LA-UR-15-22139
Approved for public release; distribution is unlimited.

Title: Ultracold Neutrons: fundamental physics and more

Author(s): Broussard, Leah Jacklyn

Intended for: AOT-OPS Beam Outage Lecture

Issued: 2015-03-31 (rev.1)

Disclaimer:
Los Alamos National Laboratory, an affirmative action/equal opportunity employer,is operated by the Los Alamos National Security, LLC for the National NuclearSecurity Administration of the U.S. Department of Energy under contract DE-AC52-06NA25396. By approving this article, the publisher recognizes that the U.S. Government retains nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes. Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Departmentof Energy. Los Alamos National Laboratory strongly supports academic freedom and a researcher's right to publish; as an institution, however, the Laboratory does not endorse the viewpoint of a publication or guarantee its technical correctness.

Ultracold Neutrons: fundamental physics and more

Leah Broussard

Los Alamos National Laboratory

March 26, 2015

Ultracold Neutrons (UCN) program

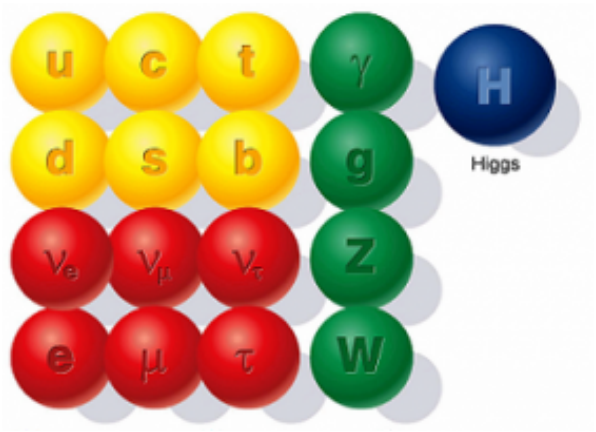
What are UCN, and why do we use them?

Tour of the facility

Recent progress on experimental efforts

- UCNA
- UCNτ
- UCNB
- nEDM
- UCNS

The Standard Model is complete! But...



- Why 3 generations?
- Why so many parameters?
- Why these masses?
- Why left-handed weak interaction?
- What is Dark Matter?
- Why more matter than anti-matter?
- Where is gravity?

Is there an underlying framework?

- No more sure-thing theories!
- High Energy frontier (LHC) vs. Precision frontier (beta decay)
- High energy: Direct search for heavy particles
- Precision: Measure deviations from SM
- Complementary limits

What are Ultracold Neutrons?

Class	Energy	Source
Fast	> 1 MeV	Fission reactions / Spallation
Slow	eV – keV	Moderation
Thermal	0.025 ev	Thermal equilibrium
Cold	μeV – meV	Cold moderation
Ultracold	≤ 300 neV	Downscattering

How cold is Ultracold?

- Temperature < 4 mK
- Velocity < 8 m/s
- Wavelength > 500 Å

Usain Bolt ~ 12 m/s

Sensitivity to the four fundamental forces

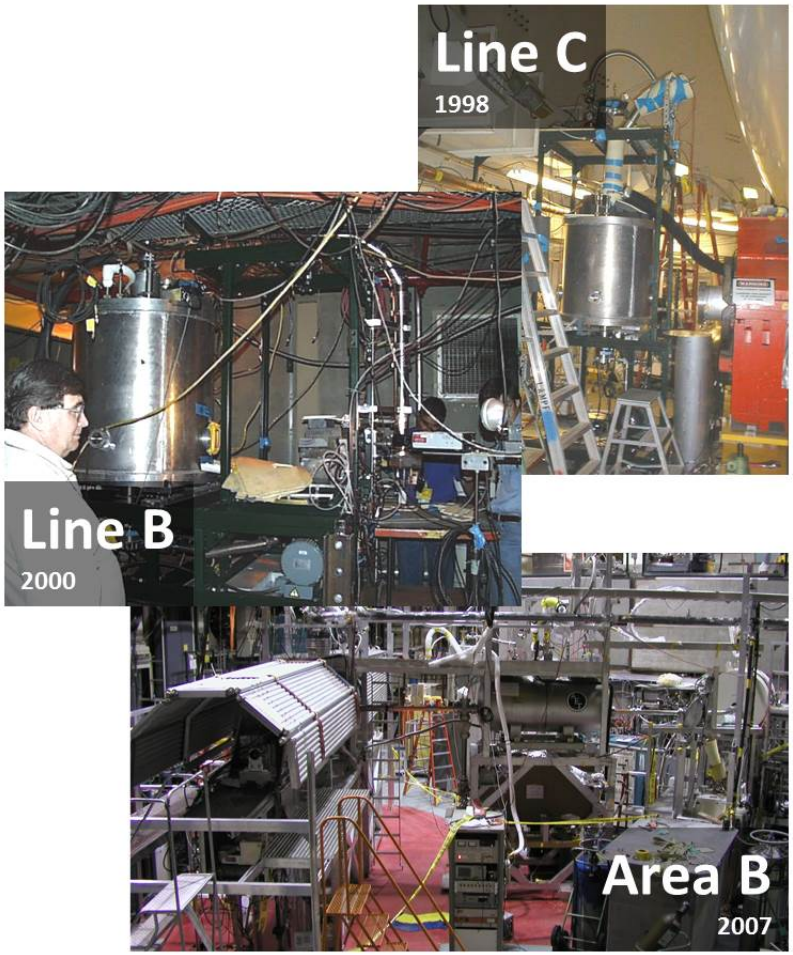
- Gravity ($V = mgh$): 100 neV / meter
- Magnetism ($V = -\vec{\mu} \cdot \vec{B}$): 60 neV / Tesla
- Strong (material) $\left(V = \frac{2\pi\hbar^2 Nb}{m}\right)$ $\begin{cases} {}^{58}\text{Ni}: & 335 \text{ neV} \\ \text{DLC}: & 250 \text{ neV} \\ \text{Cu}: & 170 \text{ neV} \end{cases}$
- Weak $\rightarrow$ β-decay

UCN live in bottles

UCN facility early timeline

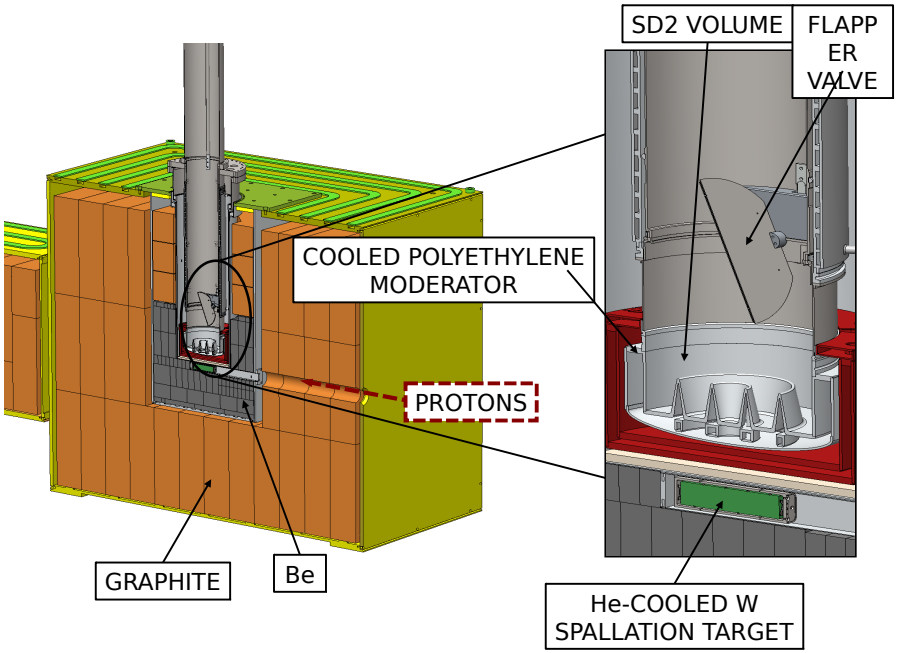
Original purpose: dedicated UCN source for UCNA experiment

