</td>
<td>~20</td>
<td>Homogeneous Gd-doped LS</td>
<td>none</td>
<td>Direct double ended PMT</td>
<td>recoil PSD only</td>
</tr>
<tr>
<td>nuLat (USA)</td>
<td>40 MW $^{235}$U fuel</td>
<td>few</td>
<td>Homogeneous $^{6}$Li doped PS</td>
<td>Quasi-3D, 5cm, 3-axis Opt. Latt</td>
<td>Direct PMT</td>
<td>Topology, recoil &amp; capture PSD</td>
</tr>
<tr>
<td>Neutrino4 (Russia)</td>
<td>100 MW $^{235}$U fuel</td>
<td>~10</td>
<td>Homogeneous Gd-doped LS</td>
<td>2D, ~10cm</td>
<td>Direct single ended PMT</td>
<td>Topology only</td>
</tr>
<tr>
<td>PROSPECT (USA)</td>
<td>85 MW $^{235}$U fuel</td>
<td>few</td>
<td>Homogeneous $^{6}$Li-doped LS</td>
<td>2D, 15cm</td>
<td>Direct double ended PMT</td>
<td>Topology, recoil &amp; capture PSD</td>
</tr>
<tr>
<td>SoLid (UK Fr Bel US)</td>
<td>72 MW $^{235}$U fuel</td>
<td>~10</td>
<td>Inhomogeneous $^{6}$LiZnS &amp; PS</td>
<td>Quasi-3D, 5cm multiplex</td>
<td>WLS fibers</td>
<td>topology, capture PSD</td>
</tr>
<tr>
<td>Chandler (USA)</td>
<td>72 MW $^{235}$U fuel</td>
<td>~10</td>
<td>Inhomogeneous $^{6}$LiZnS &amp; PS</td>
<td>Quasi-3D, 5cm, 2-axis Opt. Latt</td>
<td>Direct PMT/ WLS Scint.</td>
<td>topology, capture PSD</td>
</tr>
<tr>
<td>Stereo (France)</td>
<td>57 MW $^{235}$U fuel</td>
<td>~15</td>
<td>Homogeneous Gd-doped LS</td>
<td>1D, 25cm</td>
<td>Direct single ended PMT</td>
<td>recoil PSD</td>
</tr>
</tbody>
</table>

*From N. Bowden, AAP 2016*
NEOS

- Single-volume GdLS detector with pulse shape discrimination and 5% Energy Resolution
- Located in tendon gallery at Hanbit power reactor at ~25m from reactor core, S:B ~23, 2000 IBDs/day(!)
- Initial data run finished in 2016, spectral oscillation search starting to probe best-fit region

From T. Langford, APS 2017
Experimental strategy (oscillation)

Oscillation search experimental approach:
Comparison of measured spectrum at multiple baselines with identical detector segments
Eliminates reactor flux normalization and spectral model dependence
Reduces systematic effects
Directly test oscillation hypothesis at baselines of ~10 m (~1eV^2)

Figure from B. Littlejohn

Spectral measurement experimental approach:
Optimize design for light collection efficiency
Minimize ‘dead’ material for simplified energy response
Extensive in situ calibration capabilities
Physics Objectives:
- Search for short-baseline antineutrino oscillation at distances ~10 m
- Precision measurement of $^{235}$U reactor $\nu_e$ spectrum

This talk will focus almost exclusively on design drivers/challenges
- Operation in near-surface environment
- Goal of a model independent oscillation search
- Maximized energy resolution $\sim 4.5%/\sqrt{E}$

PROSPECT whitepaper, arXiv:1309.7647
PROSPECT Detector

- Single 4,000 L $^6$Li-loaded liquid scintillator (~3,000 L fiducial volume)
- 11 x 14 (154) array of optically separated segments
- Very low mass separators
- Double ended PMT readout, light concentrators -> good light collection and energy response
  ~4.5-5%$\sqrt{E}$ energy resolution
- Corner rods allow for full in situ calibration access
- 160k detected neutrinos per year, ~1000/day. S:B ~ 3:1
Oscillation Sensitivity

Objectives (oscillation)
4σ test of best fit after 1 year
>3σ test of favored region after 3 years

Exclusion regions shown make minimal use of reactor power normalization and knowledge of spectral shape (e.g. 100% and 10% respectively)

