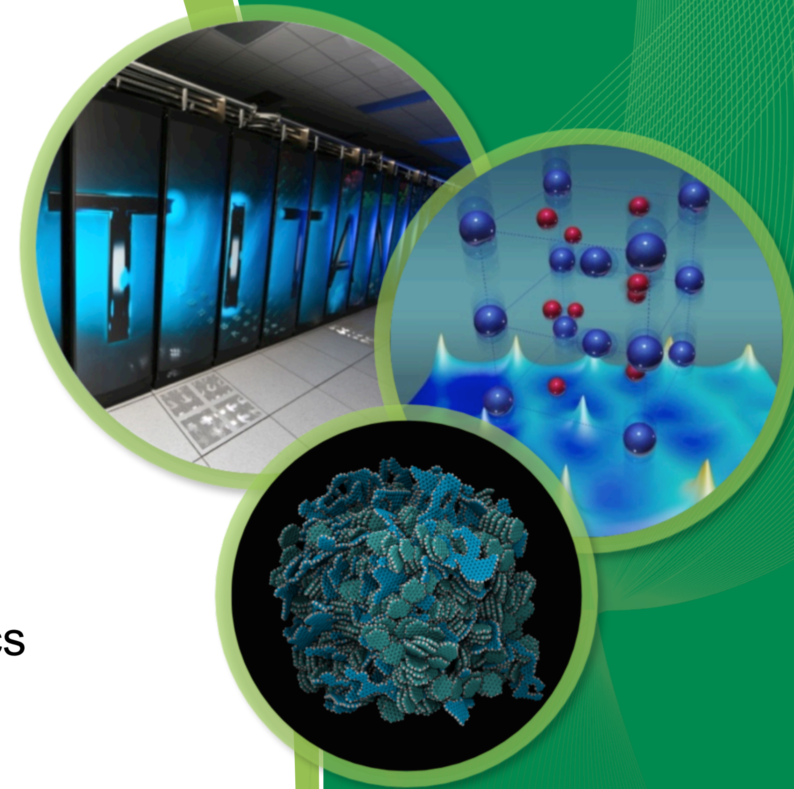
Neutrino Physics at ORNL and PROSPECT Experiment Status

Alfredo Galindo-Uribarri,
Physics Division

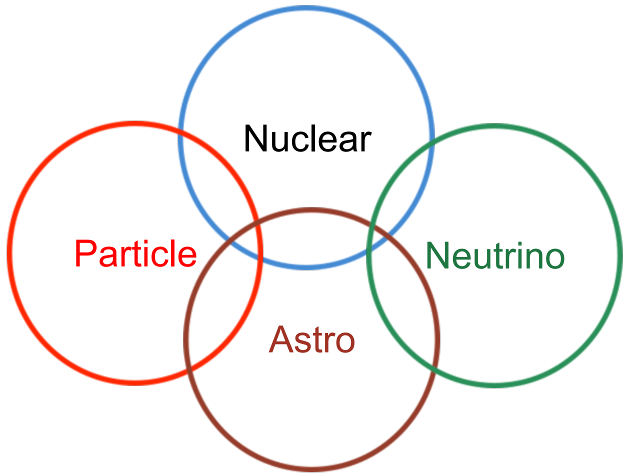


Conference on Neutrino and Nuclear Physics
Monastero dei Benedettini
Catania, Italy
October 15-21, 2017

ORNL is managed by UT-Battelle
for the US Department of Energy

Monastero dei Benedettini UNESCO World Heritage Site

Architectonical integration of different styles through different epochs.
e.g. a Roman house, the cloisters and a roof garden.



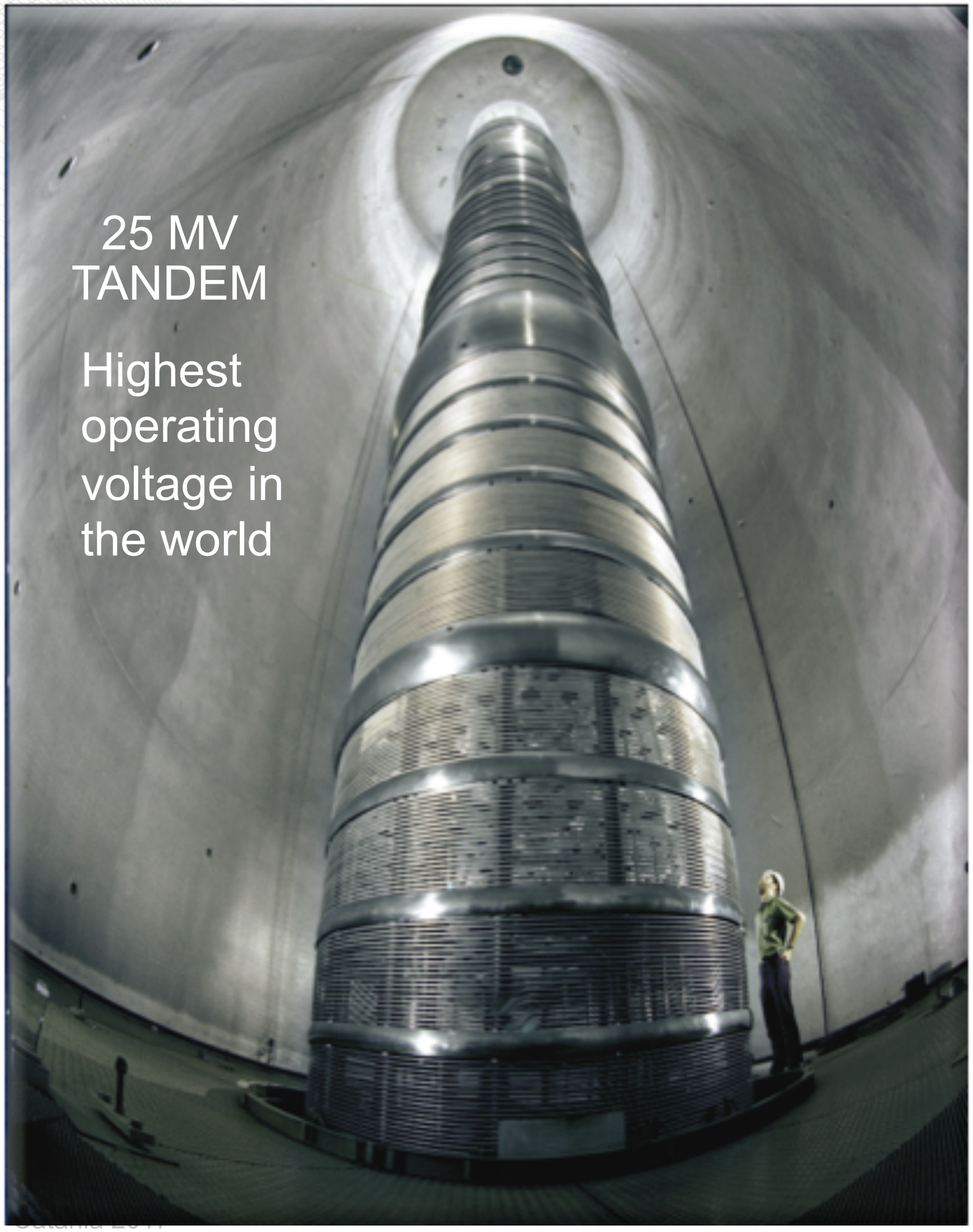
OUTLINE

- Oak Ridge -
  - Nuclear Structure
- New opportunities with neutrino sources
  - Development of Ultrasensitive Analytical Techniques
  - SNS and HFIR
- Reactors and accelerators as neutrino sources
- PROSPECT
  - Precision Reactor Oscillation and Spectrum Experiment
- Summary

HRIBF at ORNL designated an historical site by APS

July 2016 at Nuclear Structure 2016 Conference and
Neutrinos in Nuclear Physics Workshop (Precursor, CNNP-0)

ORNL HRIBF - APS Historical Site

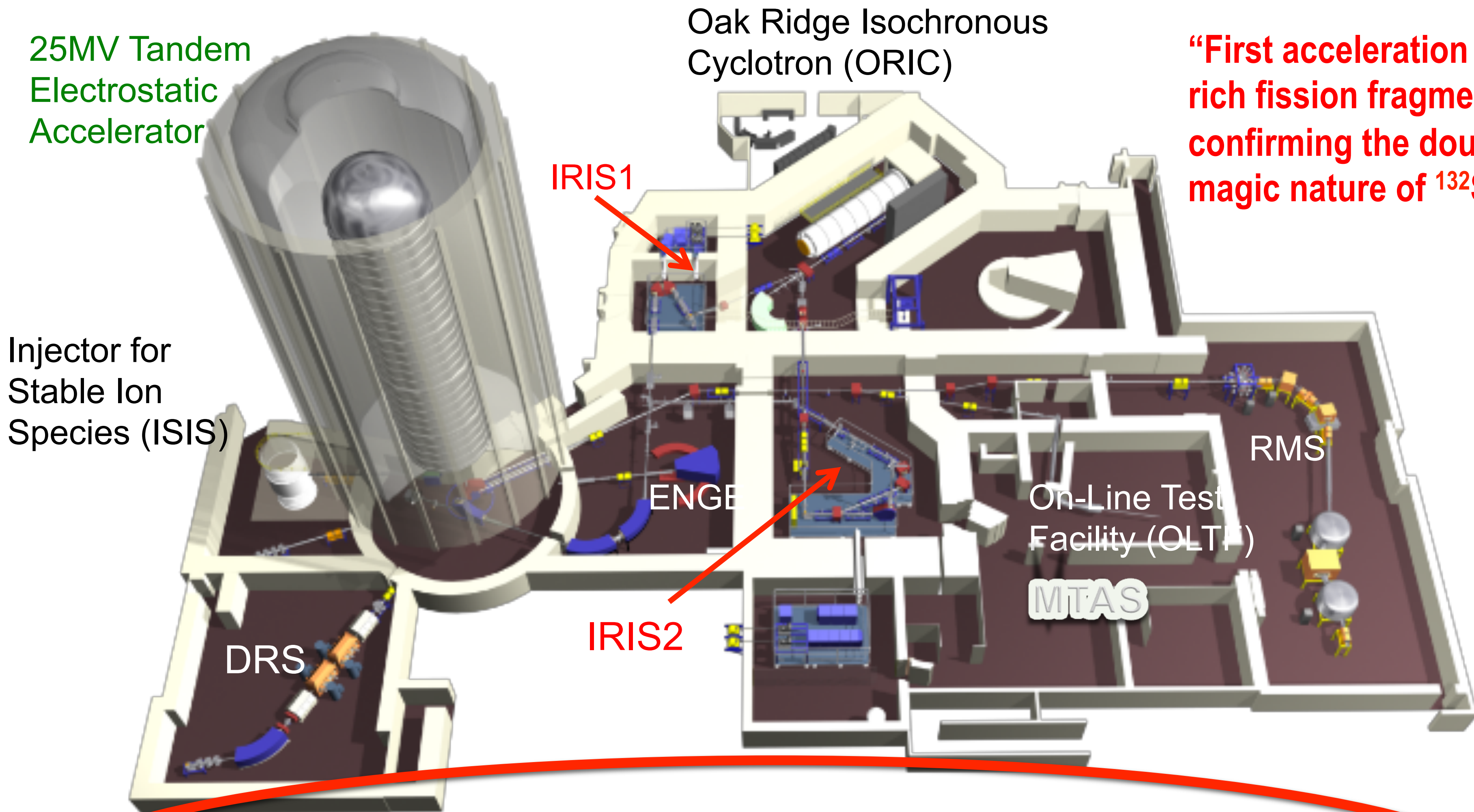


- Closed definitively

- APS Plaque for Historical Site

NS2016

HRIBF(1996-2012) pioneered techniques, methods and instrumentation in nuclear reaction spectroscopy with RIBs.



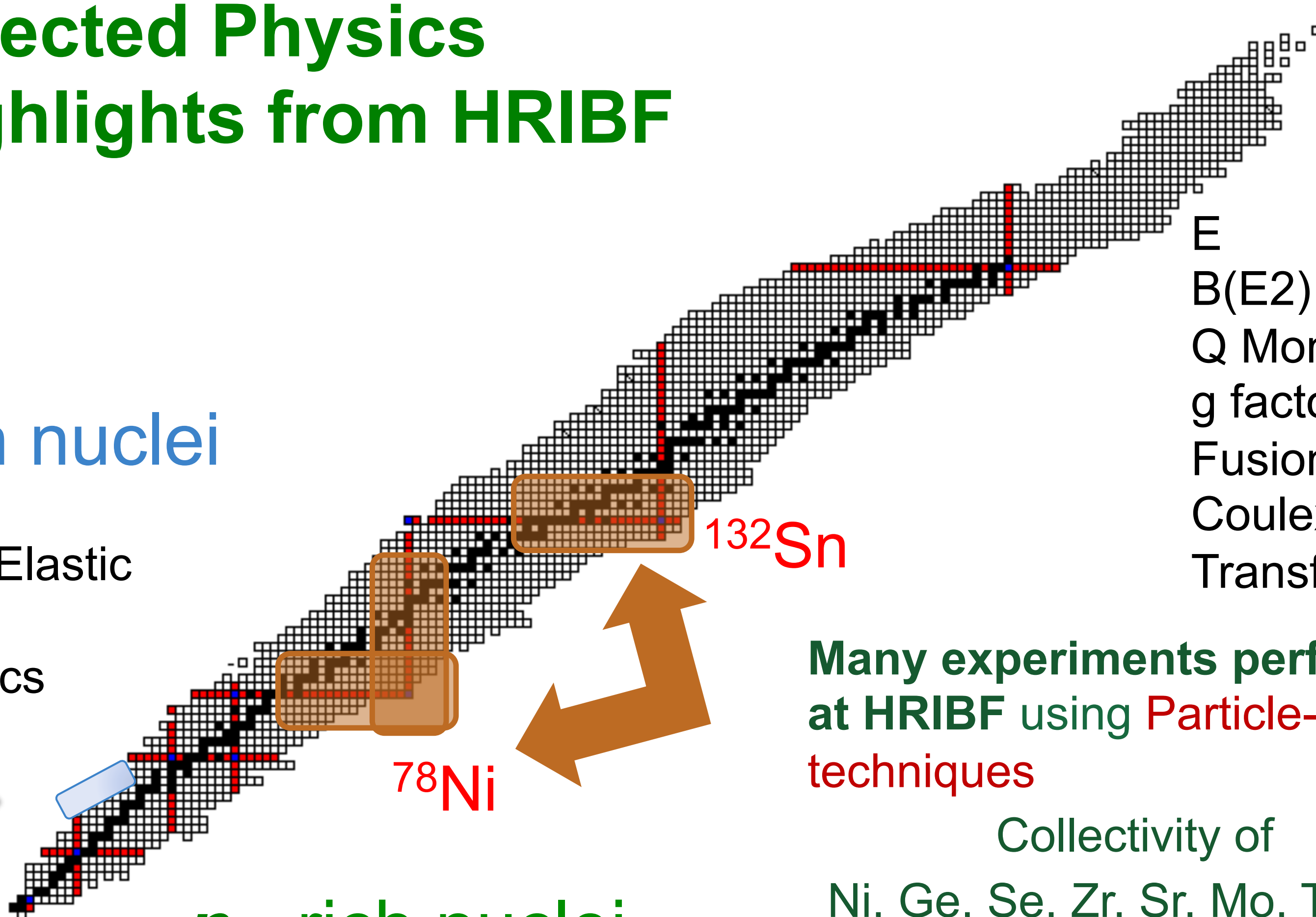
"First acceleration of n-rich fission fragments, confirming the doubly magic nature of ^{132}Sn."

As part of its infrastructure HRIBF has a variety of equipment for beam transport and analysis ideal to do AMS

Selected Physics Highlights from HRIBF

p **- rich nuclei**

Resonant Elastic
Scattering
Astrophysics
2p decay



E
B(E2)
Q Moments
g factors
Fusion reactions
Coulex reactions
Transfer reactions

n **- rich nuclei**

Systematic studies with identical techniques with both Stable and Radioactive Species
Emphasis on precision
Constraints on Theoretical Models
What Experimental data is required?

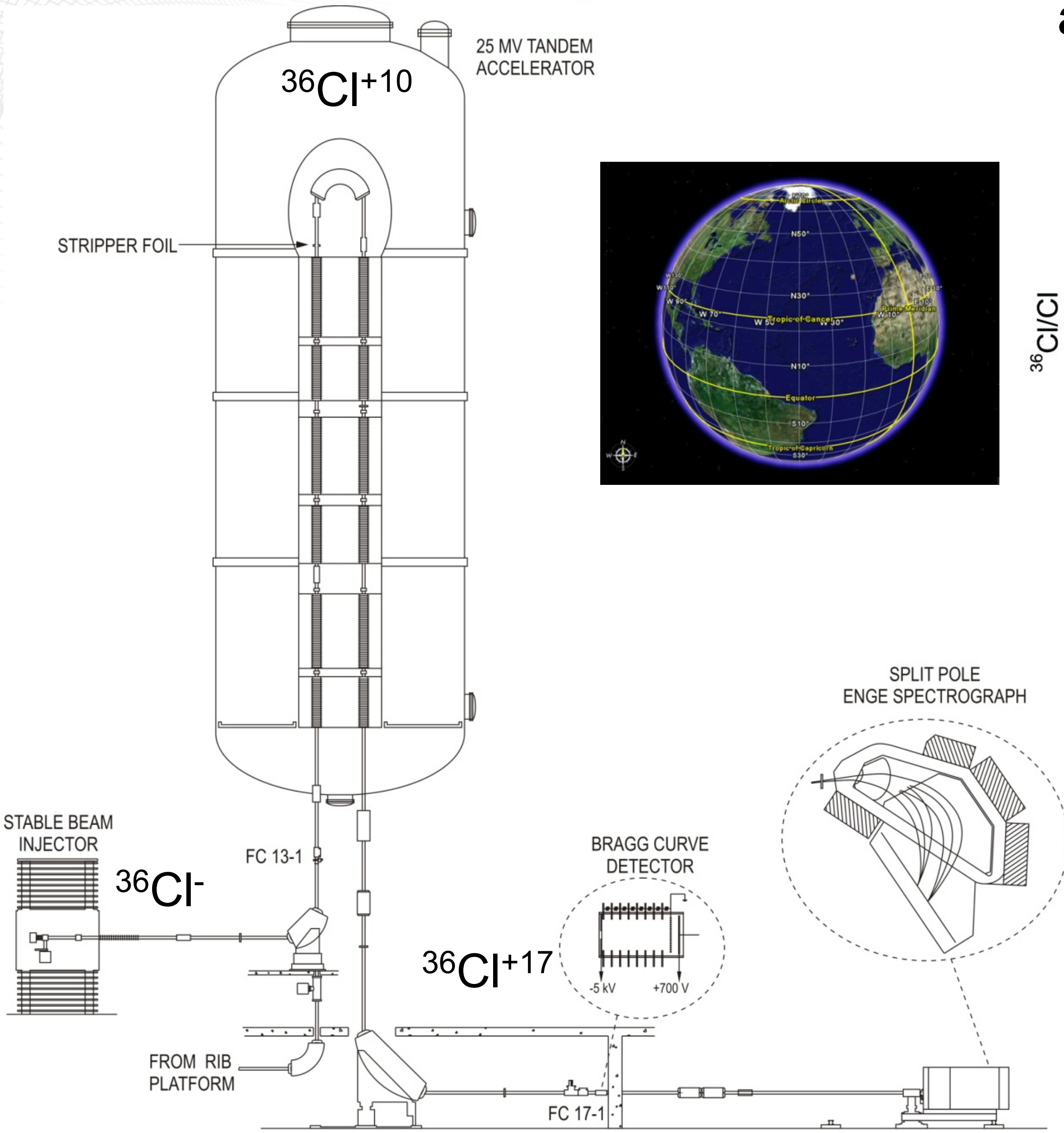
Many experiments performed at HRIBF using Particle-Gamma techniques