- 1996 — Initial UCN source development (rotor vs. SD_2)
- 1998 — UCN prototype source tests ($\sim$0 UCN/cc)
- 2000 — Blue Room tests: windowless source, SD_2 lifetime studies
- 2000 — Line B prototype ($>$100 UCN/cc, world record!)
- 2002 — Area B construction
- 2005 — UCNA experiment commissioning
- 2007 — Improved UCN transport from source
- 2007 — First UCNA measurement
- 2010 — 50 UCN/cc measured outside biological shielding



UCN production technique

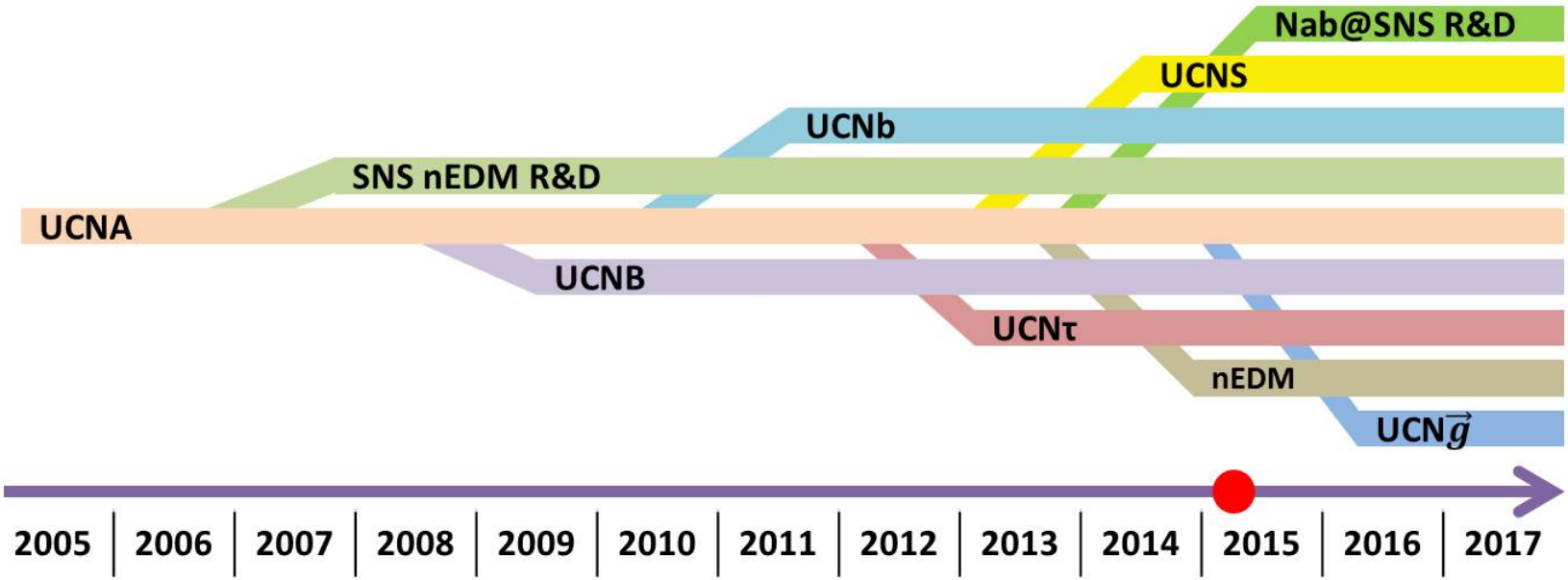
Spallation driven UCN conversion in SD_2 crystal



Continually improving UCN production and transport

- FY15 AOT/CCR led improvements: improved tuning, upgraded beam monitors for high current operation
- 6→8 μA protons; pulse structure 5→10 s
- Most UCN ever! Estimated 3× higher rate out of shielding, 10× higher decay rate for UCNB/Nab over last year, $>$ 2× (up to 10×) more stored neutrons for UCNτ

Developing a world-class UCN program



Expanding Capabilities

- Supports external experimental groups: Nab, nEDM @ SNS, international UCN source development
- Capability applied to stockpile stewardship: new program for research of actinides and fission fragment damage/sputtering
- UCN Detector development: ^{3}He-filled MWPC, ^{10}B coated ion chambers, ^{10}B+ZnS film detectors, photographic emulsion technology
- Exporing fun new ideas: Gravity (UCN$\vec{g}$), Neutron and Nuclear β spectroscopy

LANSCE UCN facility is unique

One of the brightest UCN sources in the world

- Only operational UCN source in the US
- First spallation driven SD_2 source
- UCN physics is a rapidly growing field: new sources in development at ILL, RNCP, TRIUMF, PSI, Munich, NCSU, PNPI, ...

Very low backgrounds enables high precision measurements

- First use of UCN for any n β-decay angular correlation measurement
- Only measurement of β-asymmetry using UCN

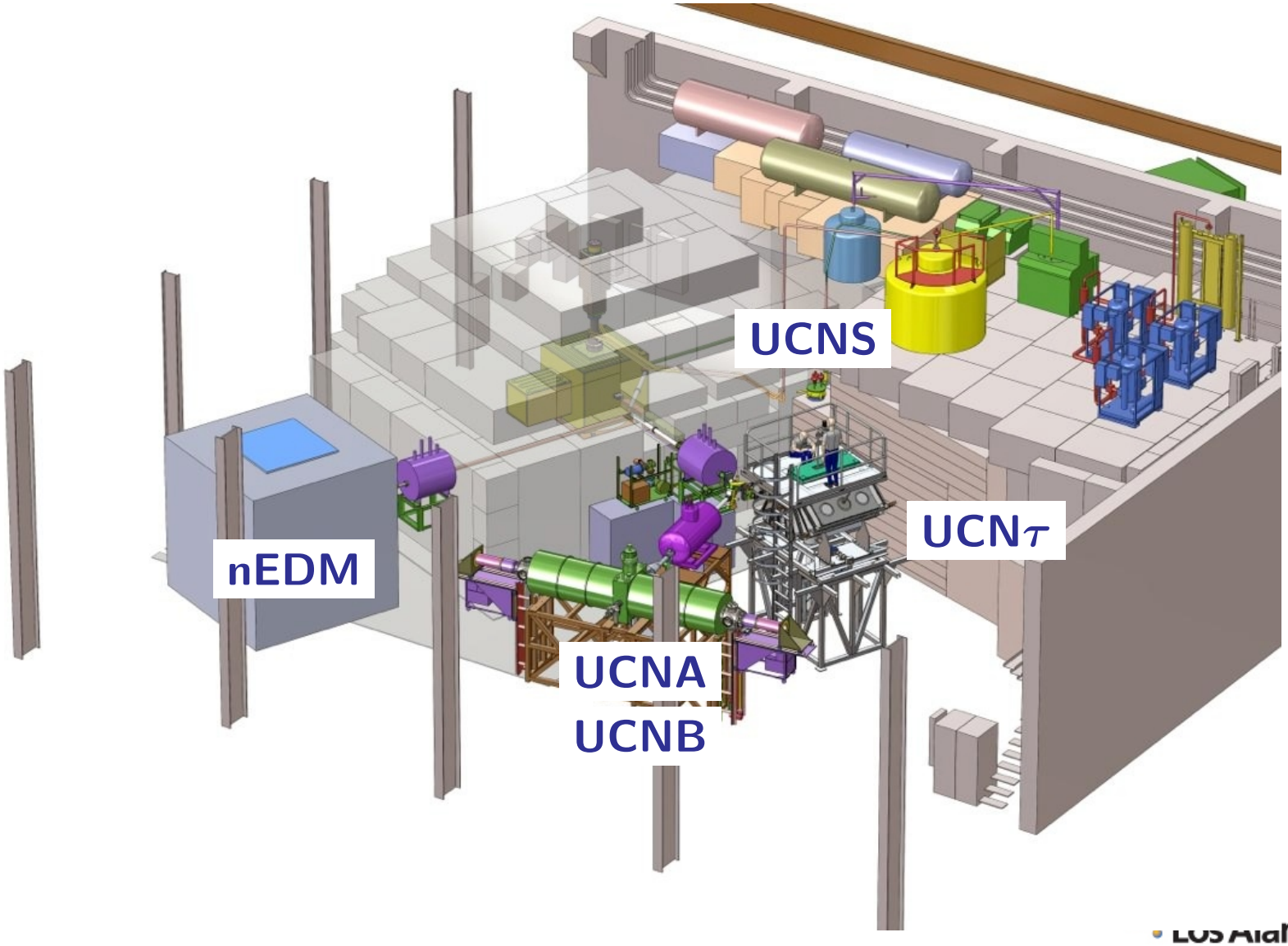
Training the next generation of scientists