Model independent test of eV-scale sterile neutrino oscillations
Model differentiation

Spectrum measurement with excellent energy resolution (4.5%@1MeV) and statistics

With ~160k IBD events per year, PROSPECT precision will surpass model uncertainties
- will be able to directly test various calculations
- HEU/LEU complementarily may provide information on the source of the ‘bump’
- provide benchmark spectrum for future HEU reactor experiments
Site selection

<table>
<thead>
<tr>
<th>Site</th>
<th>Power ($MW_{th}$)</th>
<th>Duty Cycle</th>
<th>Near Detector * Baseline (m)</th>
<th>Far Detector * Baseline (m)</th>
<th>Avg. Flux</th>
<th>Avg. Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>NIST</td>
<td>20</td>
<td>68%</td>
<td>3.9</td>
<td>15.5</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>HFIR</td>
<td>85</td>
<td>41%</td>
<td>6.7</td>
<td>18</td>
<td>0.96</td>
<td>1.93</td>
</tr>
<tr>
<td>ATR</td>
<td>120</td>
<td>68%</td>
<td>9.5</td>
<td>18.5</td>
<td>1.31</td>
<td>4.30</td>
</tr>
</tbody>
</table>

Comprehensive site evaluation (2013-2014):

Backgrounds, access, deployment locations w/ physics potential, etc…
High Flux Isotope Reactor (HFIR) at ORNL

HFIR

- User facility, easy 24/7 access
- Exterior access at grade
- Full utility access, incl. internet
- Established on-site operation for ~3 years
- Engagement with ORNL/HFIR management and safety
- Compact core (~0.5 m) and 85 MW
  - HEU (~93% 235U) Fuel

- HEU somewhat simpler, spectrum constant in time

- Available baselines ~ 7 m - 20 m

- Experiment ability to reconfigure/run for extended periods

- Detailed MCNP core model available

- Reactor off periods ~ 60% (key for background characterization)
Variable baselines

6 air casters allow installation and deployment at various baselines

Movement provides for:
- greater sensitivity at low $d_\text{m}^2$
- improved control of systematics
- better control of spatially varying backgrounds
Series of more capable prototypes
- Validates background suppression
- Validates detector performance (energy resolution, linearity, etc.)

Highlight PROSPECT-20 and PROSPECT-50

no further prototyping (will continue p50 as a monitor)
Event Detection in PROSPECT

Detection via Inverse Beta Decay

- Neutrino interacts with proton rich target

- **Positron energy (1-10 MeV) related to incident neutrino energy** *(annihilations complicate in compact detector)*

- Neutron capture can be a distinctive tag: capture time long compared to scattering physics, short compared to accidental rate.

- Pulse shape characteristics allows for the separation of gamma-like and n-like events, as well as capture.

An important implication: Most relevant backgrounds involve a neutron (s)
Pulse Shape Discrimination in PROSPECT

inverse beta decay (IBD)  
\( \gamma \)-like prompt, \( n \)-like delay

fast neutron background  
n-like prompt, \( n \)-like delay

accidental gamma background  
\( \gamma \)-like prompt, \( \gamma \)-like delay

Powerful background rejection
Lithium-6 Loaded Liquid Scintillator

6Li loading via Reverse Micelles:
- Surfactants added to base liquid scintillator
- Dynamically stable
- relatively high loading possible > 0.1%
- tolerable reduction in light yield
- tolerable reduction of PSD performance

Aqueous phase: 10 M enriched (95%) LiCl
- enriched Li₂CO₃ dissolved in HCl
- Purified via anion exchange resin

Safe, affordable:
Several non-toxic, non-flammable formulations based on EJ-309, LAB, Ultima Gold tested

EJ-309 selected as baseline
Diisopropynaphthalene (DIPN) base
Non-ionic surfactant

Pure samples of LS have stable performance over year timescales
Extensive material compatibility program; production materials validated

60Co

Maintains Light Yield
EJ-309 base:
11500 ph/MeV
LiLS: 8200 ph/MeV

Maintains excellent PSD performance for neutron capture & heavy recoils
Background Characterization

- Minimal overburden: cosmogenic backgrounds
- Close proximity to reactor and other systems
- Background control challenging

**Extensive measurement campaigns (ongoing):**
Gamma, Thermal and Fast Neutron, Muons
- Characterize background fields at HFIR
- Emphasized importance of localized shielding of penetrations, pipes, etc

Hots spots from beam penetrations to core

\[ \gamma \text{-ray intensity variations} \]

Targeted local Shielding

Cosmic background component

The usual case with neutrino experiments is kilometer scale overburden:
- Only easily vetoed muons remain from the surface.
- Surrounding rock and radio-purity of detector critical.