Collectivity of
Ni, Ge, Se, Zr, Sr, Mo, Te and
Sn isotopes
(**both** stable and radioactive)

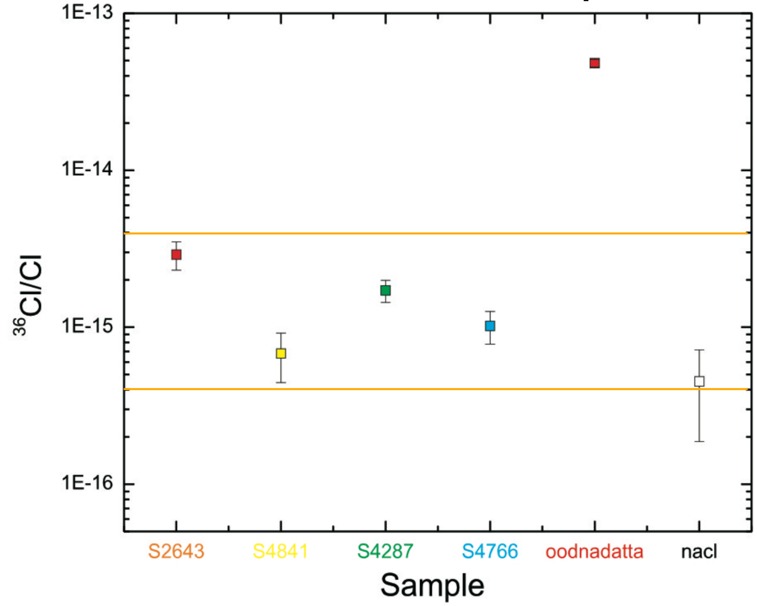
Need for analytical techniques to assess purity of materials

(See J. Detwiler and S. Schonert CNNP)

Measuring ^{36}Cl with AMS setup at ORNL at ppq



^{36}Cl in seawater samples from around the world: Comparison



Pushing the limits of accelerator mass spectrometry by an order of magnitude

Measurement of ^{36}Cl in seawater samples

A. G-U, et al. NIM B 259 (2007)123

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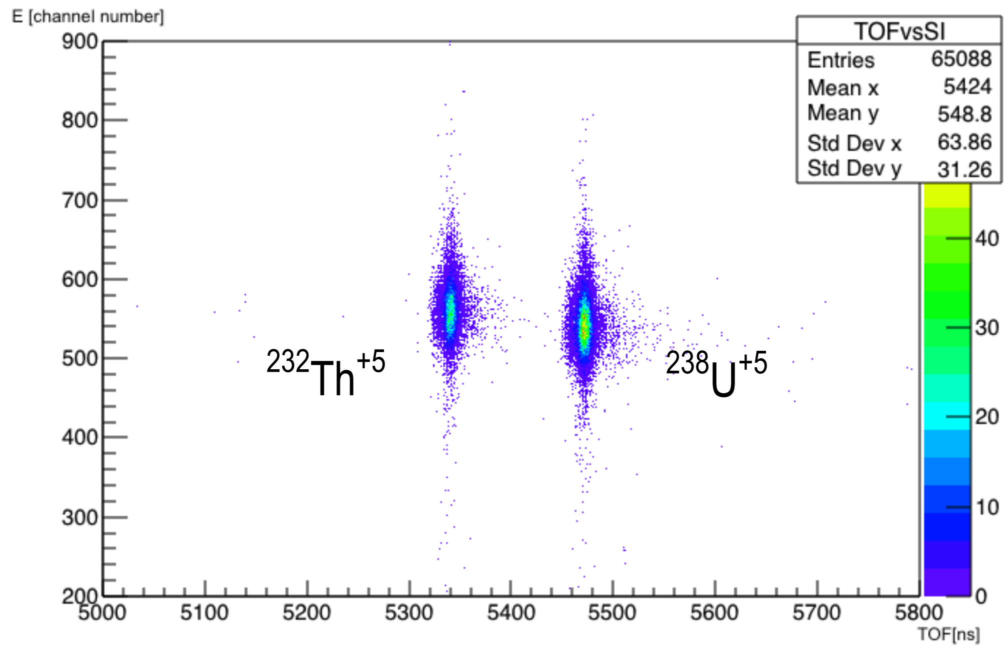
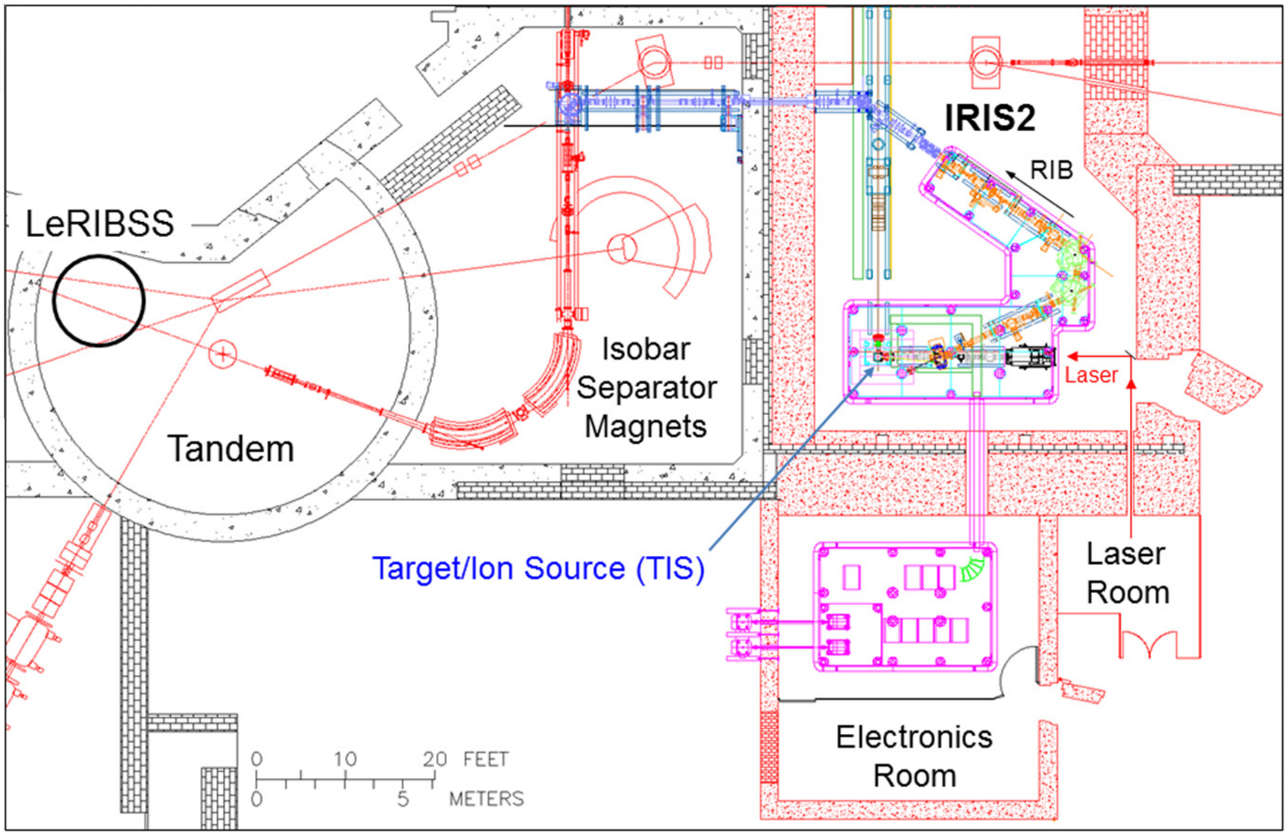
AMS as analytical tool for searches of $0\nu\beta\beta$

Detection of ^{232}Th and ^{238}U in ultrapure Cu with ANU 15 MV Tandem

- Detection of U and Th in ultrapure Cu samples produced at SURF (MJD) using UCu and ThCu molecules
- Need to develop a good "standard"



Detecting U and Th with resonant laser ionization(IRIS 2)



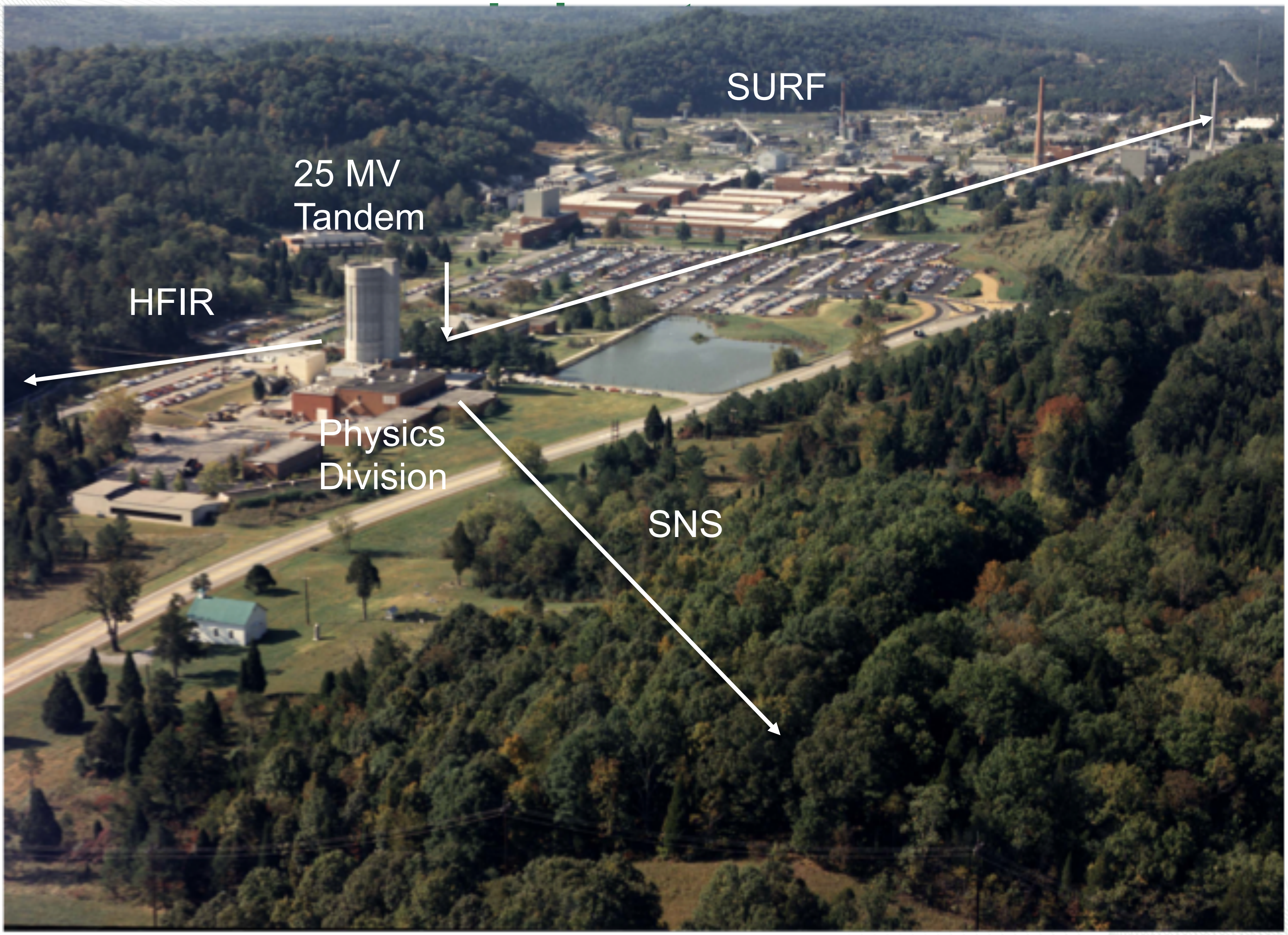
Efficient positive ion sources demonstrated for U and Th

Overall ionization efficiency of 8.7% for U and 40% for Th by resonant laser ionization

AMS (negative ions from sputtering source) efficiencies for actinides 0.01-0.1%

E. Romero-Romero AMS14 (Ottawa 2017)

New Opportunities at Oak Ridge National



Neutrino Physics at ORNL - ORLAND

Effort to establish a neutrino laboratory 20 years ago!

ORLaND — Oak Ridge Laboratory for Neutrino Detectors

F. Plasil[1] for the ORLaND Project and for the CoNDOR Collaboration

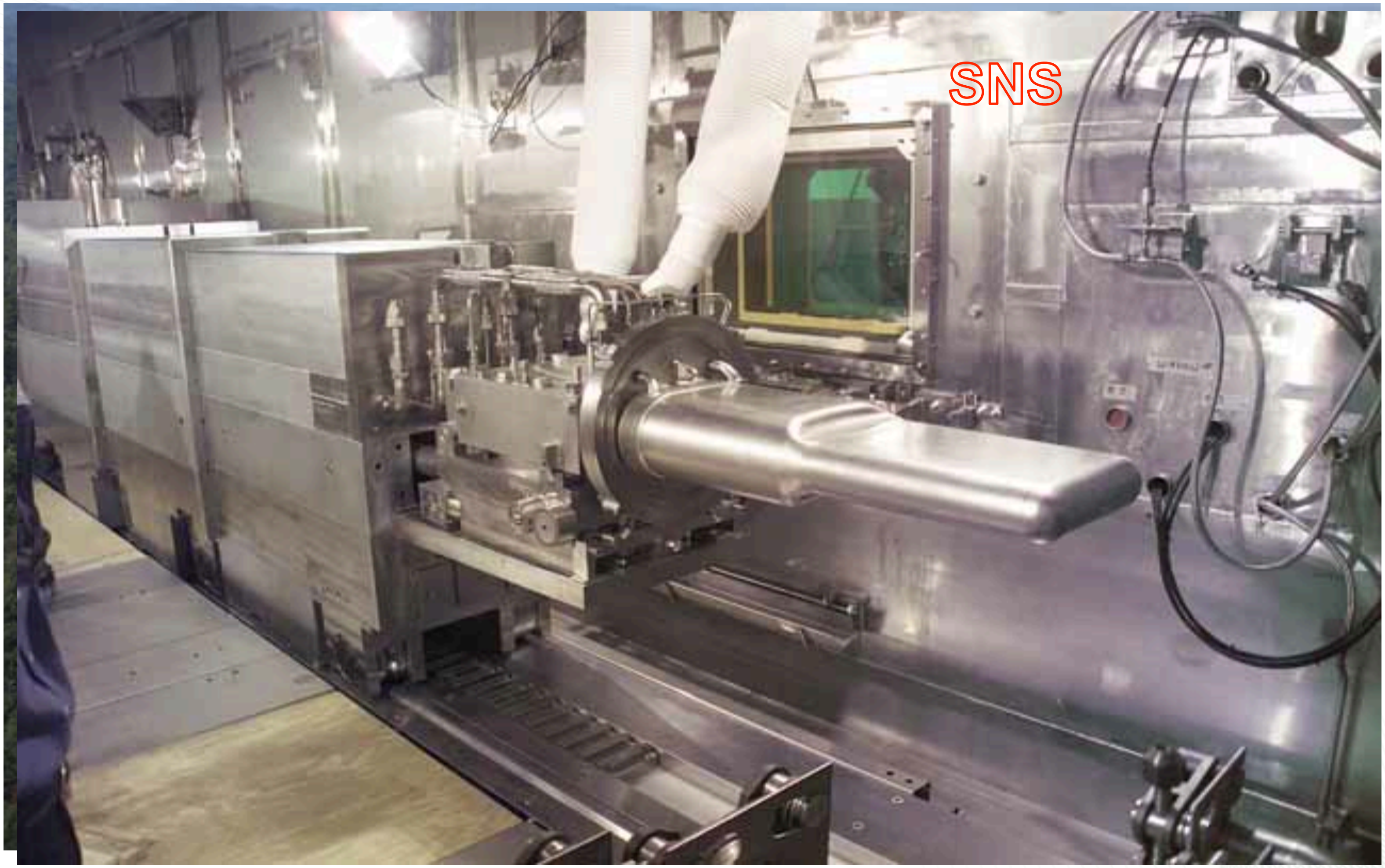
[1]Physics Division, Oak Ridge National Laboratory
Oak Ridge, TN 37831-6372, USA

Heavy Ion Physics15(2002)381

ORLaND Project and the CoNDOR Collaboration

B. Anderson,[h] F.T. Avignone,[y] T.C. Awes,[m] C. Baktash,[m] J.B. Ball,[m] D.W. Bardayan,[m] J.R. Beene,[m] S.C. Berridge,[z] F.E. Bertrand,[m] Ed Bilpuch,[e] J.C. Blackmon,[m] R.N. Boyd,[n] C.L. Britton,[m] W.M. Bugg,[z] R.L. Burman,[i,u] J. Busenitz,[r] H.K. Carter,[l] L. Chatterjee,[c] T.V. Cianciolo,[m] H.O. Cohn,[z] M. Danilov,[f] D.J. Dean,[m] L. DeBraeckeleer,[e] P. Degtiarenko,[g] G.W. Dodson,[m] Y.V. Efremenko,[m,z] M.A. Elaasar,[p] A.R. Fazely,[o] T.A. Gabriel,[m] A. Galindo-Uribarri,[m] C.R. Gould,[w] Z.D. Greenwood,[k] V. Gudkov,[y] R. Gunasingha,[o] T. Handler,[z] C.K. Hargrove,[b] E. Hart,[z] R.L. Imlay,[j] Y.A. Kamyshkov,[z] H.J. Karwowski,[v] D.D. Koetke,[aa] K. Kubodera,[y] K. Lande,[x] C. Lane,[d] R.W. Manweiler,[aa] W.J. Metcalf,[j] A. Mezzacappa ,[m,z] G.B. Mills,[i] L.W. Mo,[bb] A. Murphy,[n] T. Nunamaker,[bb] S. Nussinov,[q] A. Piepke,[r] F. Plasil,[m] J.J. Reidy,[t] C. Rosenfeld,[y] D. Smith,[cc] I. Stancu,[r] S. Stanislaus,[aa] R.I. Steinberg,[d] M.R. Strayer,[m] R.C. Svoboda,[j] R. Tashakkori,[m] W. Tornow,[e] G.J. VanDalen,[s] J. Wolf,[r] G.R. Young,[m] O. Zeldovich,[f] W.-M. Zhang[h]