- 2014-2015 run cycle: 15 students, 5 postdocs from collaborating universities
- 5 LANL staff conversions from former Area B postdocs
- 5 LANL postdocs (2 named) from former Area B graduate students

Successful multi-user facility

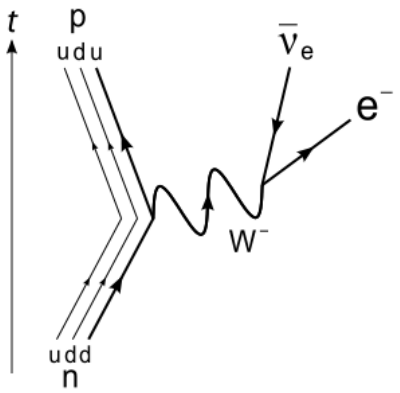
- Possible benefit to MaRIE, attracting wide user base to TA-53

UCN Experimental Program



Studying the weak interaction with neutrons

Neutron β-decay



Quark Mixing (CKM)

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Precision test:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

Left-handed coupling: **Vector** – **AxialVector**

- $H = \frac{G_F V_{ud}}{\sqrt{2}} [\bar{e}(\gamma^\mu - \gamma^\mu \gamma_5)\nu_e \bar{u}(\mathbf{g_V}\gamma_\mu + \mathbf{g_A}\gamma_\mu\gamma_5)d]$
- Standard Model: $g_v = 1$, g_A free parameter

Experimental Observables in Neutron Beta Decay

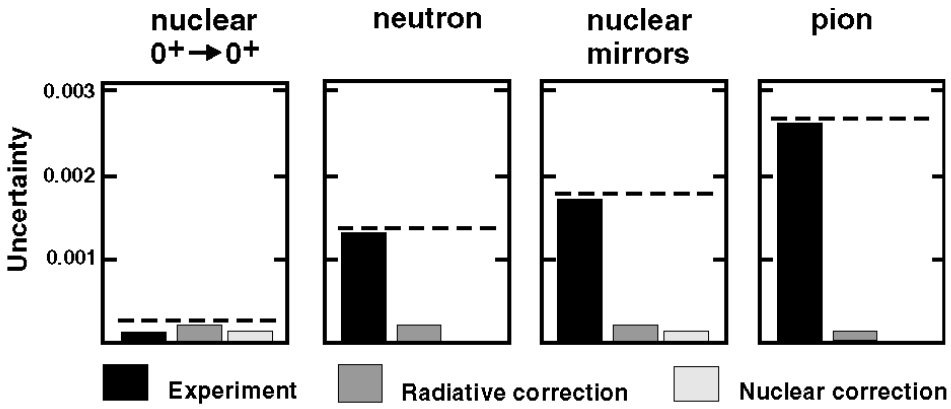
- Angular correlations polarized decay[1]:
  $\frac{dW}{dE_e d\Omega_e d\Omega_\nu} \propto p_e E_e (E_0 - E_e)^2 \left[1 + \mathbf{a}\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu} + \mathbf{b}\frac{m_e}{E_e} + \langle\vec{\sigma_n}\rangle \cdot \left(\mathbf{A}\frac{\vec{p_e}}{E_e} + \mathbf{B}\frac{\vec{p_\nu}}{E_\nu} + \mathbf{D}\frac{\vec{p_e}\times\vec{p_\nu}}{E_e E_\nu}\right)\right]$
- Lifetime:
  $\frac{1}{\tau_n} = W = K\,(G_F \mathbf{V_{ud}})^2 \left(1 + 3\left(\frac{\mathbf{g_A}}{\mathbf{g_V}}\right)^2\right)(1+\Delta_R)\, f_n p_e E_e (E_0 - E_e)^2 \left[1 + m_e \mathbf{b}\frac{f_b}{f_n}\right]$
- **A**, **a** $+ \tau \rightarrow$ **V**, **A** interactions
- **B**, **b** $\rightarrow$ **S**, **T** (BSM) interactions

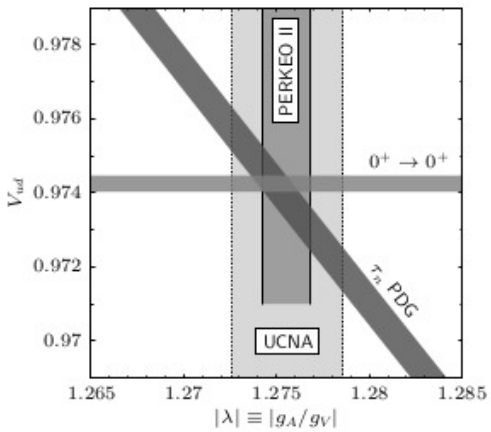
Test CKM Unitarity: Extract $\mathbf{V}_{ud}$

- $\mathbf{a_0} = \frac{1-\lambda^2}{1+3\lambda^2}$, $\mathbf{A_0} = -2\frac{\lambda(\lambda+1)}{1+3\lambda^2}$, $\mathbf{B_0} = 2\frac{\lambda(\lambda-1)}{1+3\lambda^2}$, $\tau = \frac{\text{constant}}{1+3\lambda^2}$
- **A** Most sensitive to $\lambda = \frac{\mathbf{g_A}}{\mathbf{g_V}}$
- $\tau_\mathbf{n} + \lambda \rightarrow$ extract CKM matrix element $\mathbf{V_{ud}}$