1 MWE toy shielding (equal mass iron and polyethylene)

In near-surface experiments (~m scale overburden) primary neutrons are significant and cosmic ray induced neutron showers dominate over neutrons produced in detector shielding.
Neutron background Characterization

Capture-gated fast neutron spectrometer
- verified expected overburden (50 cm concrete)
- no evidence of reactor correlated fast neutrons

Above a few MeV temporal variations (large) are dominated by:
- Barometric pressure (atmospheric depth)
- Earth’s magnetic environment

Both can be corrected to a few percent, residual variation due to local conditions

Temporal variation ~20%

Reference:
Neutrons above \( \sim 5 \) MeV can produce the prompt electron-like recoil with delayed-neutron-capture signature of an IBD through inelastic scattering.

At lower energies, neutrons yield only elastic scatters that can be vetoed with PSD.

Energy split between between protons and inelastic gammas. Remainder goes to heavier recoils.

Adapted from M. Mendenhall, AAP 2015
Fast neutron interactions

Fast neutrons penetrate shielding potentially yielding time and space correlated energy deposition

Simple model: IBD-like events for 4-12 MeV neutrons

IBD-like events that miss selective cuts with toy model of bulk liquid scintillator detector

optical segmentation on the scale of 5-10 cm allows physical separation of recoil and inelastic gammas

Adapted from M. Mendenhall, AAP 2015
Nominal event selection:

(1) Time ordered PSD

(2) Spatial topology:
- prompt and delayed signals proximate;
- multiple cell hits in the prompt signal must be compact (e.g. rejecting extended minimum ionizing tracks)
- events occurring outside the inner fiducial volume are vetoed (partial energy deposition reduces BG rejection).

(3) Timing:
- delayed capture must occur within 100 µs of the prompt ionization (set by ~40 µs neutron capture time)
- multiple hits in the prompt cluster must occur within 5 ns (reject slower-moving neutron recoil events)
- events must be isolated from other neutron recoils or captures in a ±250 µs window, (reject multi-neutron spallation showers)

Yields > 3 orders of magnitude background suppression and an expected signal to background of ~3:1.

Rate and shape of residual IBD-like background can be measured during multiple interlaced reactor-off periods.
PROSPECT-20: *in situ* validation of background models

**Targeted/Localized lead shielding**

- **Data**
- **Simulation**

**Inverse Beta Decay-like neutron coincident events**

**Coincidence timing spectrum**

- **Data**
- **Simulation**

**Energy spectrum**

- **Data**
- **Simulation**

### Background models validated in situ by a series of prototypes in both laboratory and reactor settings

- Shielding package roughly 25% of full PROSPECT shielding
- Operated 4 months at HIFR (two reactor on cycles)
- Monte Carlo performs well (with minimal adjustments to overburden and capture time) - validates full PROSPECT simulation
- Control of Reactor-correlated backgrounds

**P20 shielding (outside - in):**

- 9\": Water filled bricks
- 8\": HDPE:
- 4\": 30% borated HDPE
- 2\" or 4\": lead:
- 4\": 5% borated HDPE:
PROSPECT shielding

- <10s MeV neutrons removed by feasible shielding.
- Remaining IBD-like background events are primarily generated by >100 MeV cosmogenic neutrons
- Must be concerned with the production of secondaries
- Motivates a layered top-heavy approach
- But optimized by tight weight and space constraints

Inner detector package: 30,000 lbs
Total movable package: 76,000 lbs
PROSPECT design

Acrylic PMT housing, filled with mineral oil, fully submersed in liquid scintillator

Folded reflectors improve light collection

Laser cut acrylic PMT mounts

Hamamatsu R6594 5” PMT (outer layer 5” ET PMTs)

PROSPECT unit cell

High reflectivity, high rigidity, low mass reflector system developed

PLA 3D-printed pinwheels support panels
PROSPECT-20(Yale): validation performance

Representative aspect ratio & ability to reconfigure:

- Internal vs external reflectors, reflector coupling (TIR or not)
- Test light collection, PSD performance in an elongated geometry