SNS: Spallation ~~Neutron~~ *NEUTRINO* Source
p beams, 60 Hz, 1MW power



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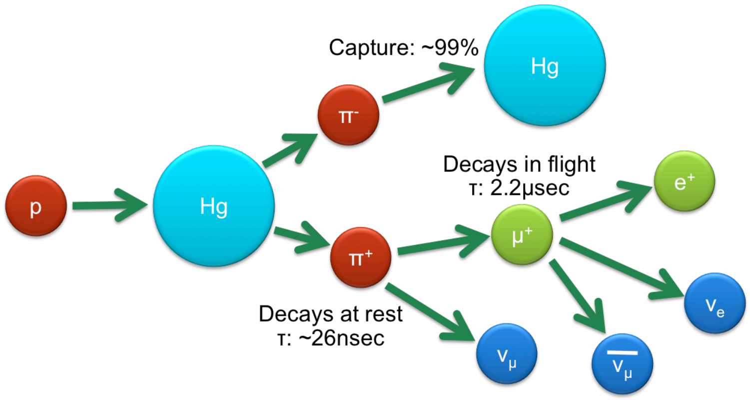
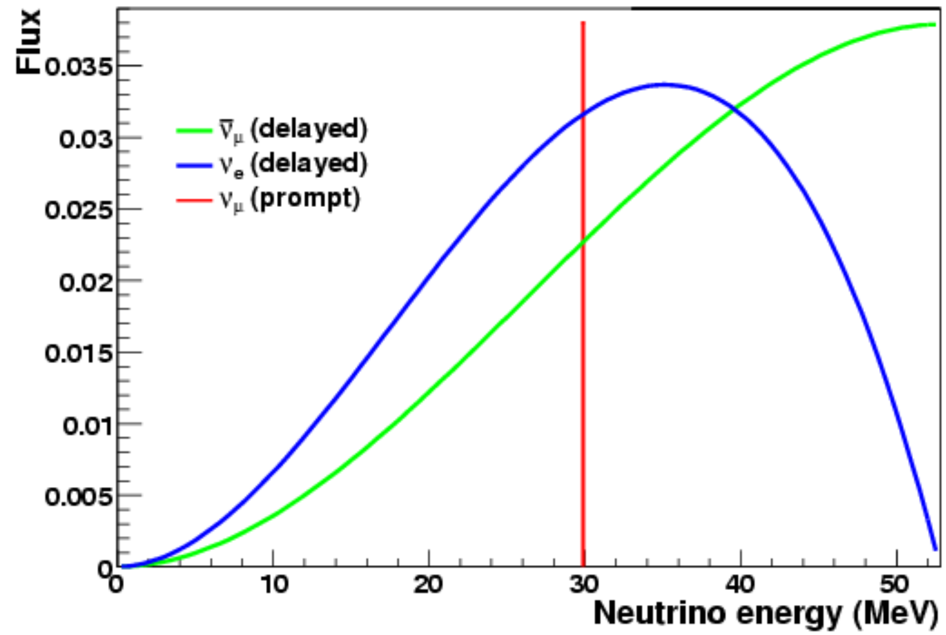
Stopped-Pion (πDAR) Neutrinos





$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

2-body decay: monochromatic 29.9 MeV ν_μ
PROMPT

$$\downarrow$$

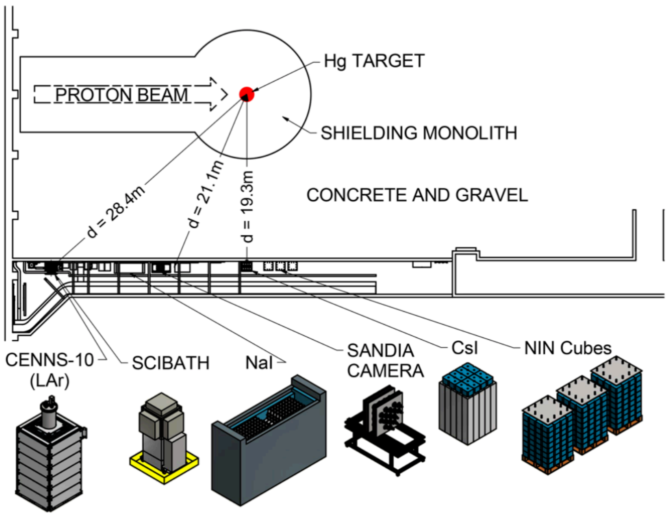
$$\mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e$$

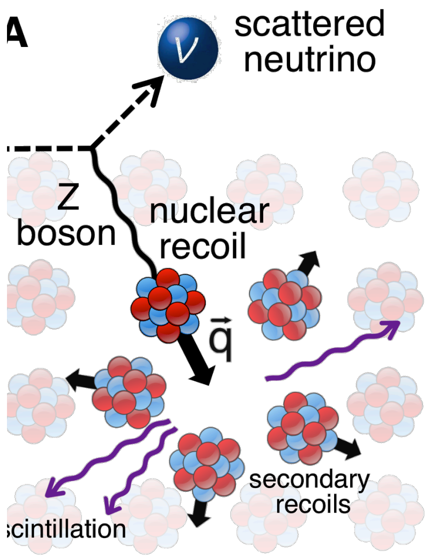
3-body decay: range of energies between 0 and $m_\mu/2$
DELAYED (2.2 μs)

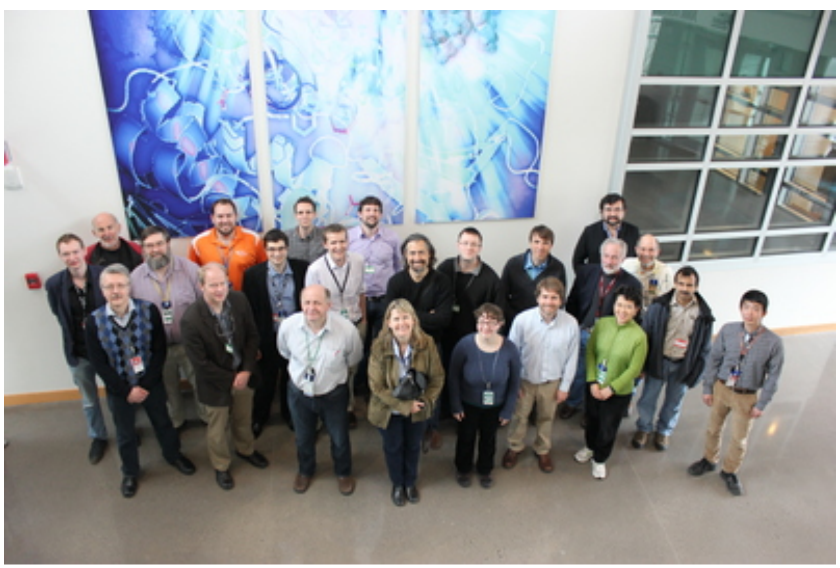
(See K. Schoelberg CNNP)

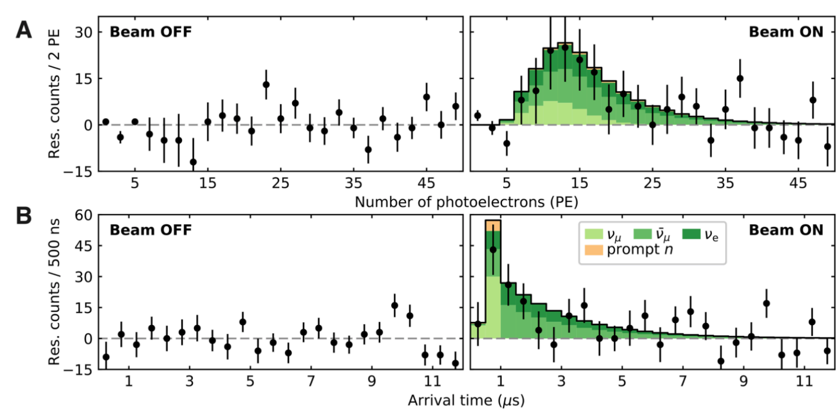
COHERENT

Science Cover
Sept 15, 2017





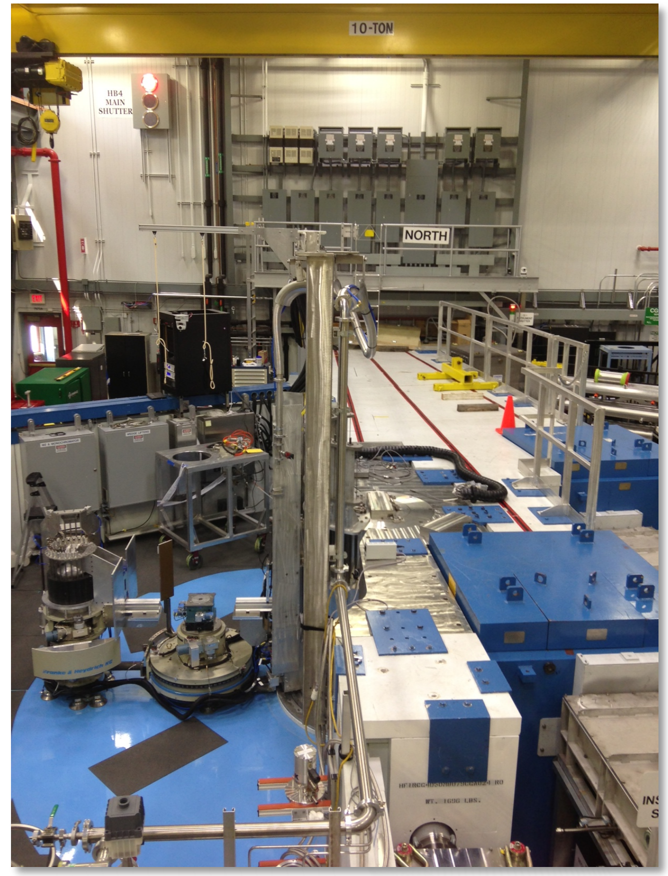




ORNL and Research Reactors

The Clinton Pile was the world's first continuously operated nuclear reactor
Critical on Nov. 1943
(Wigner, Fermi and Weinberg)

85MW Research Reactor



The HFIR became critical on Aug. 1965
(Seaborg at AEC, Cheverton, and Weinberg)

Several reactors developed: X-10, MTR, LITR, BSR, TSF, ORR, HFIR

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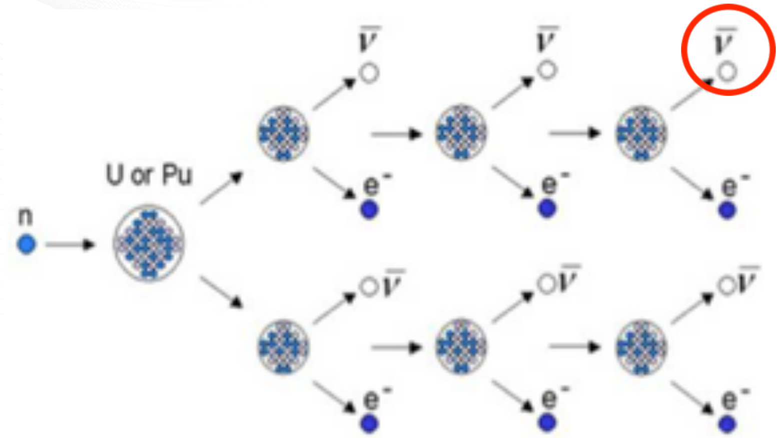
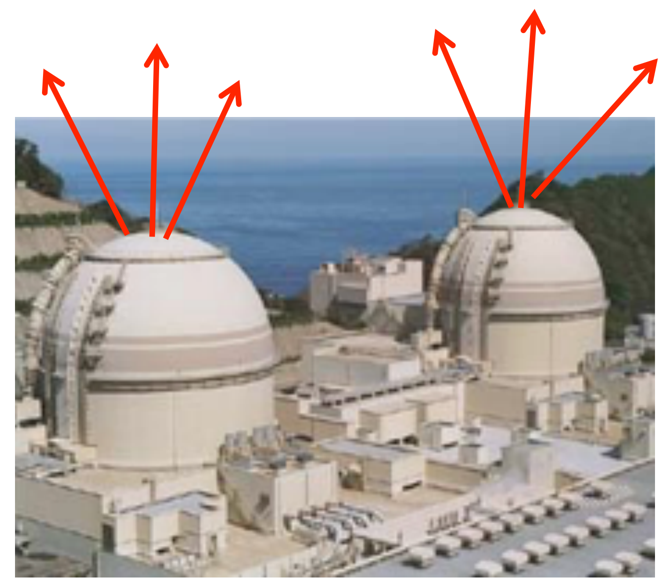
Reactors as antineutrino sources

β- decay of neutron rich fission fragments





energy per fission

Kinetic energy of fragments	165 (5)
Energy of prompt photons	7 (1)
Kinetic energy of neutrons	5 (0.5)
Energy of β decay electrons	7 (1)
Energy of β decay antineutrinos	10
Energy of γ decay photons	6(1)

~ 200 MeV/fission and 6 $\bar{\nu}_e$/fission

Pure source of $\bar{\nu}_e$

~ 5% energy taken away by neutrinos

3 GW reactor produces ~6×10^{20} $\bar{\nu}_e$/sec

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Chalk River Laboratories

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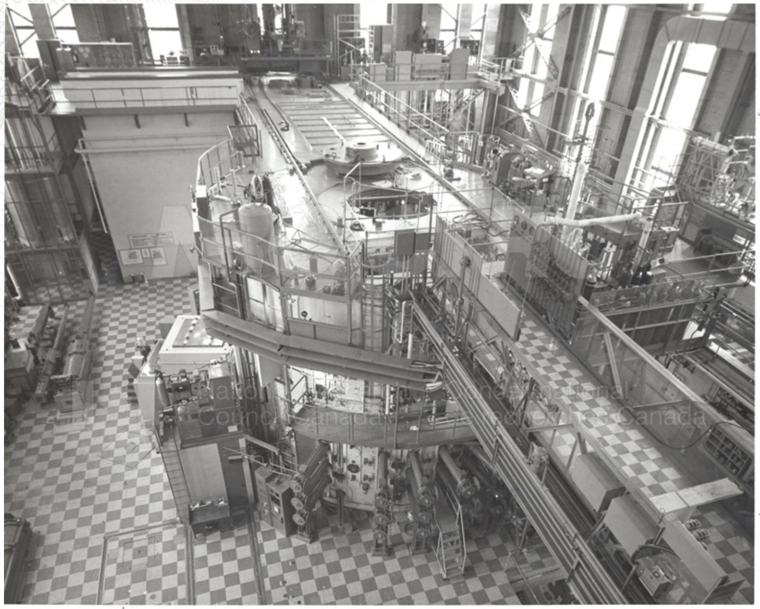
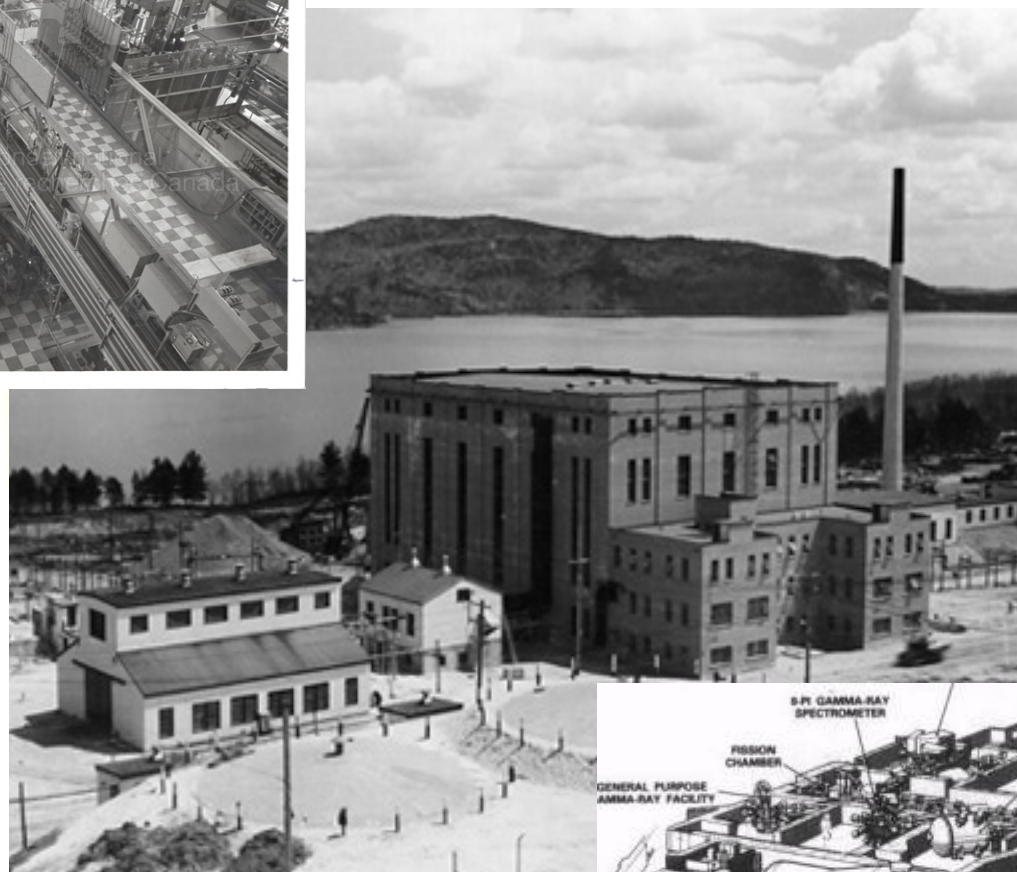
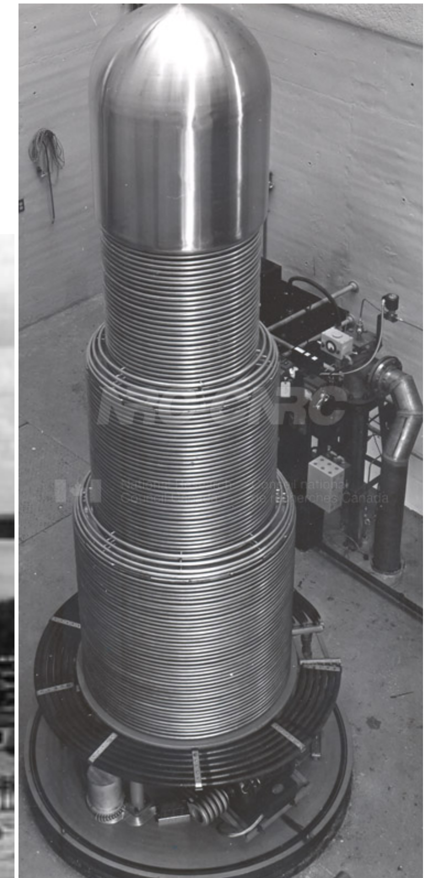
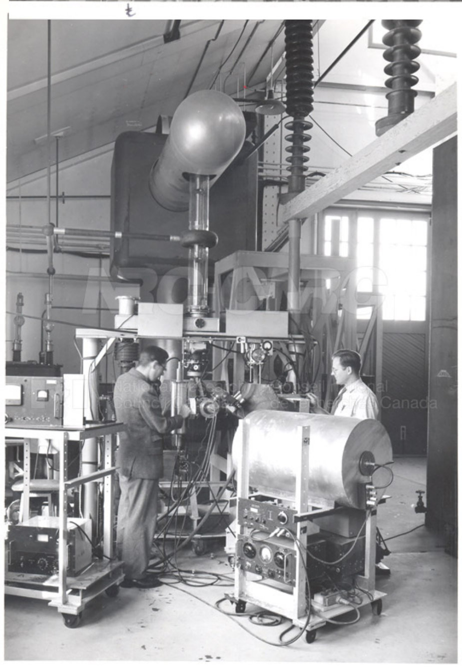