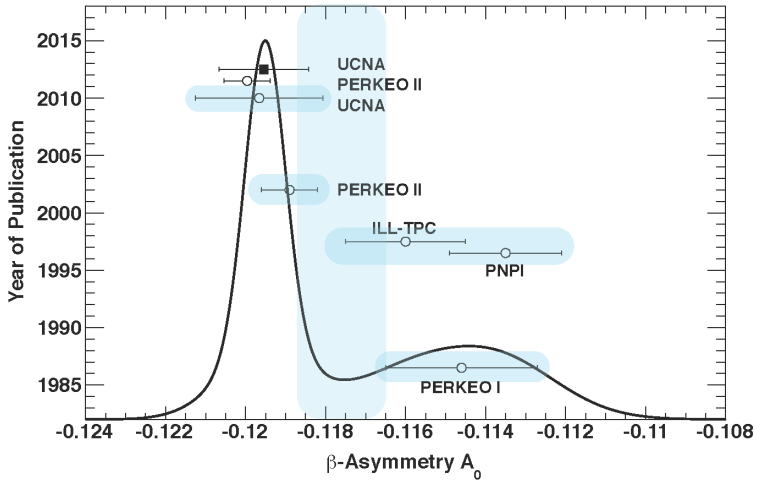
[1] Phys. Rev. C **106** 517 (1957)

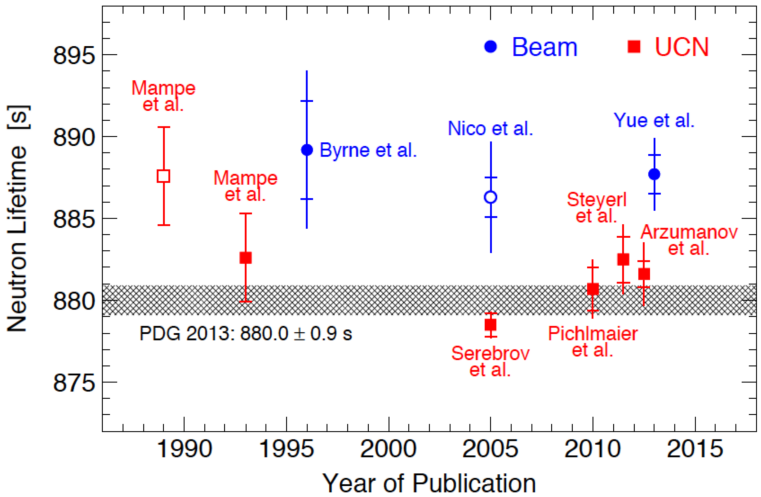
V_{ud} from Neutron Decay: UCNA and UCNτ





- Superallowed Fermi $0^+ \to 0^+$ decays: V_{ud} at 0.02% level
- From neutron decay, require $\frac{\delta A}{A} \sim 0.1\% + \delta\tau \sim 0.35\text{s} \to V_{ud}$ at 0.02% level





UCNA Collaboration

California Institute of Technology
R. Carr, B. W. Fillippone, M. P. Mendenhall, A. Perez-Galvan, R. Picker, S. Slutsky

Idaho State University
R. Rios, E. Tatar

Indiana University
A. T. Holley, C.-Y. Liu, D. Salvat

Institut Laue-Langevin
P. Geltenbort

Los Alamos National Laboratory
M. Blatnik, T. J. Bowles, L. Broussard, S. Clayton, S. Currie, G. Hogan, T. M. Ito, M. Makela, P. McGaughey, J. Mirabal, C. L. Morris, R. Pattie, J. Ramsey, A. Saunders (co-spokesperson), S. Seestrom, E. Shaw, S. Sjue, W. Sondheim, T. Womack

Michigan State University
C. Wrede

North Carolina State University
E.B. Dees, J. Hoagland, B. VornDick, A. Young, B. Zeck

Shanghai Jiao Tong University
J. L. Liu

Texas A&M University
D. Melconian

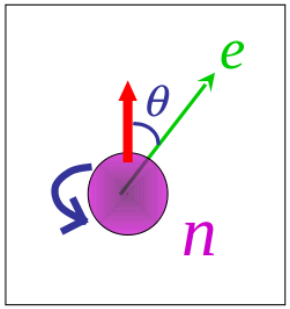
University of California, Los Angelos
K. Hickerson

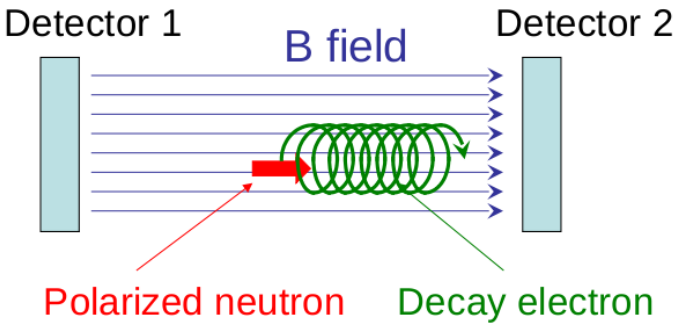
University of Kentucky
M. Brown, S. Hasan, B. Plaster