![Diagram showing internal reflectors and test setup](image)

**Left Graph:**
- Energy vs PSD parameter
- Two categories: $n$-like and $\gamma$-like

**Right Graph:**
- Figure of merit vs position along cell (cm)
- Data points for PMT L, PMT R, and Average

![PSD by PMT](image)
Representative aspect ratio & ability to reconfigure:

- Internal vs external reflectors, reflector coupling (TIR or not)
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PROSPECT-20(Yale): validation performance
Representative aspect ratio & ability to reconfigure:

- Internal vs external reflectors, reflector coupling (TIR or not)
- Test light collection, PSD performance in an elongated geometry
Calibration

Each cell adjacent to both a source tube and a laser-based optical fiber tube.

Sources are to be deployed along 35 3/8” Teflon tubes running inside pinwheel optical supports.
Calibration source deployment

Source capsule

3D printed belt drive system reproducibly positions sources to ~mm

Sources positioned along PTFE tubes running the length of the cell support pinwheels

Mockup of source transport system > 2,000 successful cycles

Evaluating sources

encapsulated gamma sources (e.g. $^{22}$Na and $^{137}$Cs)
- LiLS linearity/response
- energy scale

positron sources (e.g. $^{68}$Ge)
- validates 511 response models

Neutron sources (e.g. AmBe or $^{252}$Cf)
- neutron detection efficiency
- PSD studies

w/ 35 sources allows full automated calibration
Light calibration system

- Pulsed light source at 400-450 nm
- ~1 ns pulse width
- optically split into 35 fibers + one gain monitoring PMT
- optical diffuser in the center of the cell

Pulsed laser source
- LiLS transmission
- PMT/electronics linearity and timing

Cell mass measurement

R&D on spiking LS with trace of $^{227}$Ac:
- Cell uniformity, Relative LS mass measurements
  
  $^{219}$Rn $\rightarrow^{(4s)}_{\alpha}^{215}$Po $\rightarrow^{(1.8\text{ms})}_{\alpha}^{211}$Pb
Monitoring of PROSPECT-20 at HFIR

Natural backgrounds (cosmogenic and radioactive) and spectral features effective for continuous monitoring of detector response

Long term gain drift by spectral feature
PROSPECT-50:

- 50 liters of $^6\text{LiLS}$
- Two PROSPECT segments

Test platform of each subsystem

- Thin-walled reflector panels
- PMT enclosures
- Filling system and procedure
- Calibration system
  - LED optical
  - Source capsules
- Cell-to-cell variation

From T. Langford, APS 2017
Prototyping: PROSPECT-50

Assembly

Installed in shielding box

assembled shielding

pinwheel captured reflector

PMT housing

2 stacked cells
In operation since March 2016, near continuous data-collection

- Measured light collection with $^6$LiLS: >550PE/MeV
  - 5% energy resolution at 1MeV
- Measured PSD Figure of Merit: 1.25 at (n,Li) capture
  - >99.9% background rejection
- Double-ended readout
  - Position reconstruction along cell length

Prototyping: PROSPECT-50

From T. Langford, APS 2017
Full assembly in progress

Housing assembly and testing

LiLS production

Cleaning of laser cut PMT mounts

Construction underway!

First production PMT housing!
http://prospect.yale.edu

4 national laboratories
10 universities
68 collaborators

Supported by:

NIST
BROOKHAVEN NATIONAL LABORATORY
Lawrence Livermore National Laboratory
Oak Ridge National Laboratory
Yale
Wildey University
Drexel
Georgia Tech
W&M
Virginia Tech

HEISING-SIMONS FOUNDATION

DEPARTMENT OF ENERGY
UNITED STATES OF AMERICA

Pieter Mumm
Status and Conclusions

- The reactor flux and spectrum shape anomalies are unresolved after new TAS data and recent $\theta_{13}$ experiments.
- New data and experiments are required to address these anomalies.
- Many complementary experiments online or coming online soon. Precision data in the next couple of years.

PROSPECT specifically will:
- Measure the $^{235}$U spectrum to the highest precision to date; complementary to LEU experiments.
- Perform a model-independent sterile oscillation search, covering the current best fit at $>3\sigma$ within three years.

- PROSPECT is now proceeding with detector construction.
- Data collection will commence in the later part of 2017.