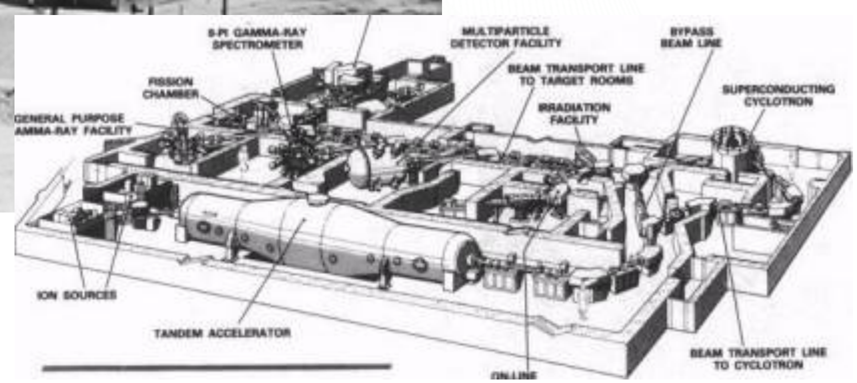
Combined basic and
applied research
Research reactors
and accelerators



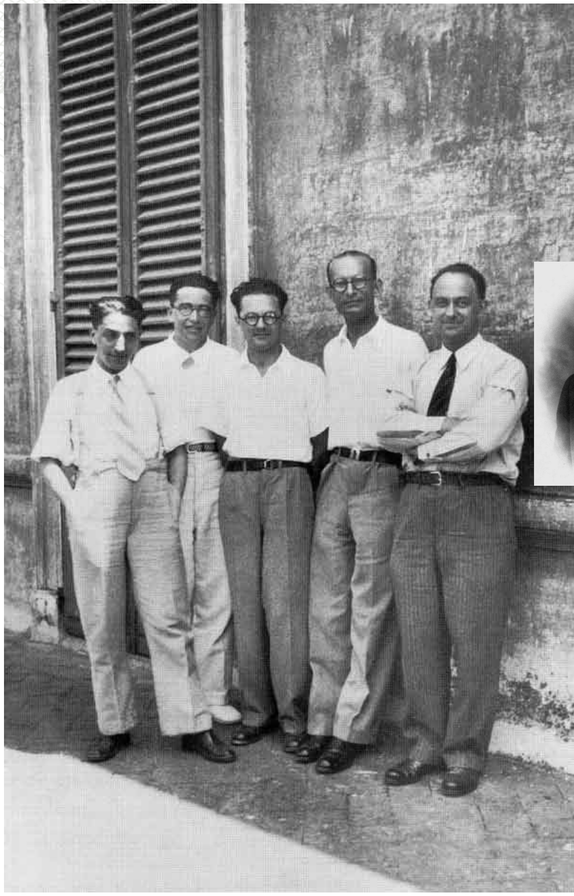




TASCC
Tandem Accelerator
Superconducting Cyclotron



Italian Physicists - Bruno Pontecorvo

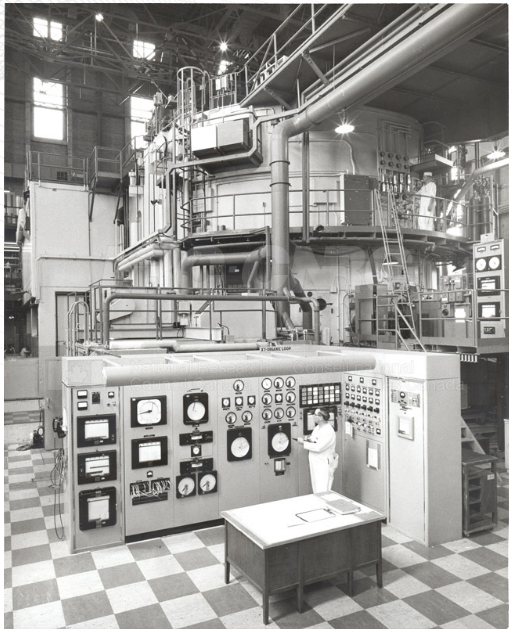


Ragazzi Via Panisperna
D'Agostino, Segre,
Amaldi, Rassetti, Fermi

Majorana +

Bruno Pontecorvo in Anglo-Canadian nuclear research laboratory in Montreal (1943-1945) and Chalk River (1945-1949)

Nuclear Reactors as a Neutrino Source



NRX critical July 22, 1947.
Most powerful research reactor

Cockcroft 1944
Build large heavy water and natural Uranium reactor

Pontecorvo declined Segre's offer job at Berkeley hoping to use the 20 MW Chalk River NRX (National Research eXperimental) for neutrino research

At that time neutrino was considered an undetectable particle

Reactors are intense and pure sources of $\bar{\nu}_e$

B. Pontecorvo Natl. Res. Council Canada Rep. (1946) 205
Helv. Phys. Acta. Suppl. 3 (1950)97

Good for systematic studies of neutrinos

Pontecorvo and neutrino detection radiochemical method (too early?)

Invention of the radiochemical methods to detect neutrinos

(he felt his work was not fully recognized)

The inverse process consists in a radioisotope created by free neutrino interaction with stable nuclei and positron emission. Detection of a radioisotopes is proof of neutrino existence.

The radioactive atoms produced have different chemical properties. The few atoms produced can thus be extracted from the large irradiated volume and concentrated for detection.

Pontecorvo never did the experiment Chlorine-Argon method.

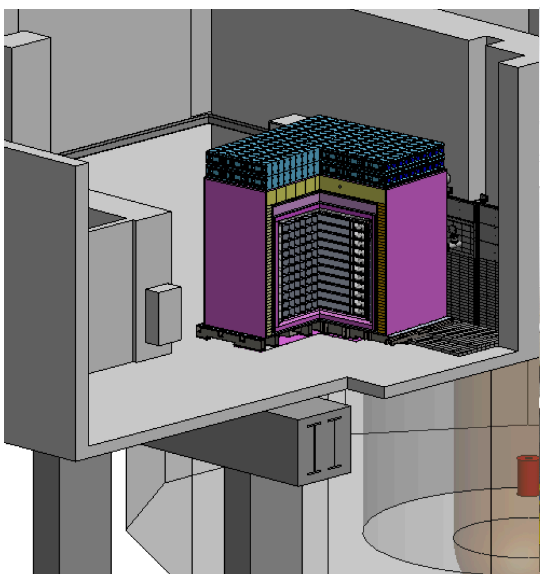
(Confusing status of ^{37}Cl data)

- **Railway tank wagon was ever filled with carbon tetrachloride and taken into a Canadian Rocky Mountains tunnel.**
- **NRX reactor Most powerful research reactor and intense sources of antineutrinos**

Pontecorvo left for Dubna August 1950

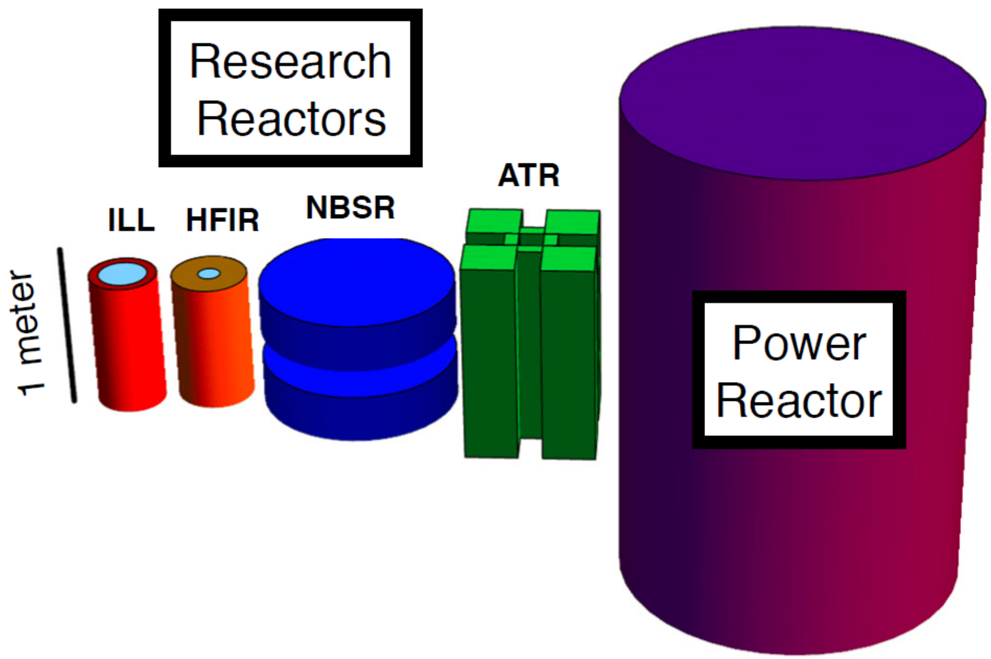
PROSPECT

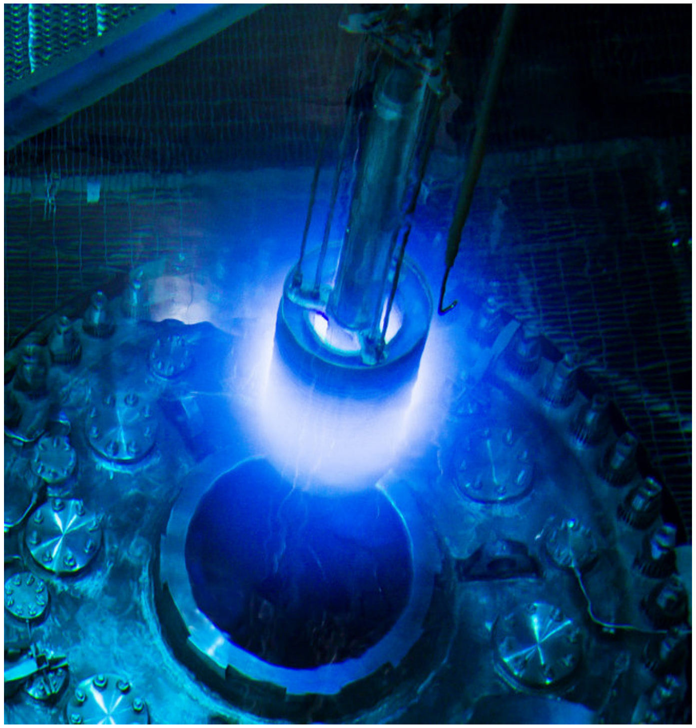
- A Precision Oscillation and Spectrum Experiment

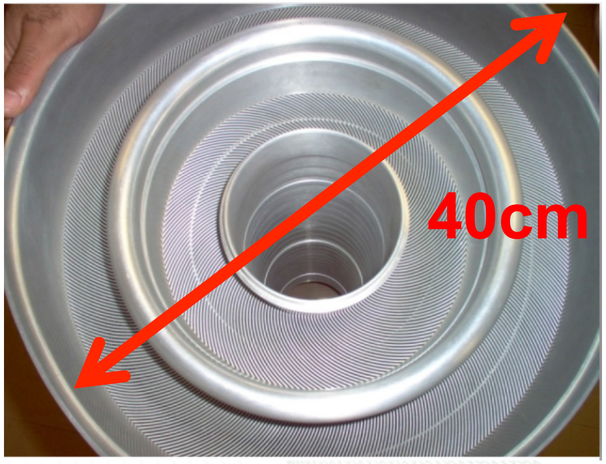


The High Flux Isotope Reactor HFIR

- 85 MW Thermal Power Research Reactor
- ~93% enriched ^{235}U fuel
- Very compact core (h=0.6m d=0.4m)
- Very near access available
- 24 day cycle means no ^{239}Pu buildup (<0.5%)
- ~50% duty cycle allows good background characterization







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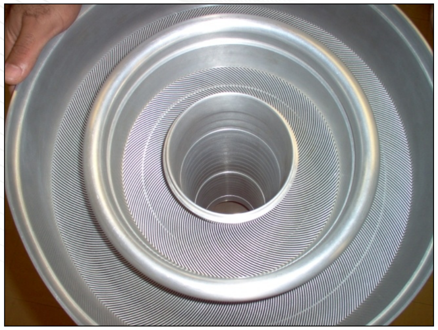
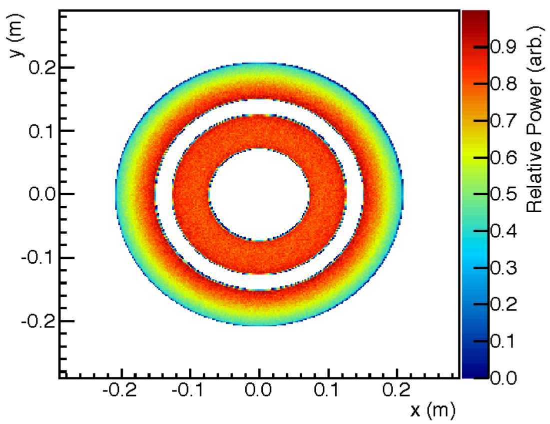
Experimental site: High Flux Isotope Reactor

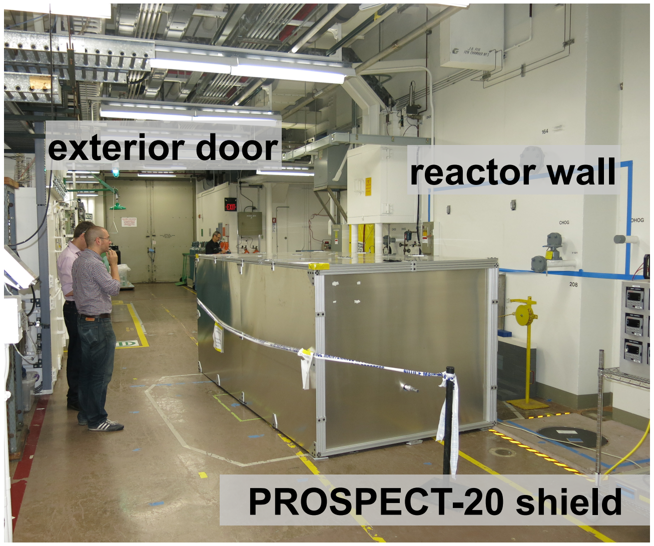
Compact Reactor Core

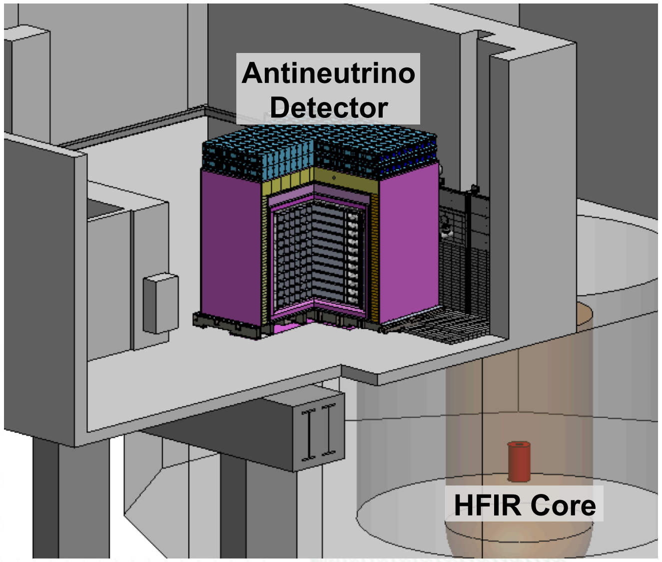


Power: 85 MW
Fuel: HEU (^{235}U)
Core shape: cylindrical
Size: h=0.5m r=0.2m
Duty-cycle: 41%



- Established on-site operation
- User facility, 24/7 access
- Exterior access at grade
- Full utility access





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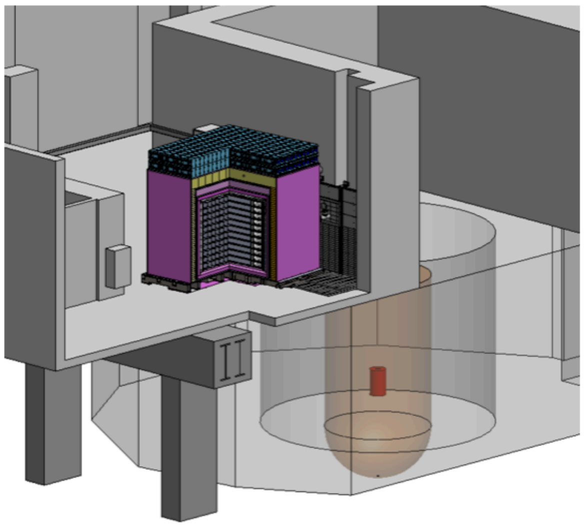
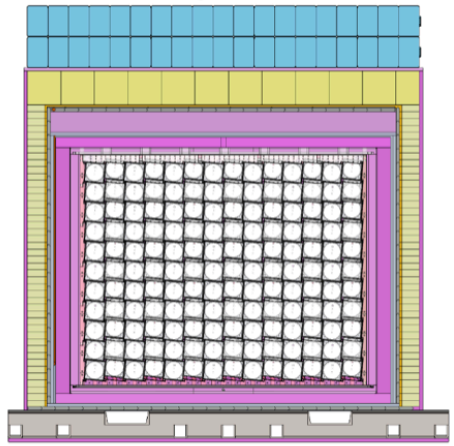
Precision Reactor and Oscillation Experiment