University of Winnipeg
J. W. Martin

Virginia Tech
X. Ding, M. L. Pitt, R. B. Vogelaar

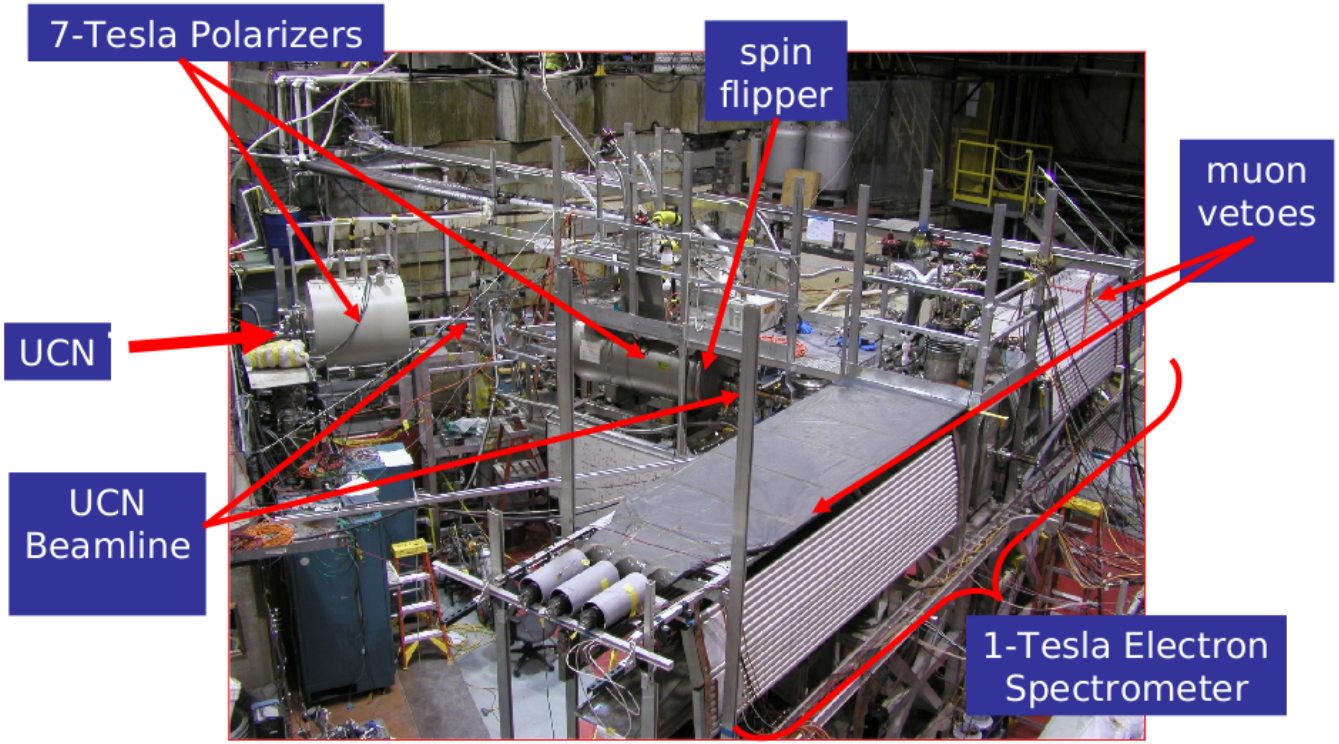
UCNA Experiment



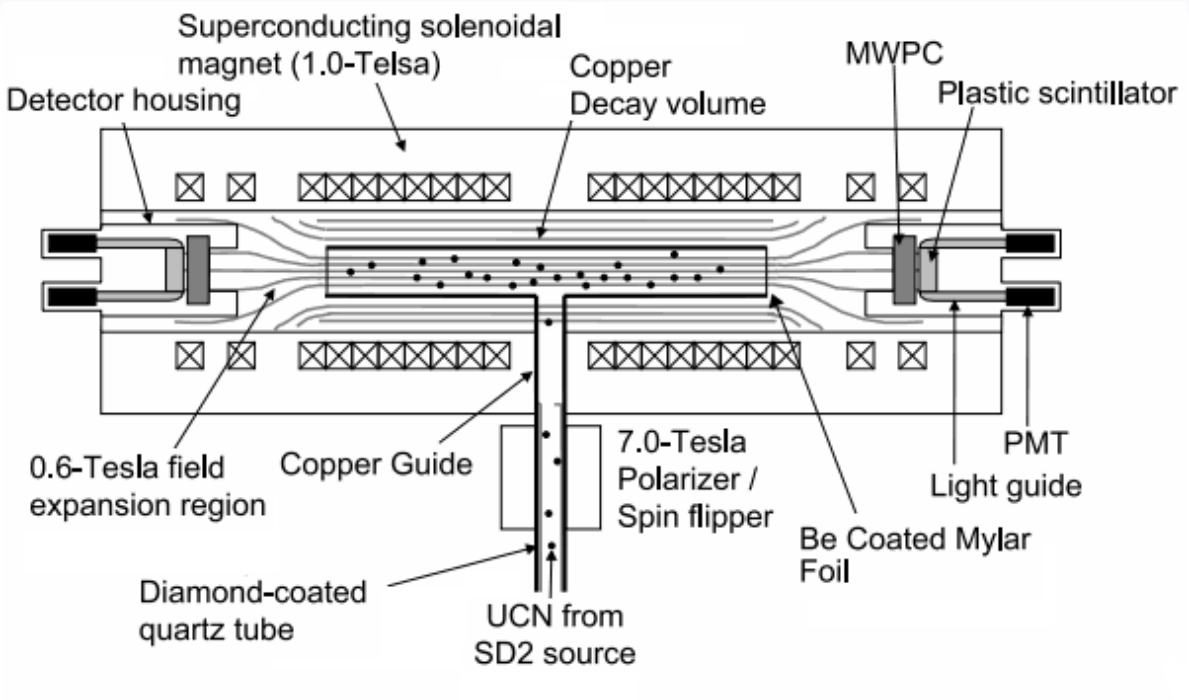


$$W(E) \propto 1 + \frac{v}{c}\langle P\rangle A(E) cos\theta$$

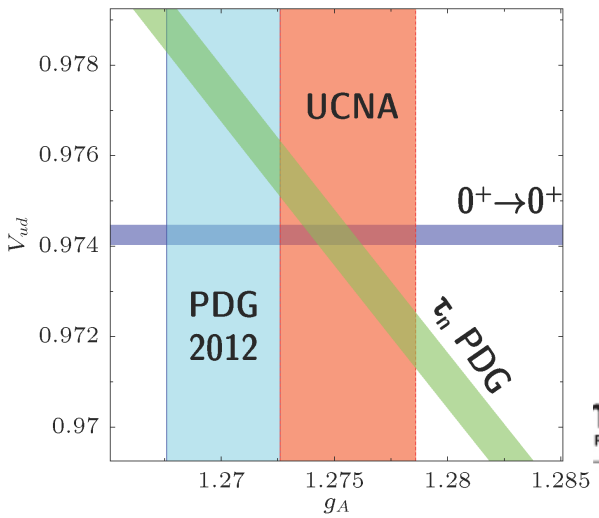
- 1 T field: $\langle cos\theta\rangle = \pm\frac{1}{2}$
- P: limit depolarization



UCNA Experiment



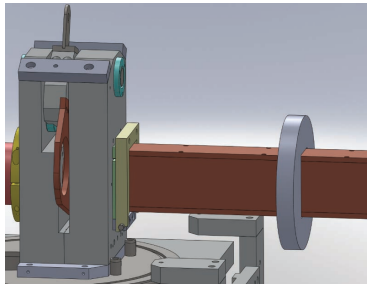
- Reduce backscatter: low Z, field expansion
- Plastic Scintillator: β energy
- MWPC: β position info, suppress backgrounds, backscatter reconstruction
- 2010 data-set: 20M β-decay events $A_0 = 0.11972(55)_{stat}(98)_{sys}$

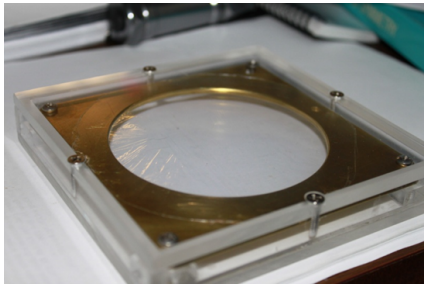


UCNA: 2011–2012 data sets and beyond

Improvement of UCNA Systematics (preliminary)

Uncertainty (%)	2010 dataset (Mendenhall 2013 PRC)	2011-2012 datasets (in analysis)	Next Step	Source of improvement
Statistics	+/- 0.46	+/- 0.40	+/- 0.28	Decay rate!
Depolarization	+0.67 +/- 0.56	+0.7 +/- 0.1	+0.7 +/- 0.1	Shutter+ ex situ
Backscatter	+1.36 +/- 0.34	+0.56 +/- 0.15	+0.56 +/- 0.15	Thin windows
Angle effect	-1.21 +/- 0.30	-0.8 +/- 0.2	-0.8 +/- 0.1	Windows+APD
Energy Reconstruction	+/- 0.31	+/- 0.08	+/- 0.08	Xenon + LED
Total Sys.	+/- 0.82	+/- 0.28	+/- 0.22	
Total	+/- 0.94	+/- 0.5	+/- 0.35	





UCNτ Collaboration

DePauw University
A. Komives

Hamilton College
G. Jones

Indiana University
E. R. Adamek, N. B. Callahan, W. Fox, C.-Y. Liu, D. J. Salvat, B. A. Slaughter, W. M. Snow, K. Solberg, J. Vanderwerp

JINR
E. I. Sharapov

Los Alamos National Laboratory
D. Barlow, M. Blatnik, L. J. Broussard, S. M. Clayton, T. M. Ito, M. Makela, J. Medina, D. J. Morley, C. L. Morris, R. W. Pattie, Jr., J. Ramsey, A. Saunders, S. J. Seestrom, S. K. L. Sjue, P. Walstrom, Z. Wang, T. L. Womack

North Carolina State University
C. Cude-Woods, E. B. Dees, B. Vorndick, A. R. Young, B. A. Zeck

University of California Los Angelos
K. P. Hickerson

Virginia Tech
X. Ding, B. Vogelaar

Tennessee Tech
A. T. Holley

The Neutron Lifetime τ

Beam of cold neutrons

- Count the dying

PHYSICAL REVIEW C **71**, 055502 (2005)

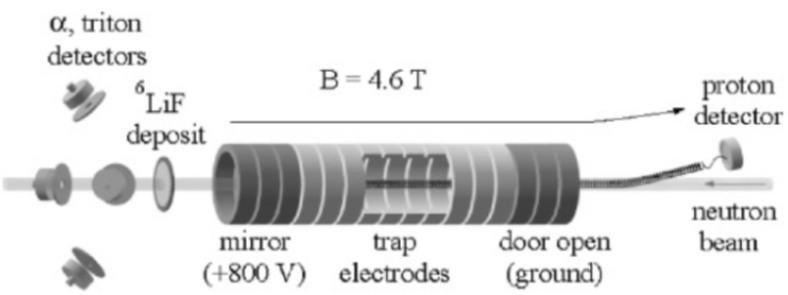
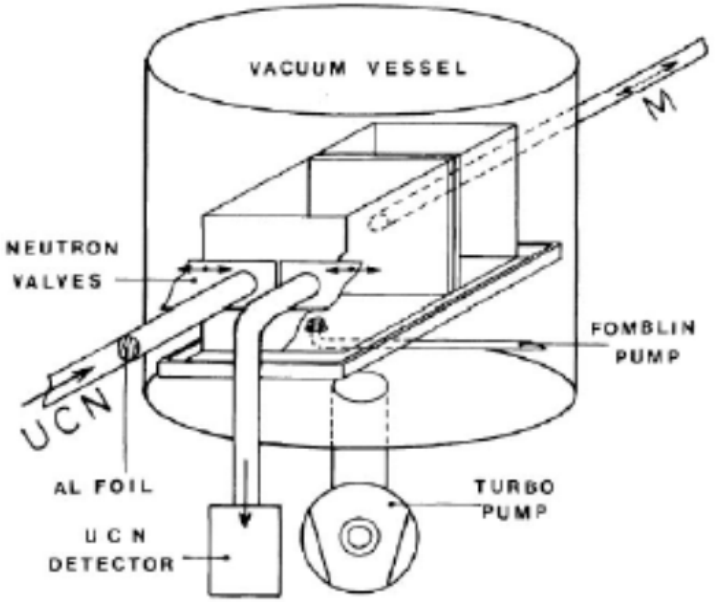


FIG. 2. Experimental method for measuring lifetime by counting neutrons and trapped protons.

Challenge: neutron flux measurement

Bottle of ultracold neutrons

- Count the survivors



$$1/\tau_{\text{storage}} = 1/\tau_n + 1/\tau_{\text{loss}}$$

Beam vs. Bottle disagree by 8 s!

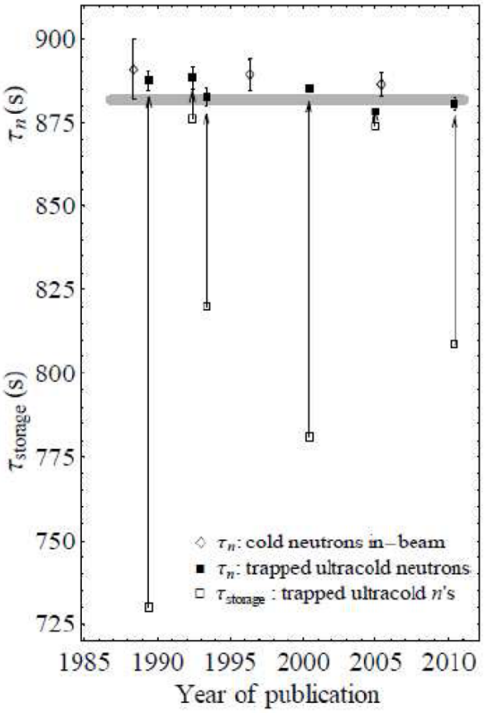
UCNτ Experiment

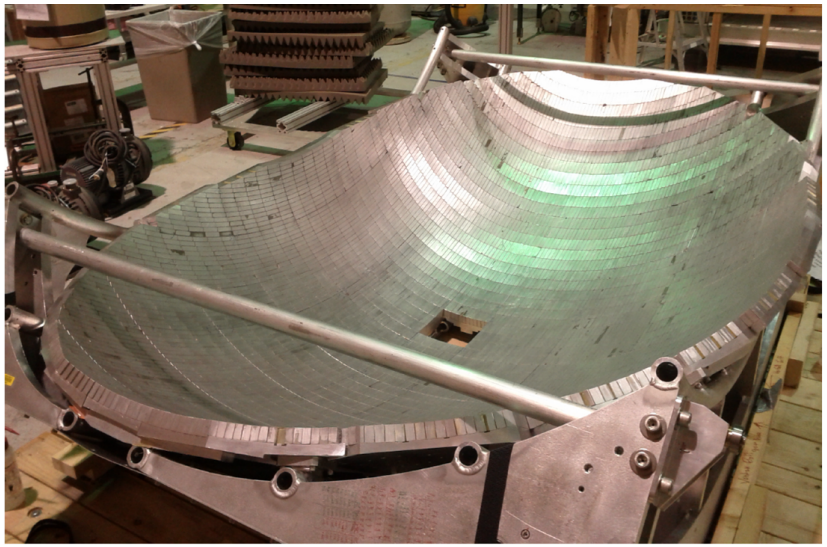
Material Bottles

- Extrapolate wall losses: large corrections

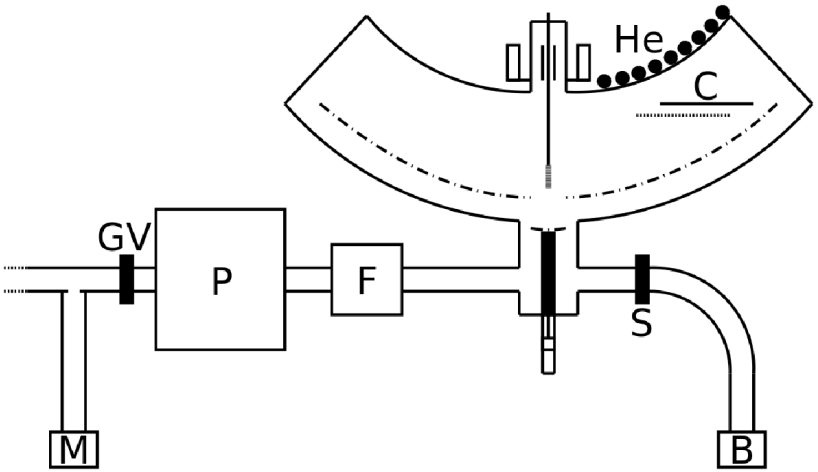
Magneto-gravitational Trap

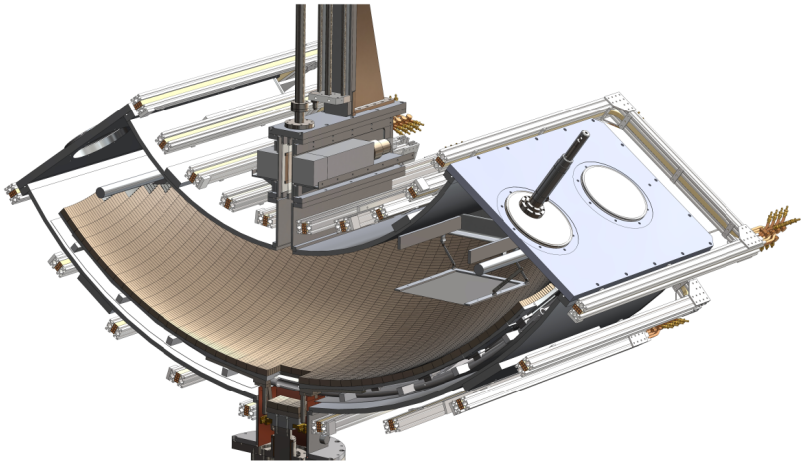
- World's largest permanent magnet array
- No material interactions
- Asymmetric design: phase space mixing $\rightarrow$ no quasi-bound orbits