PROSPECT

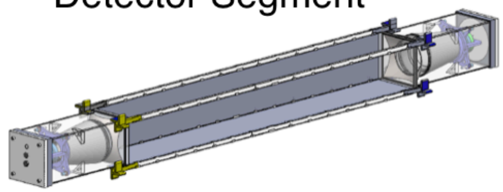
Segmented, ^{6}Li loaded Detector



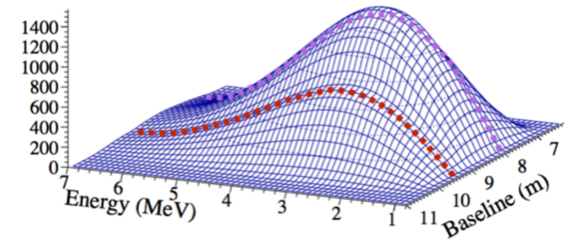
Active Inner Detector
+Shielding



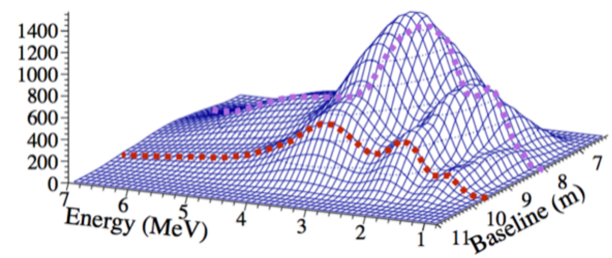
Detector Segment



unoscillated spectrum



oscillated spectrum



Detector Design

- ^{6}Li liquid scintillator
- minimum dead material
- double-ended PMT readout,
- light guides, 5” PMTs
- ~5%/√E resolutions

Segmented Detector

relative measurement of L/E within detector

Relative Spectrum Measurement

search for relative shape distortions independent of reactor models/ predictions

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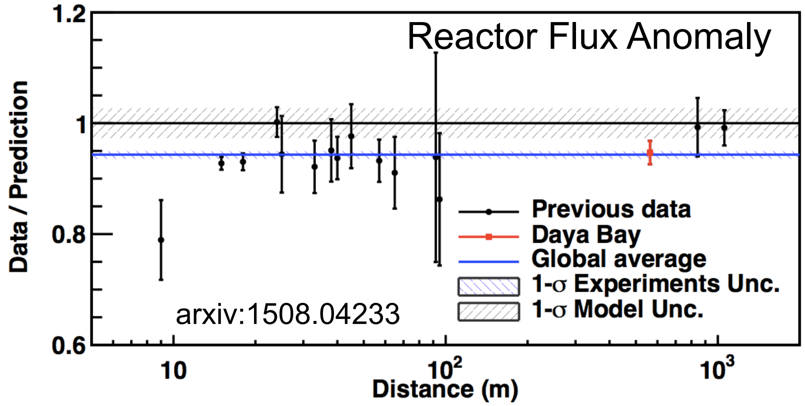
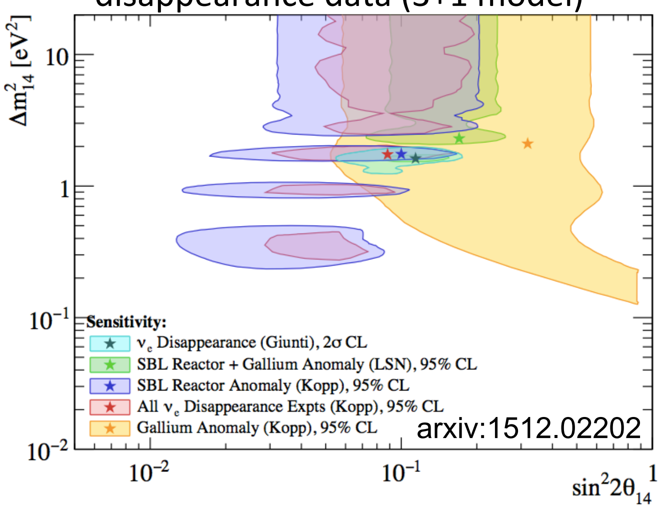
Motivation

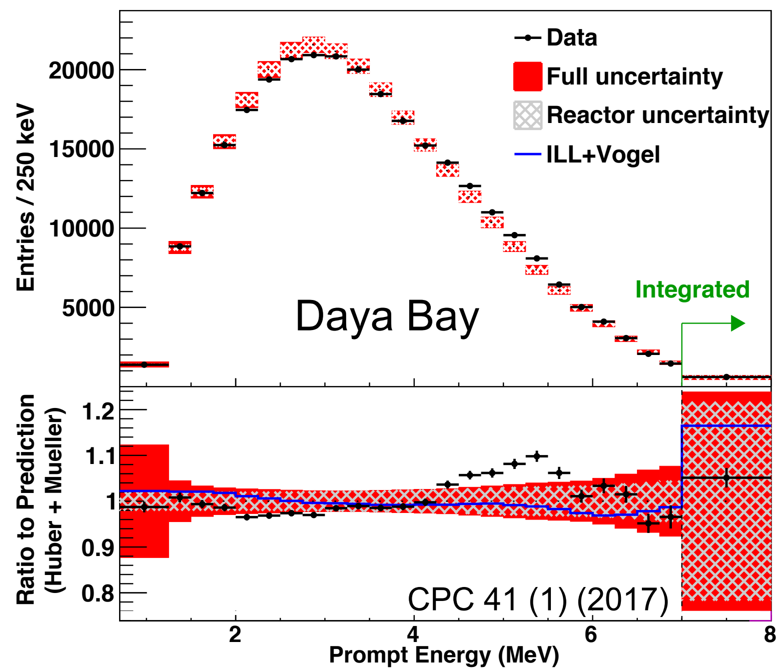
Directly test the hypothesis of a new oscillation with $\Delta m^2 \sim 1$ eV^2, i.e. oscillation length of few meters



Allowed regions for ν_e disappearance data (3+1 model)



Provide new tests of reactor models by making precision measurements of novel reactor spectra, esp. ^{235}U fuel



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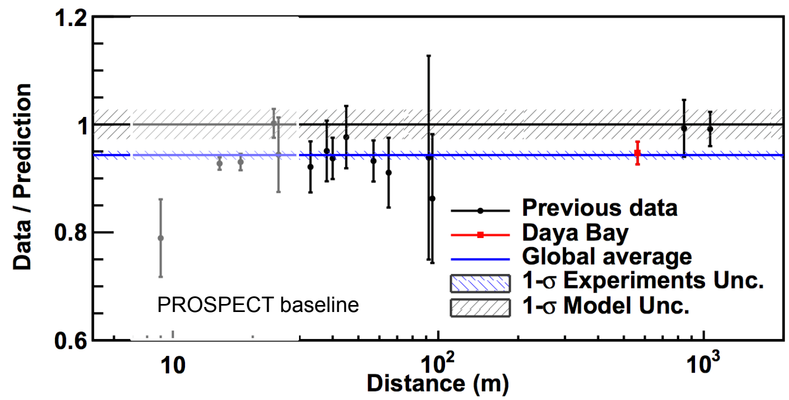
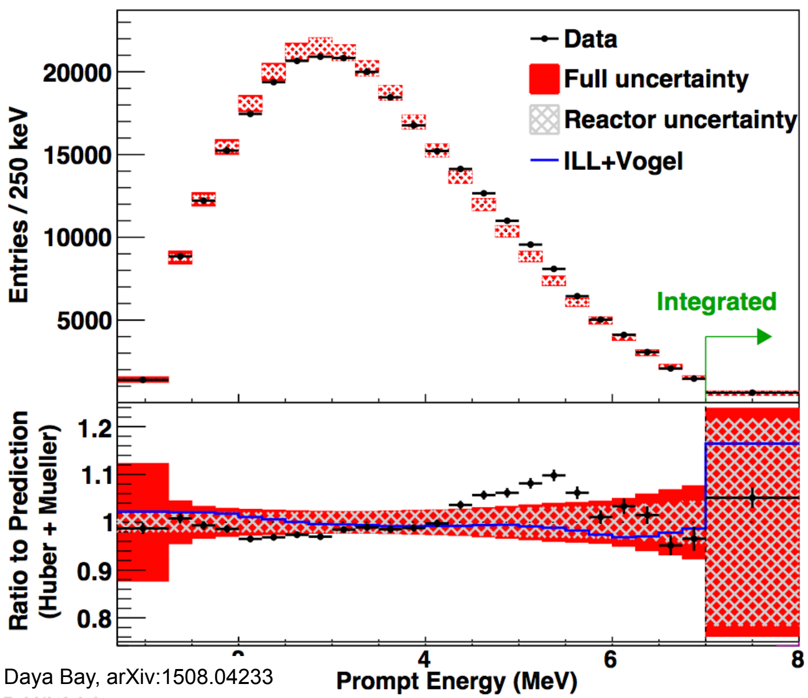
Reactor anti-neutrino anomalies

Motivation behind PROSPECT





Daya Bay, arXiv:1508.04233

Flux Deficit

- 6% flux deficit
- Few measurements made at very short baselines (<10m from core)

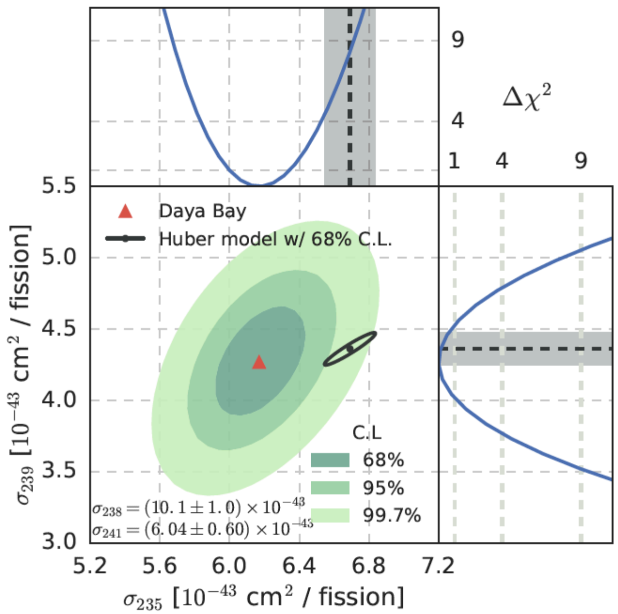
Spectral Anomaly

- 10% excess of events in 4-6 MeV region

Recent Developments: Flux evolution & IBD Yields

Daya Reactor Flux Evolution

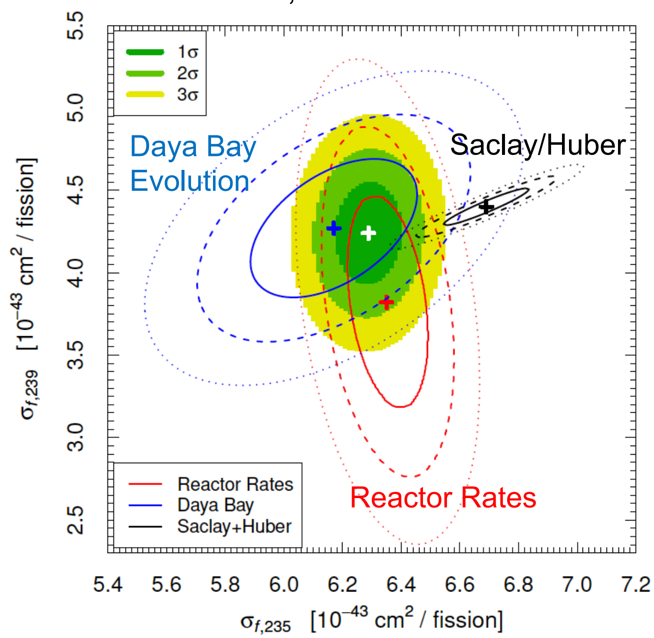
Daya Bay, PRL 118 251801 (2017)



Report IBD yields for U-235 and Pu-239 using change due to fuel evolution – demonstrates prediction for U-235 (at least) is incorrect

Improved Cross Section per Fission Determination

Giunti, arXiv:1704.02276



Tension between IBD yield from 26 previous reactor measurements and Daya Bay

Direct, model independent, search for short baseline oscillation remains well motivated

"not enough information to use the antineutrino flux changes to rule out the possible existence of sterile neutrinos"

Hayes et al, arXiv:1707.07728

"the search for the explanation of the reactor antineutrino anomaly still remains open"

Giunti et al, arXiv:1708.01133

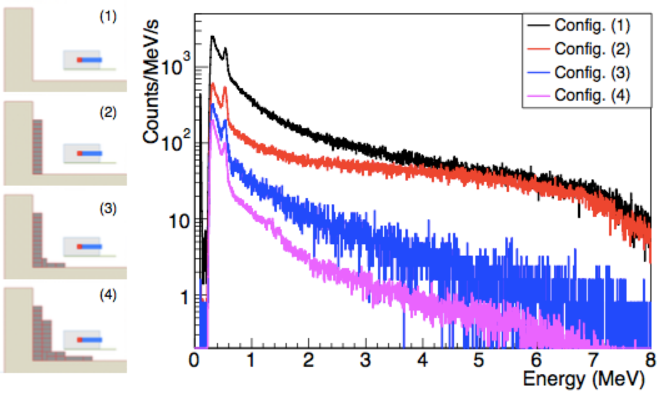
(See L Hayen and C. Giunti CNNP)

Reactor Background Measurement & Shield Design

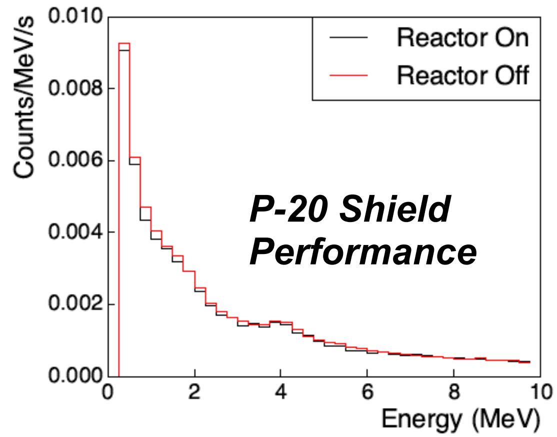
Shield design based on surveys & multiple onsite prototype deployments

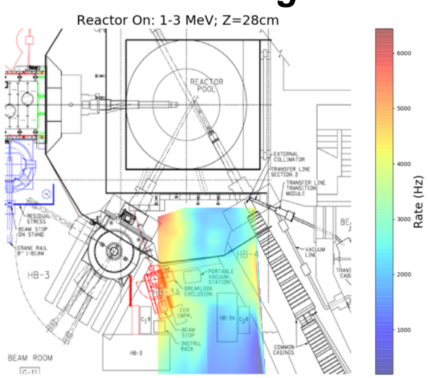
Extensive measurement campaigns (*ongoing*):

- Characterize background field at HFIR
- Emphasize importance of localized shielding of penetrations, pipes, etc



Localized shielding studies



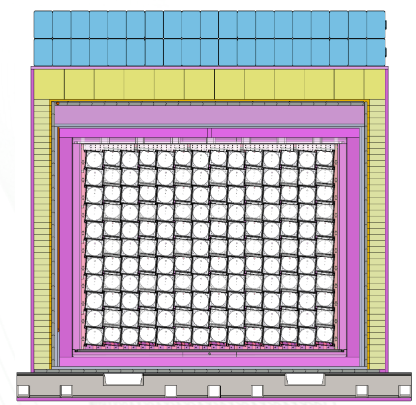


γ-ray intensity variation at HFIR

Nucl. Instrum. Meth. A806 (2016) 401–419, arXiv:1506.03547, PROSPECT Collaboration

PROSPECT AD Shielding

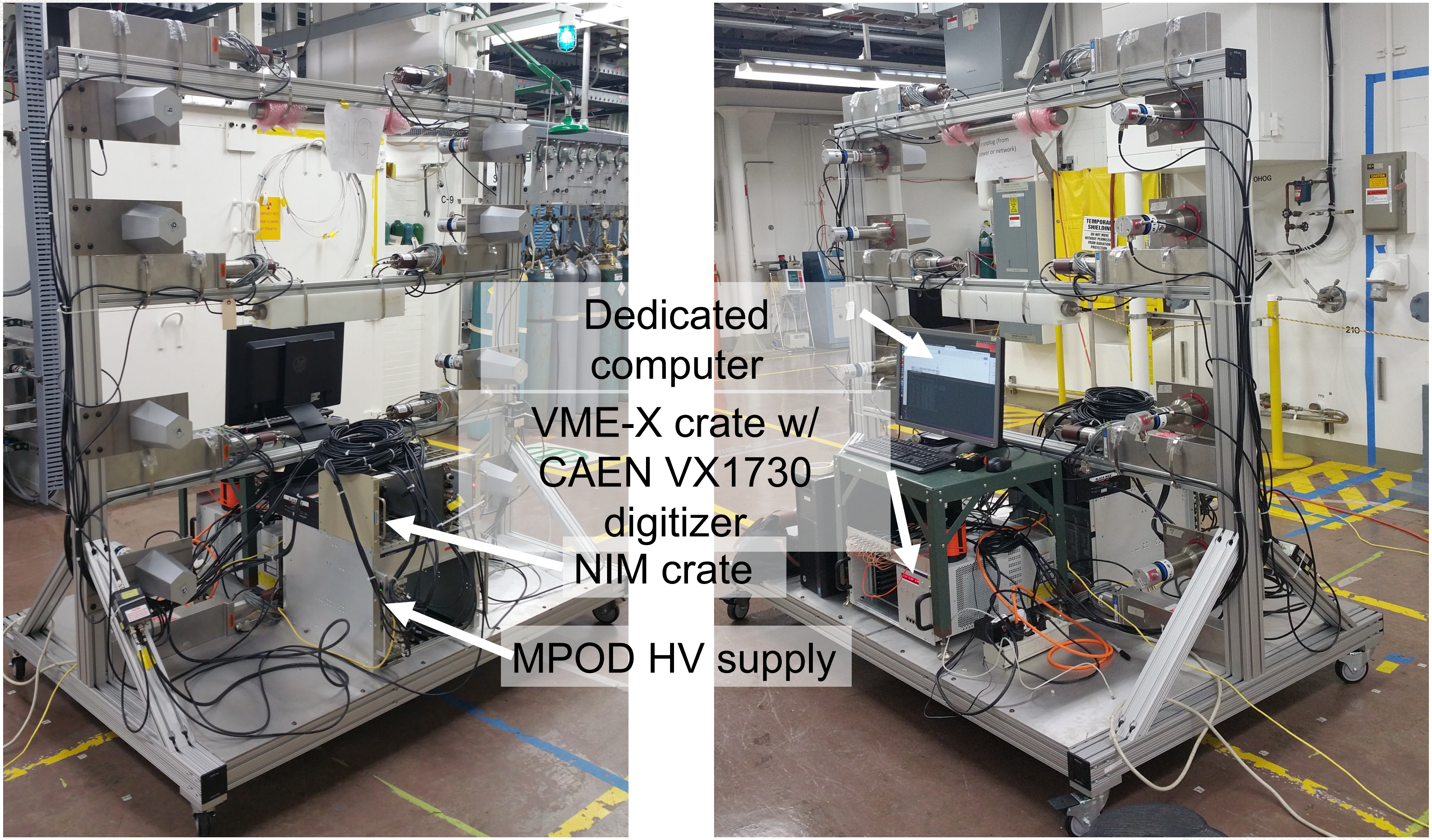
- local shielding next to reactor wall
- multi-layer passive shield:
  - water bricks, HDPE, borated HDPE, lead