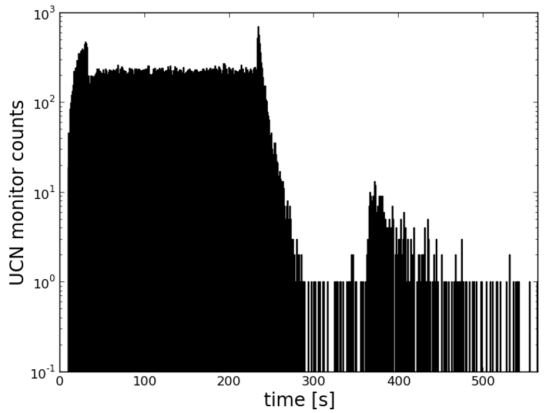


UCNτ Experiment





Ex-situ: fill and dump



0: Start UCN flow: beam on, shutter open, trap door open; cleaner inserted

1: Shutter closes

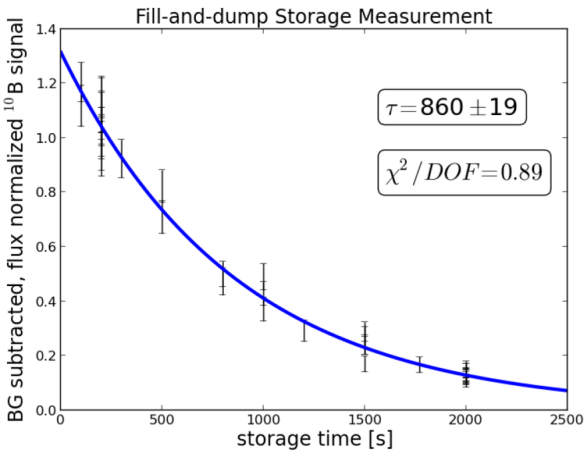
2: Filling and cleaning; superbarrier UCNs to monitor

3: Trap door closes, shutter opens; beam off; UCNs in guide to monitor; cleaning

4: Cleaner retracted; storage begins

5: Storage

6: Trap door opens; UCNs in trap to monitor



Storage time $>$ 10 hours!

UCNτ Experiment FY15 Progress

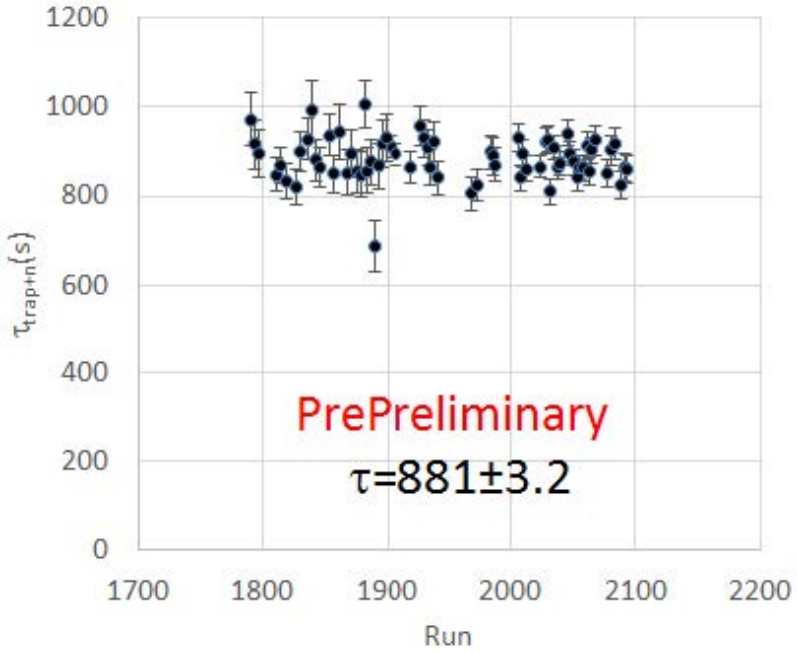
Improved UCN loading and trapped n's: new trap door

New data acquisition system

Improved *in situ* detector efficiency/backgrounds

More production data: 4 s stat. uncertainty

FY16 focus: systematic studies for 1 s uncertainty



Beyond the Standard Model: UCNb and UCNB

Access via b, B[1]

$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto w(E_e)(1 + \frac{m_e}{E_e}\bar{b} + \bar{a}(E_e)\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \bar{A}(E_e)\frac{\vec{\sigma}_n \cdot \vec{p}_e}{E_e} + \bar{B}(E_e)\frac{\vec{\sigma}_n \cdot \vec{p}_\nu}{E_\nu} + \cdots)$$

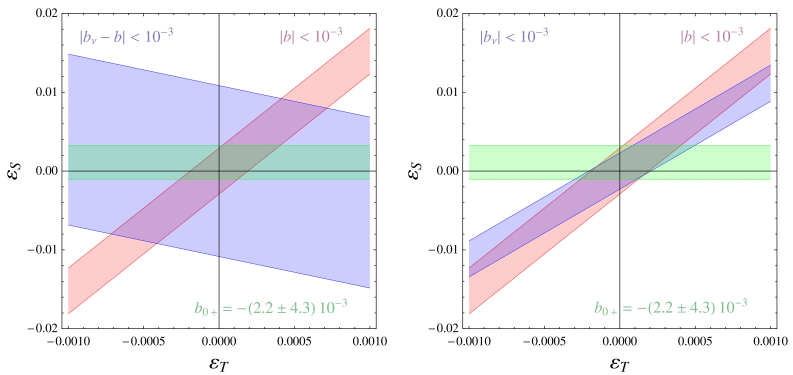
- $\bar{B}(E_e) = B^{SM}(E_e) + \frac{m_e}{E_e}(b_\nu^{SM} + \mathbf{b}_\nu^{\mathbf{BSM}}) + \ldots$
- $\bar{b} = b^{SM} + \mathbf{b}^{\mathbf{BSM}}$

New Scalar and Tensor physics in $\mathbf{b}^{\mathbf{BSM}}$, $\mathbf{b}_\nu^{\mathbf{BSM}}$

- $\mathbf{b}^{\mathbf{BSM}} \sim 0.34 g_S \epsilon_S - 5.22 g_T \epsilon_T$ $\qquad b^{SM} = -\left(\frac{m_e}{M_N}\frac{1+2\mu_V+\lambda^2}{1+3\lambda^2}\right)$
- $\mathbf{b}_\nu^{\mathbf{BSM}} \sim 0.44 g_S \epsilon_S - 4.85 g_T \epsilon_T$ $\qquad b_\nu^{SM} = -\left(\frac{m_e}{M_N}\frac{(1+\lambda)(\mu_V+\lambda}{1+3\lambda^2}\right)$

Experimental determination of B

- Actually measure $B_{exp} = \frac{\bar{B}(E_e)}{1+\bar{b}m_e/E_e}$
- $B_{exp} \propto \mathbf{b}_\nu^{\mathbf{BSM}}$ - $\mathbf{b}^{\mathbf{BSM}}$