AD-1 Multi-Layer Shield

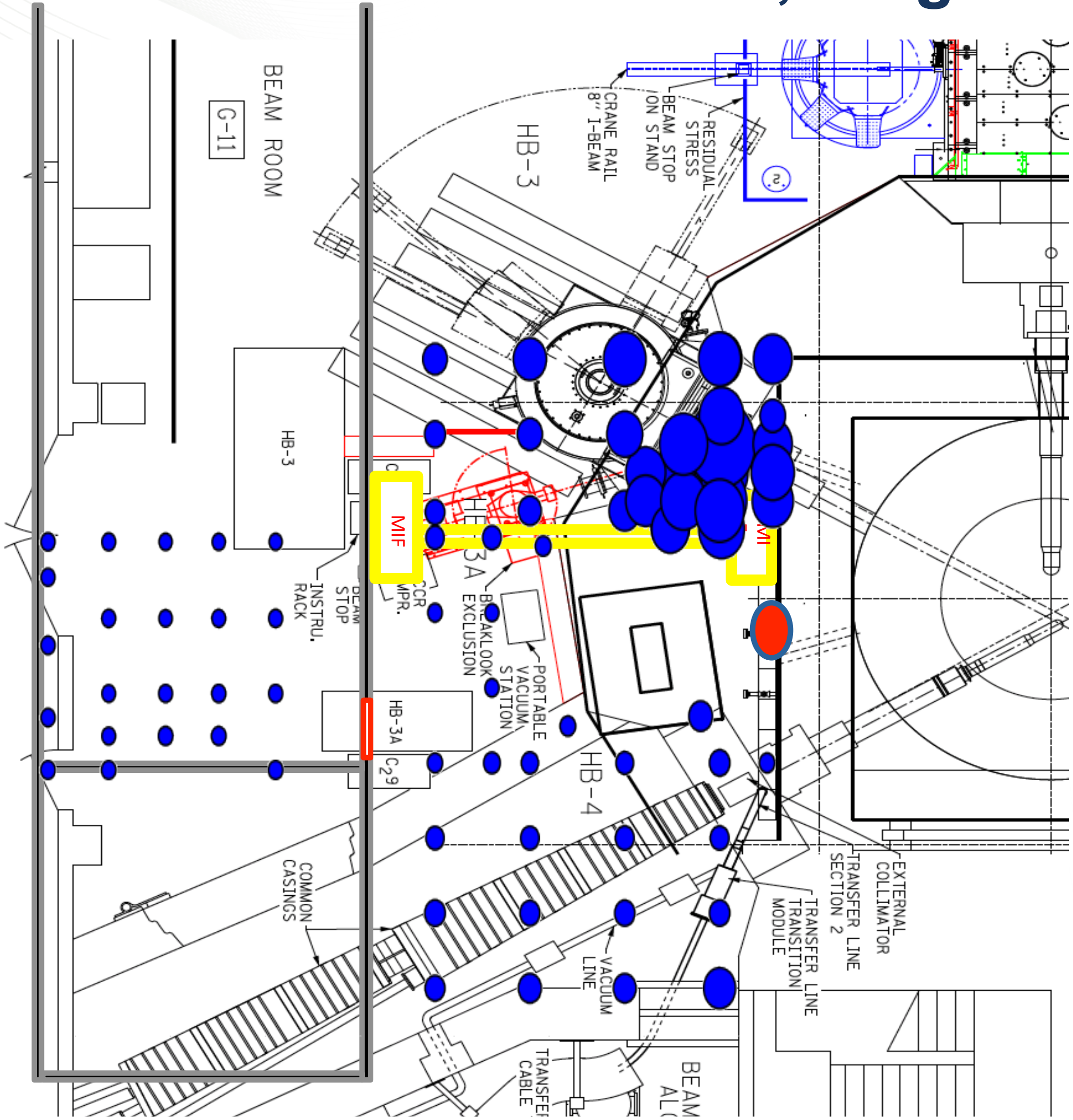
Detector Array to measure Neutrons and Gamma rays (DANG)

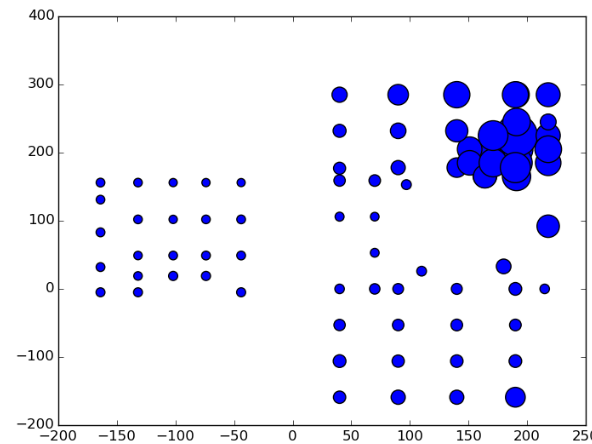
Electronics



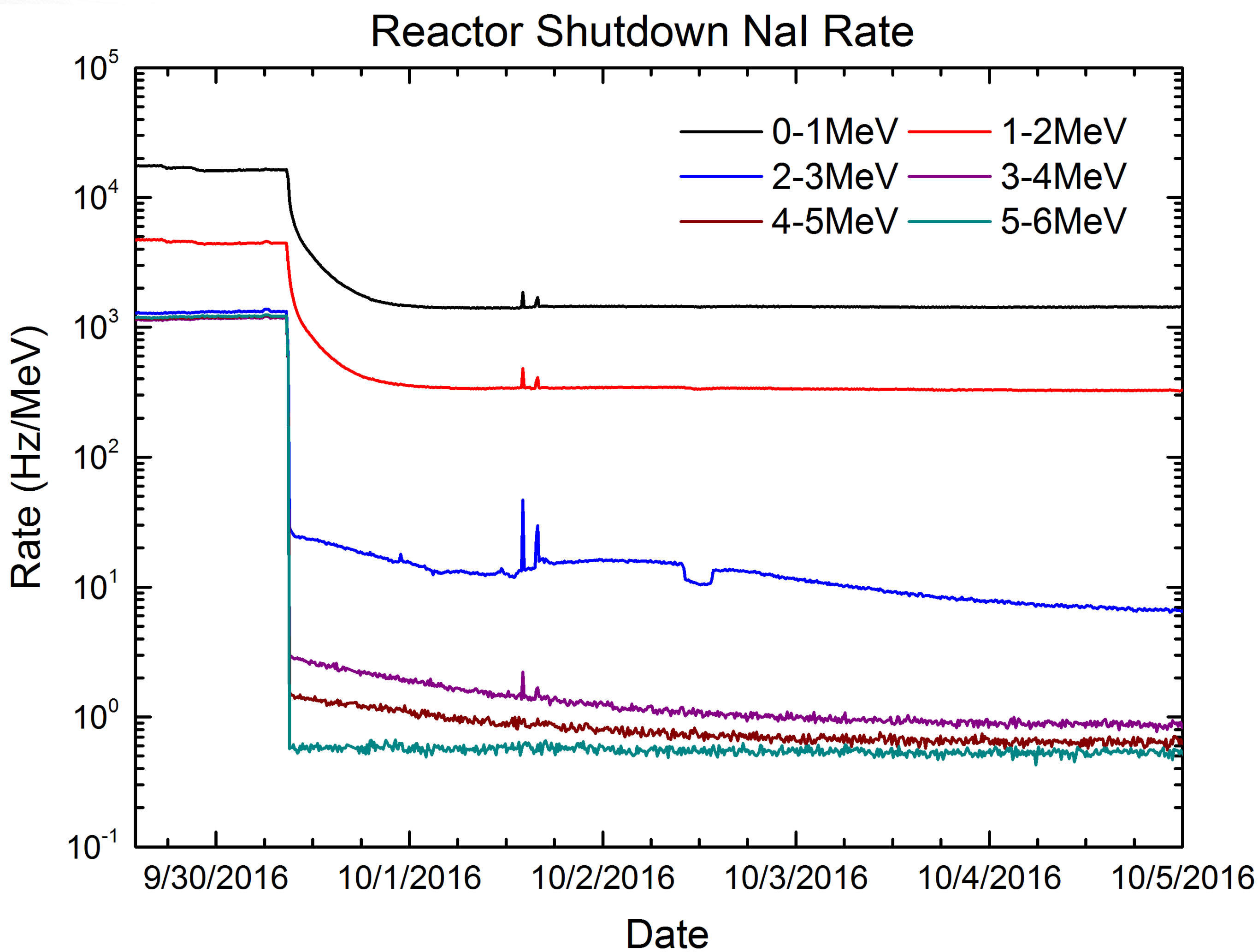
Spatial gamma survey – 3”x3” NaI

03-30 – 04-25 Reactor Off, Singles Rates 1-3 MeV



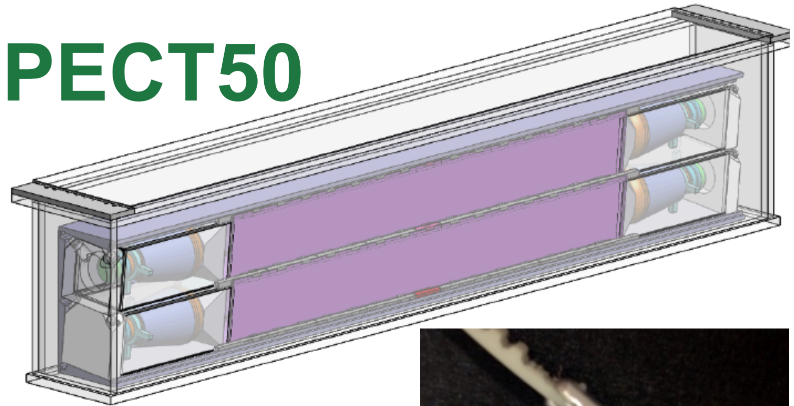


Background Characterization
Time Variations reflect Reactor activity

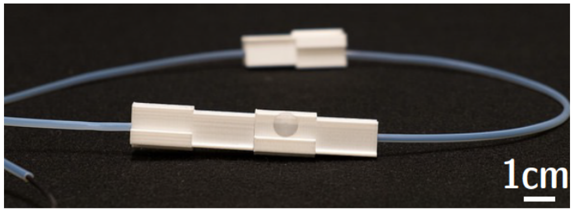


System Prototyping – PROSPECT50

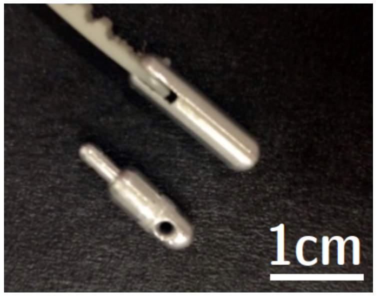
Validates AD component design



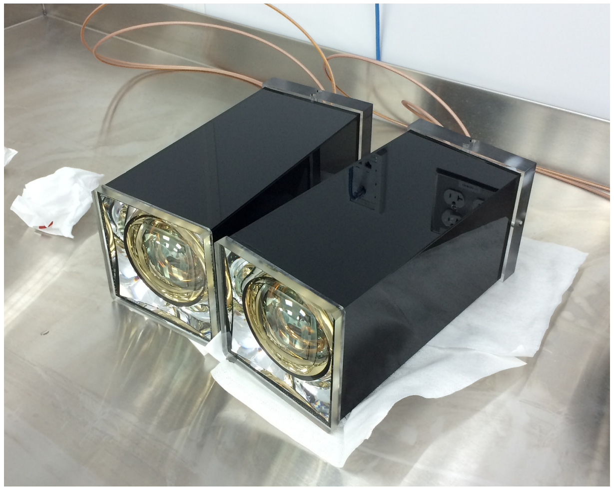
- Low-mass Optical Separators
- Support Structure
- PMT modules
- Filling System
- Calibration: LED & γ/n Sources



Mid-Segment LED Calibration

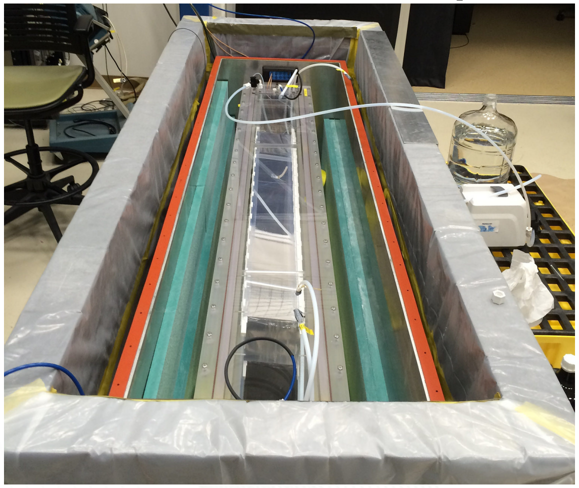


Source Capsule



PMT Modules

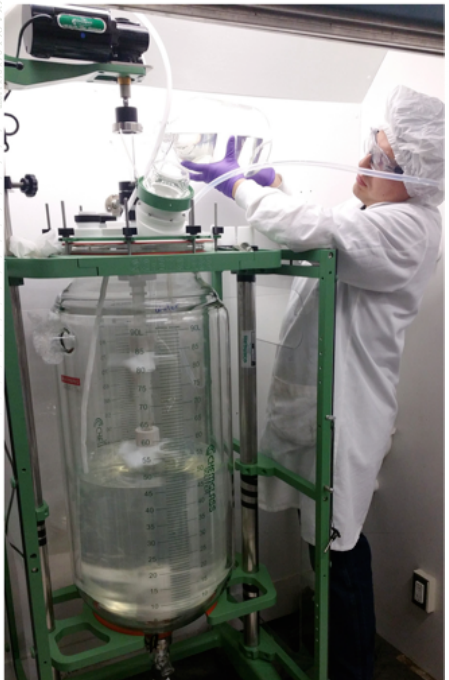
Segment Assembly



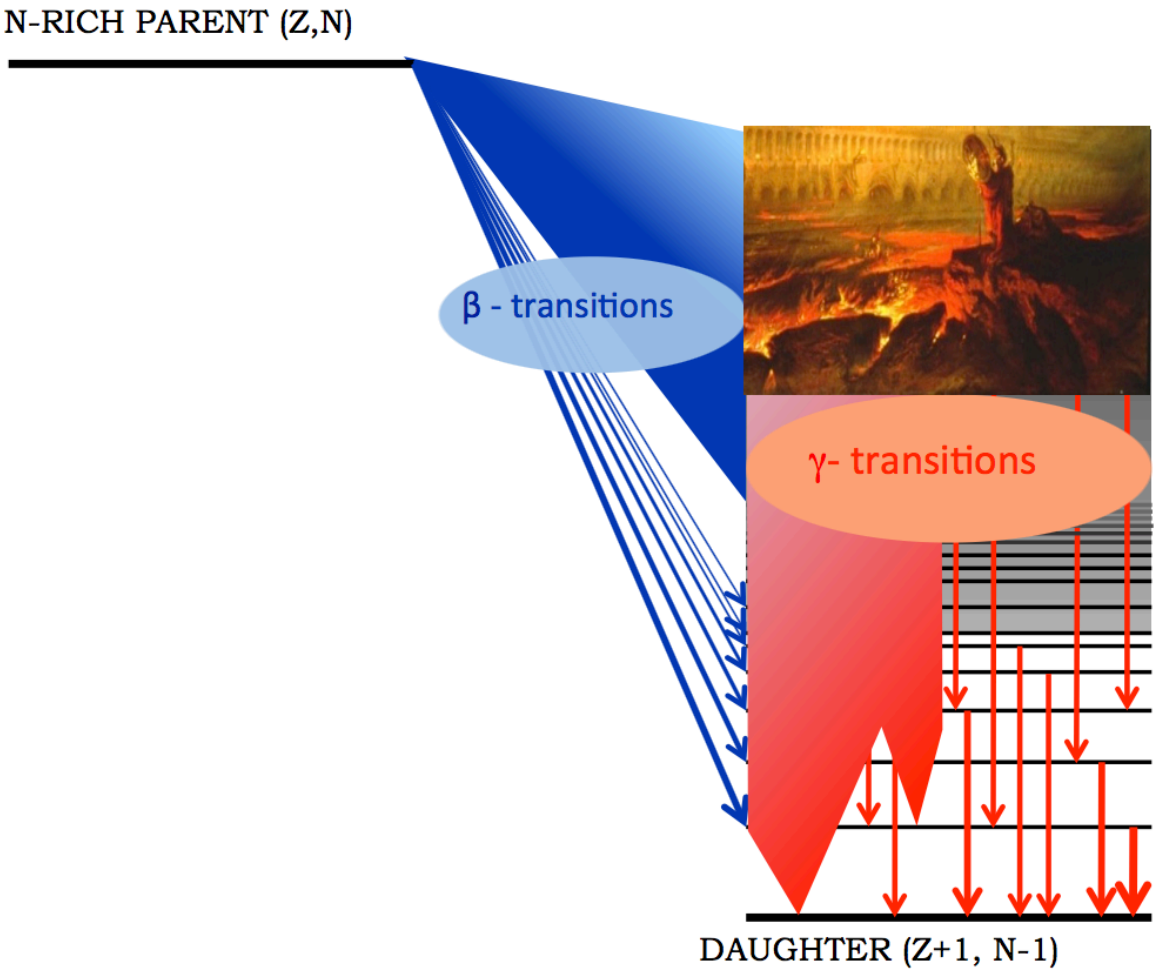
P-50 Installed in Shield

PROSPECT50 performance as expected based on earlier prototypes

AD Construction is underway



How Is β Decay Measured?



Pandemonium Effect

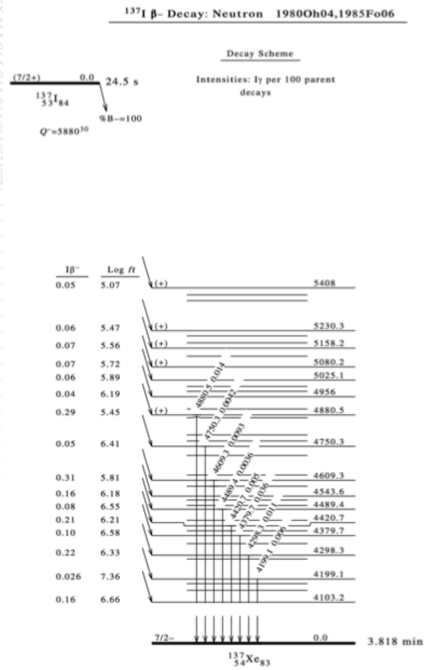
For high-precision, low efficiency detectors, the combination of low efficiency with a high density of states fed by β decay means many multi-γ decays will be misinterpreted as direct β feeding to lower energy levels.

Hardy et al, PL B 71,1977

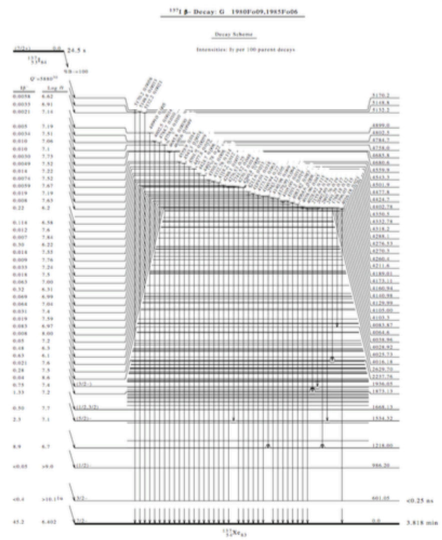
Greenwood *et al.*,1997,
Algora *et al.*, 2010,
Zakari-Issoufou *et al.*, 2015

Correcting the Pandemonium Effect General Trends by Average Energy by Particle Type:

$$\gamma \uparrow : \beta^- \downarrow : \bar{\nu}_e \downarrow$$



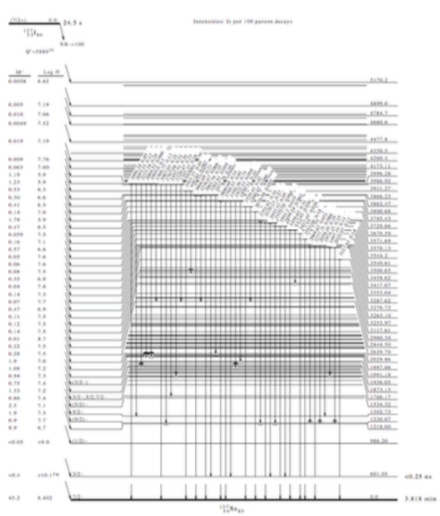
Example of β Decay

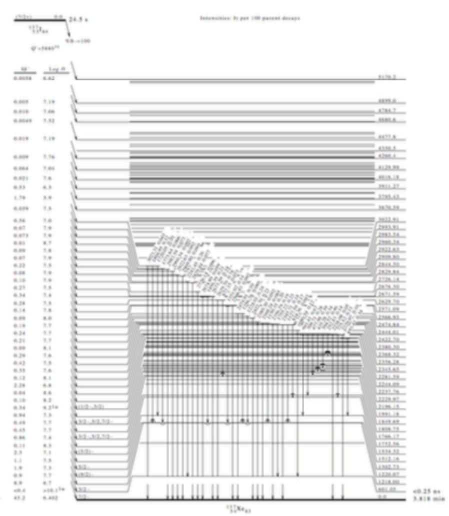


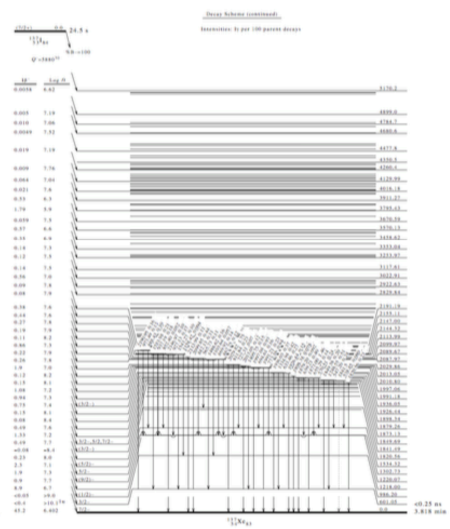
β decays are not all peaches and cream like ^{137}Cs and ^{14}C.

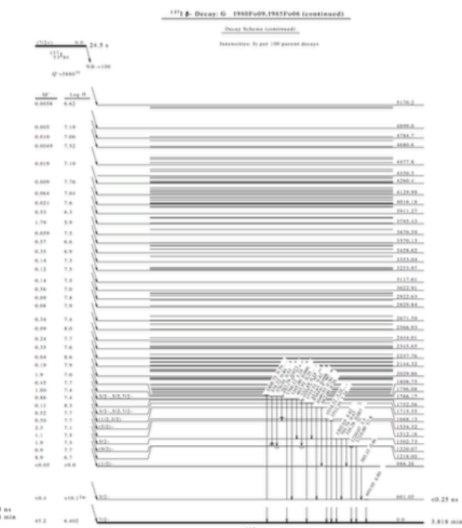
This is the ENSDF for ^{137}I β decay to ^{137}Xe.

And it is incomplete.
(More about this later)



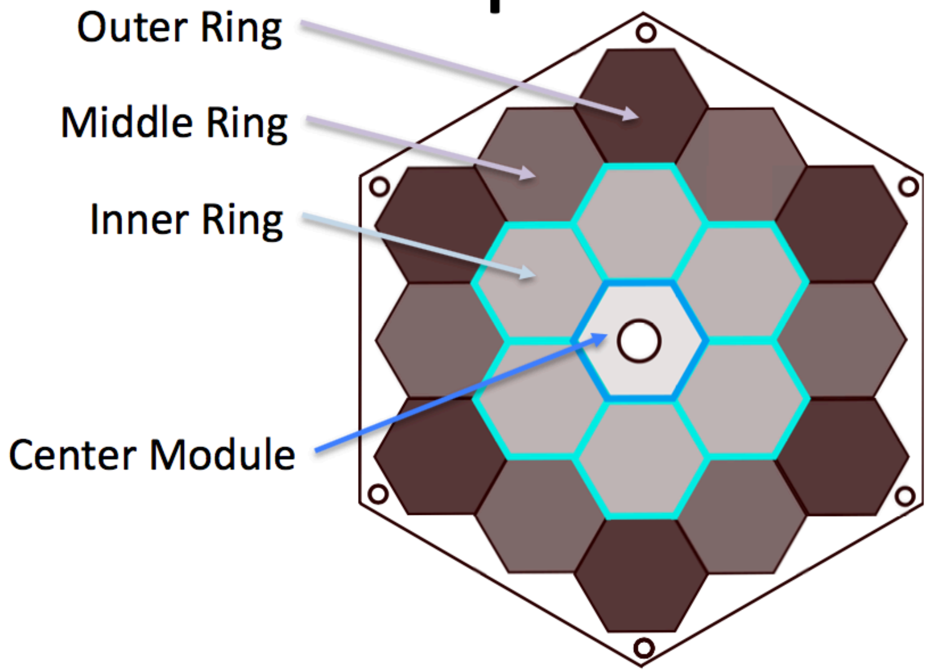


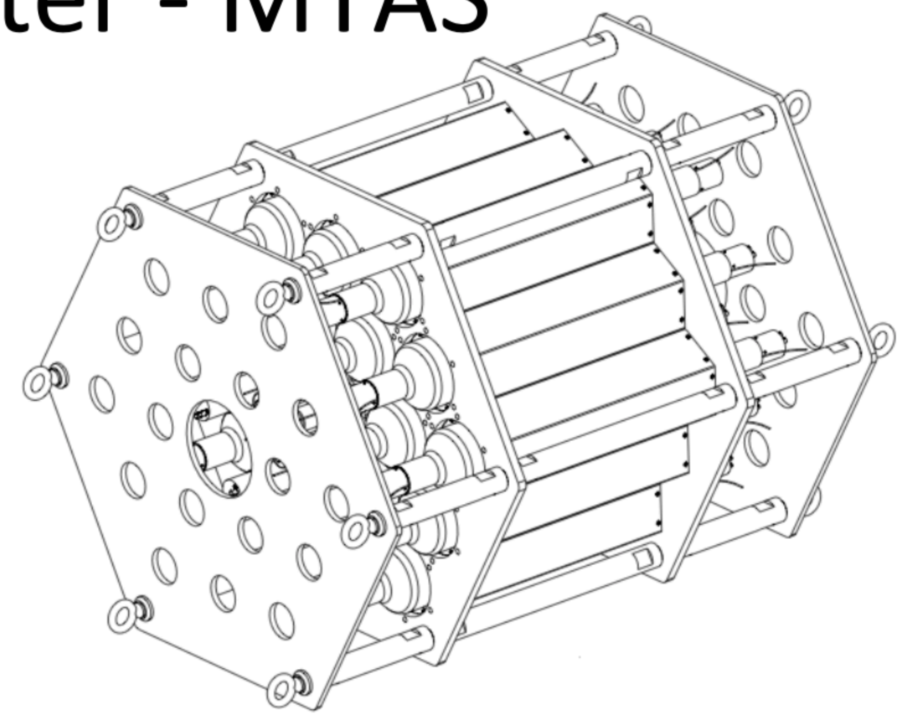




C. Rasco 2017

The Modular Total Absorption Spectrometer - MTAS





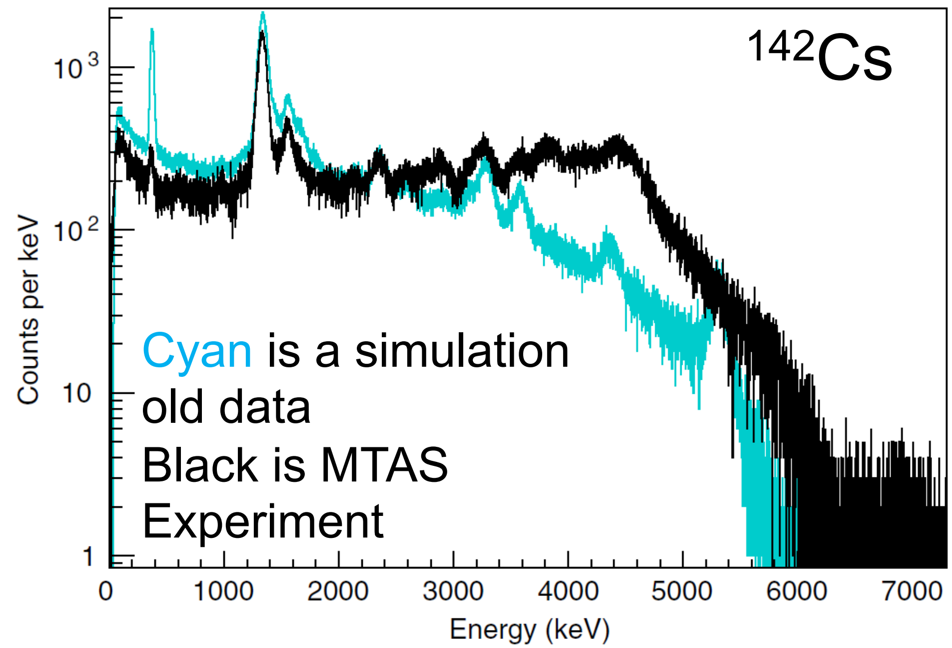
MTAS: 18 - 8"x 7"x 21" (20cm x 17.8cm x 53.3cm) hexagon NaI(Tl) modules
Organized in 3 Rings of 6 modules each (Inner, Middle, and Outer)
1 - Center module, same dimensions but with a 2.5" diameter hole
Over 1 ton of NaI(Tl)!

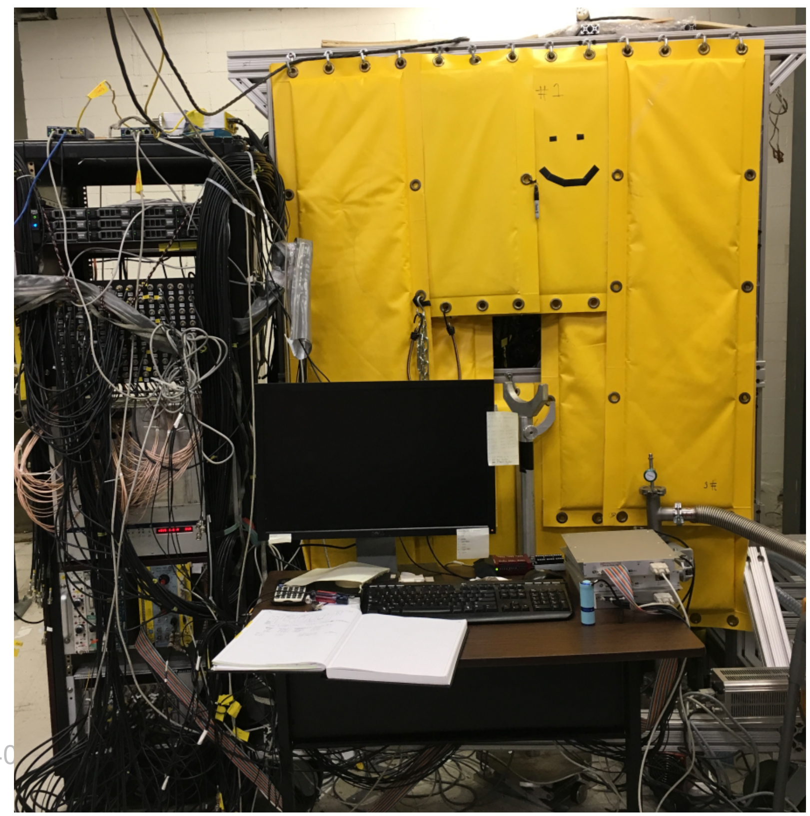
Over 5 tons of lead shielding + neutron shielding

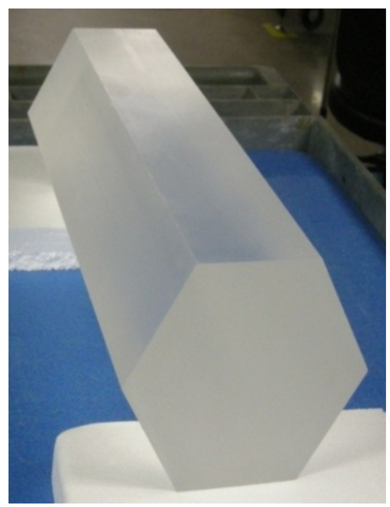
OAK RIDGE National Laboratory

A Sterile Neutrino or Erroneous Models? ORNL Efforts to Revise β^- Decay Data

Recently the nuclear physics community has been revisiting the β decay branching ratios of the top ν_e spectrum contributors

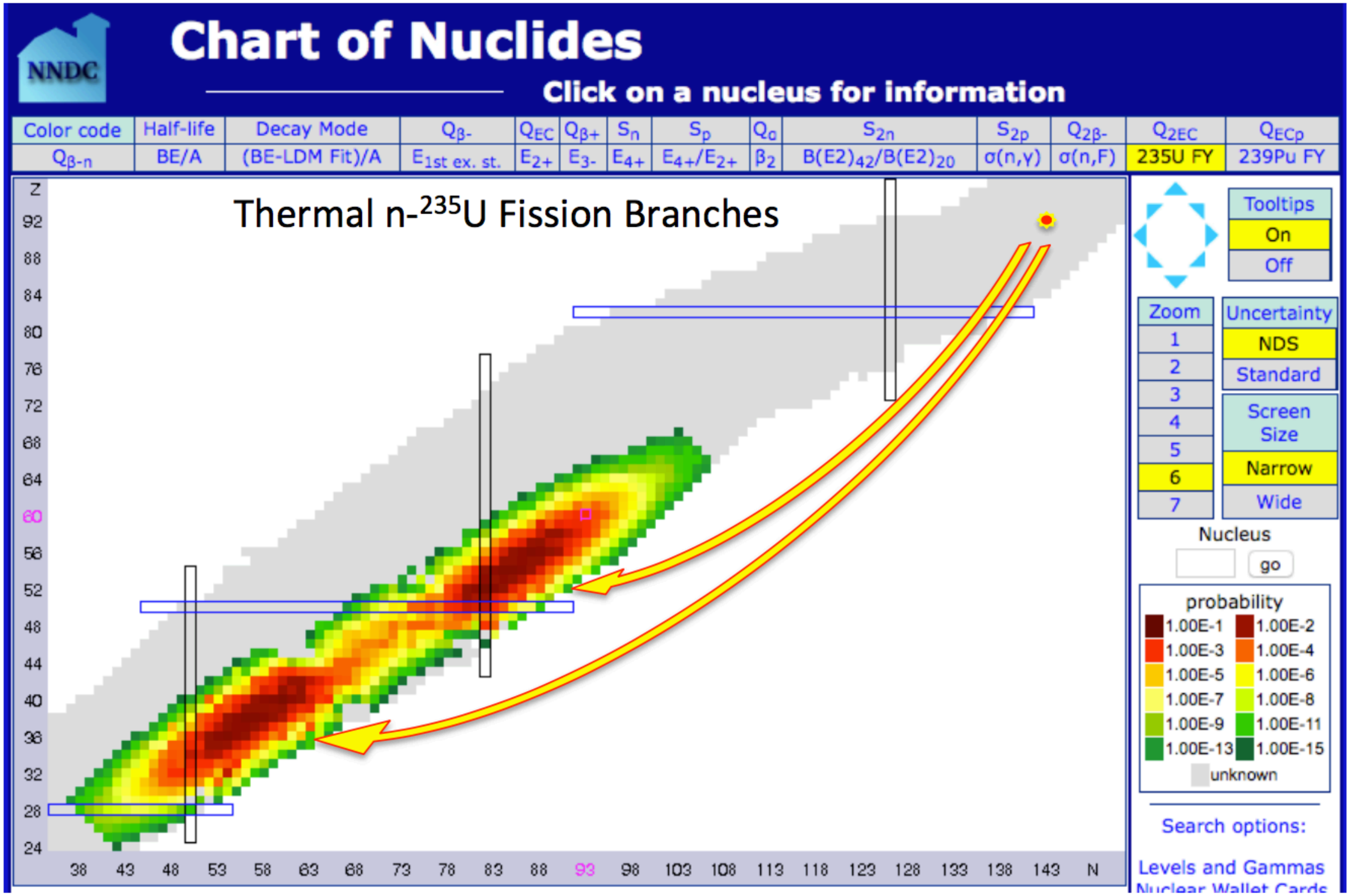






B.C. Rasco et al. PRL **117**, (2016) 092501

Reactors, Decay Heat, and β Decay



What are the fission decay products?

More than 800 nuclei per fuel type.

P. Egelhof
CNNP

PROSPECT Collaboration

BROOKHAVEN NATIONAL LABORATORY
NIST
LE MOYNE COLLEGE A·D·1946
UNIVERSITY OF WATERLOO
W&M
Lawrence Livermore National Laboratory
OAK RIDGE National Laboratory
GT
Drexel
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Yale

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prospect.yale.edu

Opportunities of Neutrino Physics at ORNL

World Class Neutrino Sources
- Spallation Neutron Source
- HFIR (85MW HEU reactor)

REDC - Radiochemical Engineering Development Center (e.g. hot cells)

Calibration sources fabrication

Relevant Instrumentation
- Advanced Ge detectors
- Total Absorption Spectrometer (MTAS)
- Scintillators

Development of Powerful Analytical Techniques
- Accelerator Mass Spectrometry
- Neutron Activation Analysis

Isotope Enrichment Capabilities

3 HV Platforms (Implantation, LE detection testing)
- Positive and negative ions; Stable and radioactive species; Sputtering source, ECR sources, Laser Ion Sources, Thermal Ionization Sources

(see A. Nucciotti, L. Gastaldo CNNP)

PROSPECT, COHERENT, … underway

Exciting times!

Thank you!


ETTORE MAJORANA
Les Véréides
CATANIA


IN QUESTA CASA IL 5 AGOSTO 1906 E' NATO
ETTORE MAJORANA
FISICO TEORICO
IL SUO GENIO SOLITARIO E SCHIVO
HA SCRUTATO E ILLUMINATO I SEGRETI DEL
MONDO COL BAGLIORE DI UNA METEORA
CHE TROPPO PRESTO SI DILEGUAVA
NEL MARZO DEL 1938 LASCIANDOCI
IL MISTERO DEI SUOI PENSIERI
LIONS CATANIA ETNA 1993


Palazzo Majorana
Sec XIX
Qui nacque Ettore Majorana
Fisico e scienziato
Catania 5 Agosto 1906
Morte presunta 27 Marzo 1938

INSTITUTE FOR NUCLEAR THEORY

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Programs & Workshops

2017 Workshops

The Flavor Structure of Nucleon Sea (INT-17-68W)
October 2 - 13, 2017
C. Aidala, W. Detmold, J. Qiu, W. Vogelsang

Neutron-Antineutron Oscillations: Appearance, Disappearance, and Baryogenesis (INT-17-69W)
October 23 - 27, 2017
K. Babu, Z. Berezhiani, Y. Kamyshkov, B. Kerbikov

Quantum Computing for Nuclear Physics (INT-17-66W)
November 14-15, 2017
D. Dean, M. Hjorth-Jensen, M.J. Savage

2018 Programs

Nuclear ab initio Theories and Neutrino Physics (INT-18-1a)
February 26 - March 30, 2018
C. Barbieri, O. Benhar, A. Galindo-Uribarri, A. Lovato, J. Menéndez

Inst

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Application form
For full consideration, please apply by October 31, 2017.

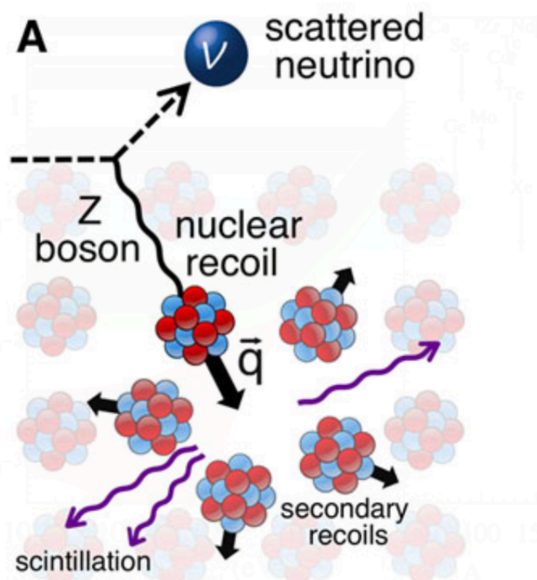
Talks Online

Exit Survey

INT Program INT-18-1a

Nuclear ab initio Theories and Neutrino Physics

February 26 - March 30, 2018



Coherent neutrino-nucleus scattering - from the COHERENT collaboration's website.

The program is designed to foster interactions among nuclear theorists, nuclear experimentalists and neutrino physicists, thus facilitating (much needed) inter-disciplinary collaborations and discussions

Week 1: Ab initio methods
Ab initio nuclear many-body approaches: strengths, limitations and further directions. Challenges and opportunities for nuclear structure and nuclear astrophysics as posed by neutrino-oscillation and $0\beta\beta$-decay experiments.

Week 2: Workshop on: Neutrino detection and interactions: challenges and opportunities for ab-initio nuclear theory
The workshop will cover the most relevant aspects of neutrino interactions with atomic nuclei and infinite matter. It is intended to foster interactions between nuclear theorists and neutrino experimental programs (oscillations, $\beta\beta$-decay, supernovae...).

A workshop registration fee will apply; amount to be determined. The registration fee includes participation in the workshop, lectures, and coffee breaks.

Week 3: Nuclear interaction and currents
Development and fitting of next generation nuclear interaction (problem of saturation and prediction in neutron rich elements). Challenges in constructing and exploiting (electroweak) currents consistent with the interactions. Estimation of theoretical errors.

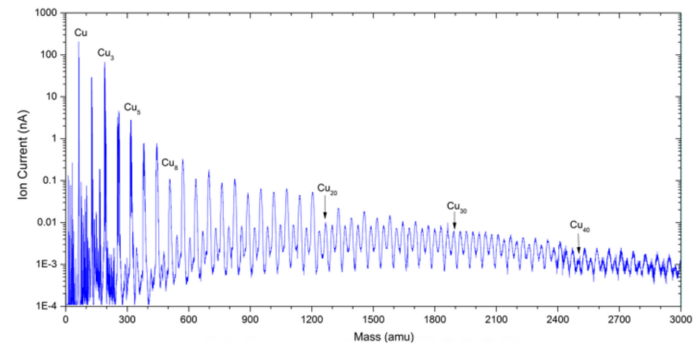
Week 4: Neutrino-nucleus response and oscillation experiments
How to approach neutrino energies in the few GeV region. Factorization of nuclear transition matrix elements and spectral functions. Matching relativistic current to low-energy structure. Application to neutrino response in infinite matter. Estimation of theoretical errors.

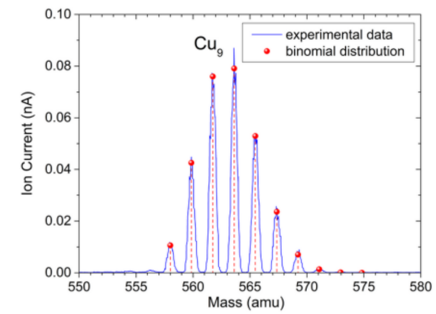
Week 5: Applications for $\beta\beta$-decay.
Develop a roadmap to explore possible many-body mechanisms and many-body currents at the origin of the g_A "quenching". Relation between "quenching" in β and $\beta\beta$ decays. Connection between toy $\beta\beta$ decays in light systems and $\beta\beta$ decay emitters. Use of experimental data to constrain the theoretical predictions.

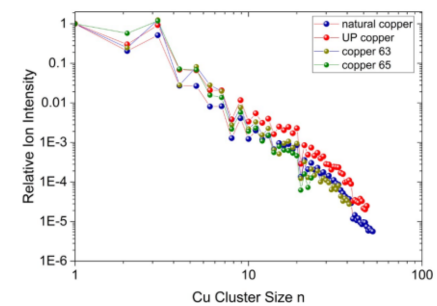
OTHER

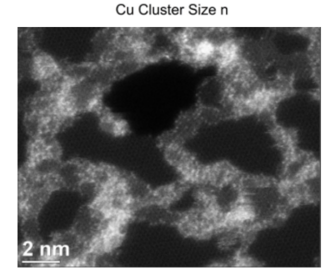
Four primary outcomes:

- mass spectra,
- binomial distribution,
- power law dependence,
- bombarding graphene with copper cluster ion,
- We want to make a comparison of cluster formation using graphite versus buckyballs as the source material.





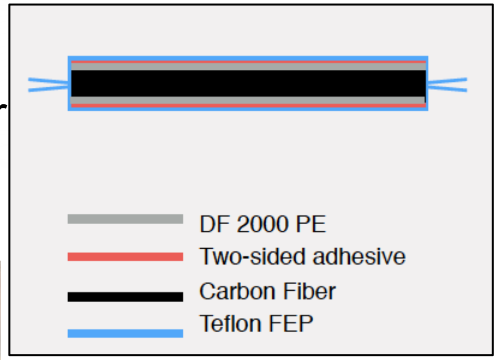




Development of PROSPECT Detector Components

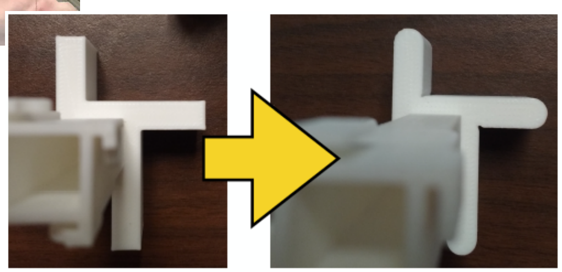
Low-Mass Optical Separators

High reflectivity, high rigidity, low mass reflector system developed

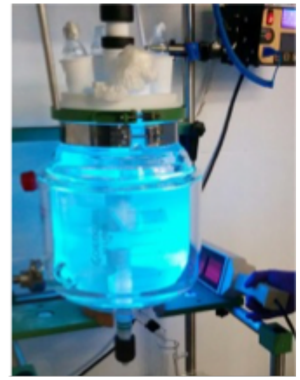


- Array formed using 3D printed "pinwheel" spacers
- Chemical compatibility of all materials validated

Component design refined for final production

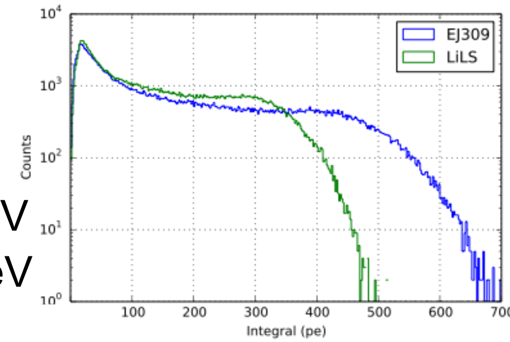


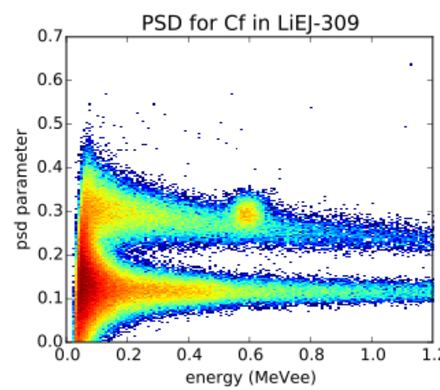
^{6}Li-Loaded Liquid Scintillator



- Developed non-toxic, non-flammable formulations based on EJ-309, LAB, Ultima Gold
- EJ-309 selected as baseline

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

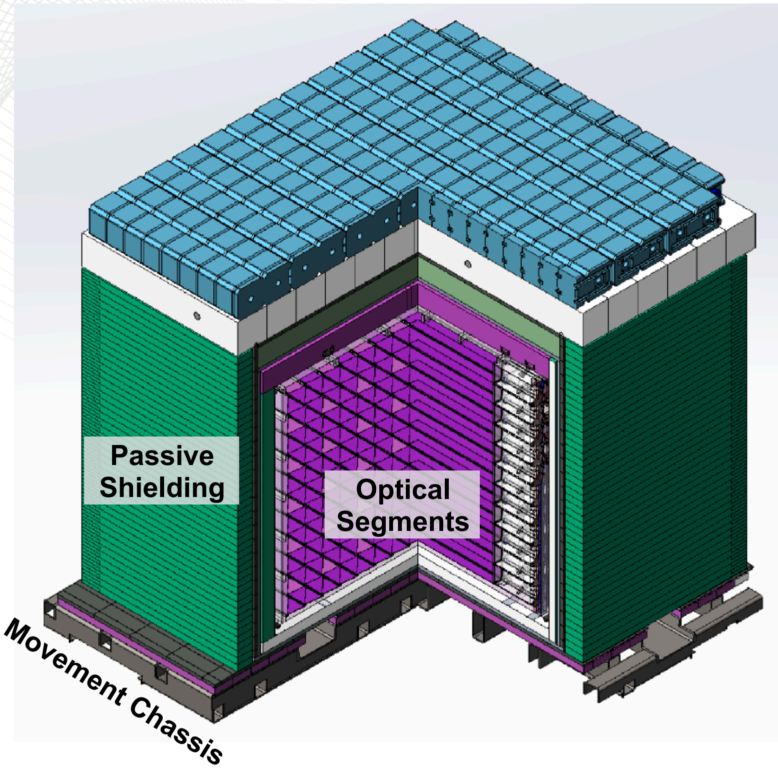


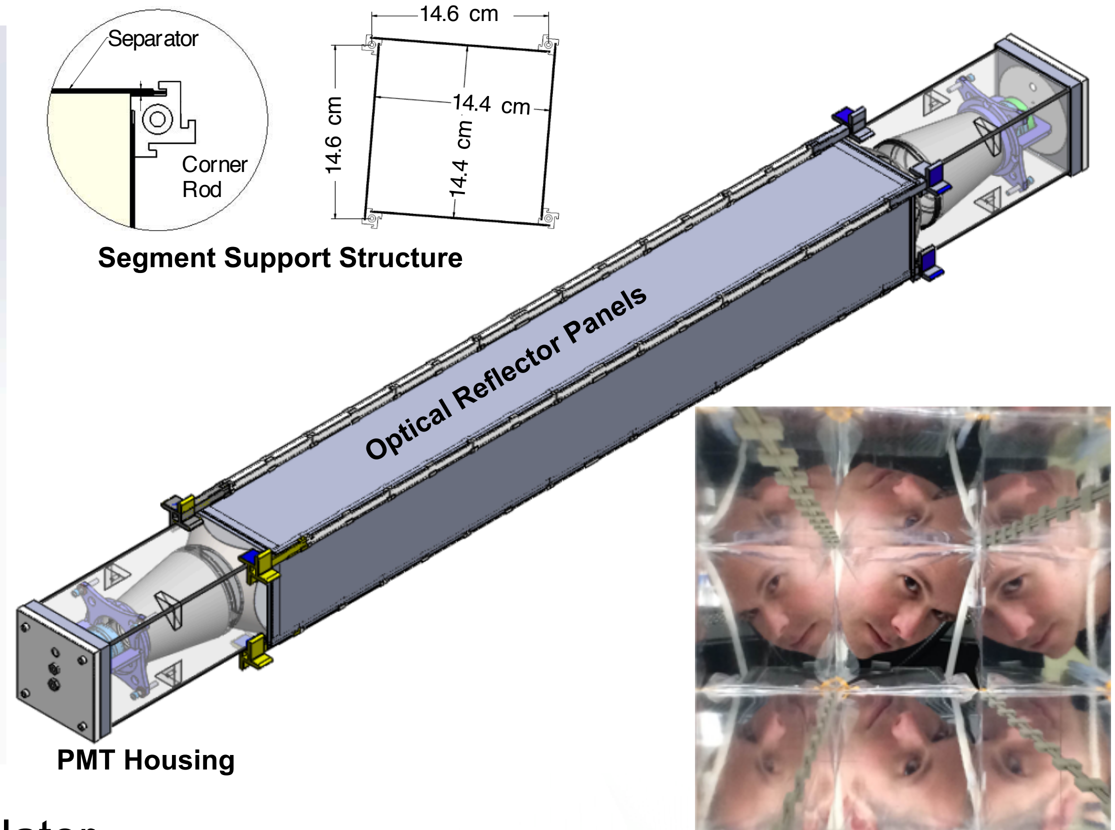


Excellent PSD performance for neutron capture & heavy recoils

Full-scale production for PROSPECT AD underway

PROSPECT Antineutrino Detector



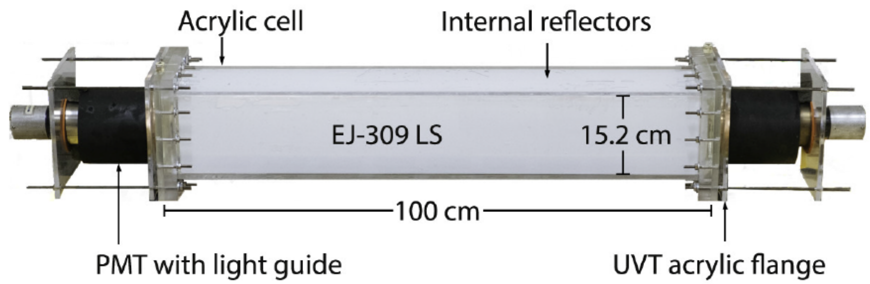


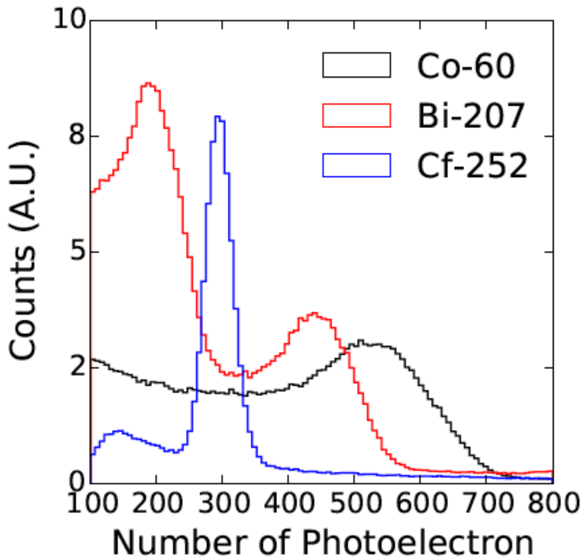
- ~4000L of ^{6}Li loaded liquid scintillator
- 11x14 segmented optical array, ~15 x 15 x 120 cm^3 segment dimensions
- Double ended PMT readout, light guides, ~4.5%/√E resolution
- Low mass optical separators, minimal dead material
- Full volume calibration access

Full Scale Prototyping - PROSPECT20

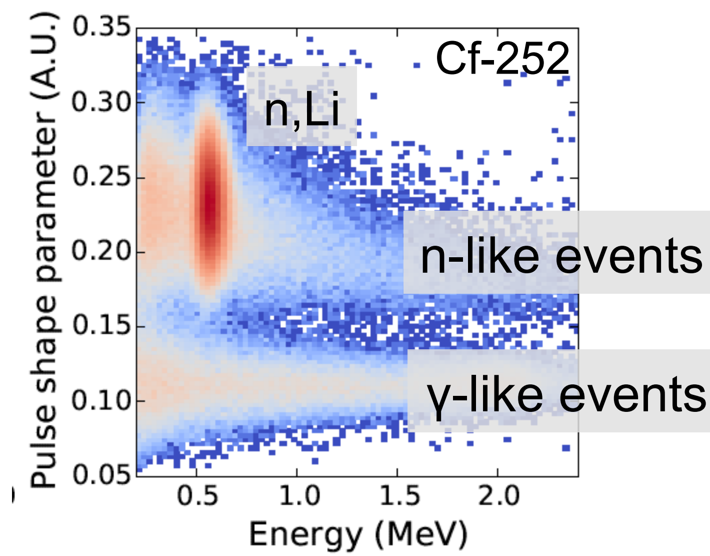
Validates optical system design

- Li-loaded liquid scintillator
- Reflector panels





Light Yield/ PE Spectra



Pulse Shape Discrimination

- Compton edge of ^{60}Co and ^{217}Bi γ-rays and the quenched (n, Li) capture peak from ^{252}Cf neutrons
- light collection: **522±16 PE/MeV**

Unloaded LS studies described in 2015 JINST 10 P11004, arXiv:1508.06575, PROSPECT collaboration