[1] *Phys.Rev.D* **85**, 054512 (2012)

UCNB Collaboration

Los Alamos National Laboratory

L. Broussard, M. Makela, P. McGaughey, J. Mirabal, C. Morris, R. Pattie, J. Ramsey, A. Saunders, S. Sjue, J. Wang, S. Wilburn, T. Womack

Caltech

C. Feng, B. Filippone

University of California, Los Angelos

K. Hickerson

Indiana University

A. T. Holley, D. J. Salvat, C.-Y. Liu

North Carolina State University

E.B. Dees, J. Hoagland, B. VornDick, A. Young, B. Zeck

University of Kentucky

M. Brown, S. Hasan, B. Plaster

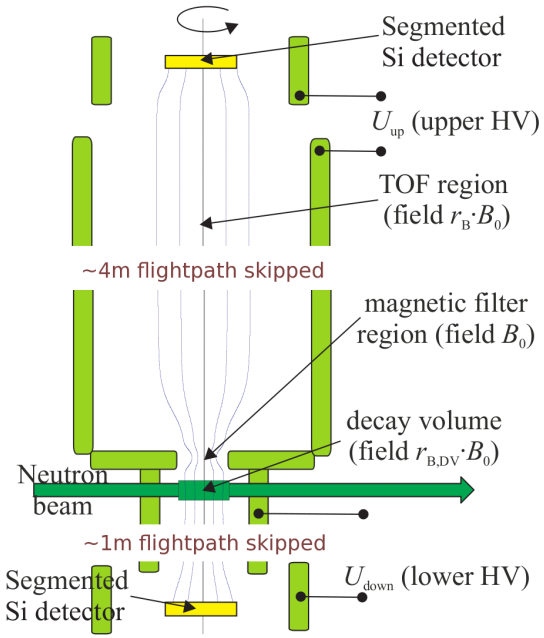
University of Virginia

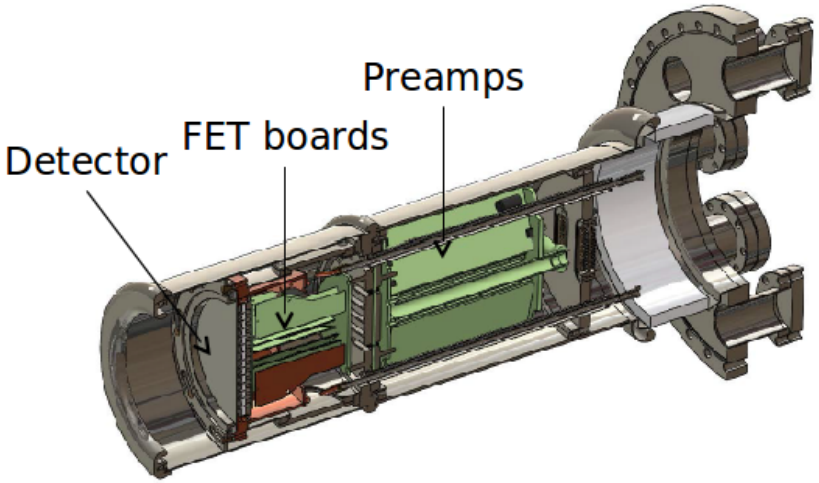
A. Bacci, S. Baessler, D. Pocanic

Virginia Tech

D. Bravo, X. Ding, R. B. Vogelaar

UCNB partnership with Nab



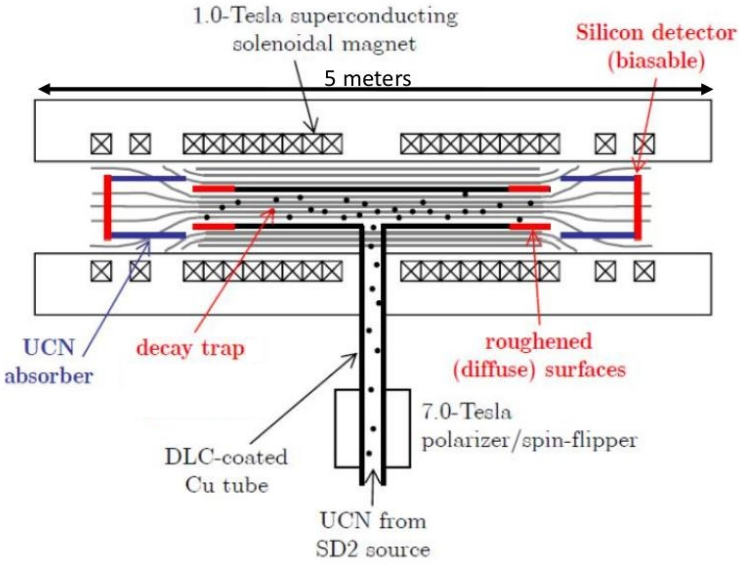


- Planned for Spallation Neutron Source at Oak Ridge National Laboratory

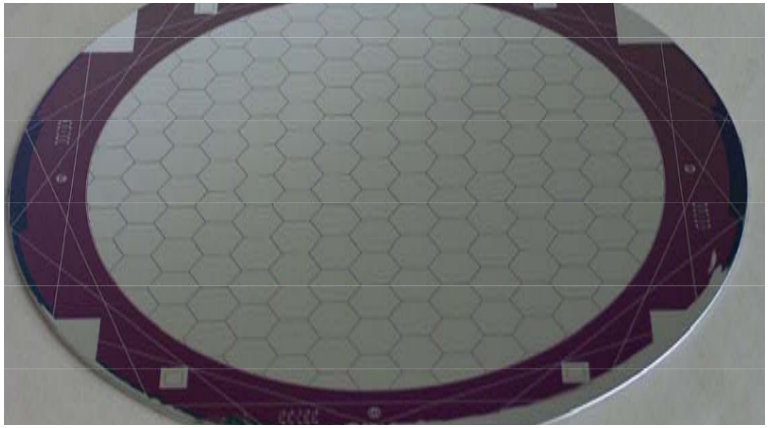
$$\frac{dW}{dE_e d\Omega_e d\Omega_\nu} \propto p_e E_e (E_0 - E_e)^2 \left[1 + \mathbf{a}\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu} + \mathbf{b}\frac{m_e}{E_e} + \langle\vec{\sigma_n}\rangle \cdot \left(\mathbf{A}\frac{\vec{p_e}}{E_e} + \mathbf{B}\frac{\vec{p_\nu}}{E_\nu} + \mathbf{D}\frac{\vec{p_e}\times\vec{p_\nu}}{E_e E_\nu}\right)\right]$$

- Will measure **a** (similar sensitivity to λ as **A**) and **b**
- Shared detector/preamp technology with UCNB

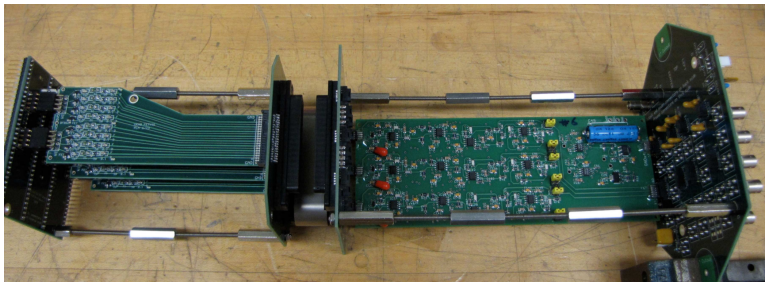
UCNB/Nab Detector Development



Segmented, thick, large area Si detector



Fast, low noise preamps built at LANL

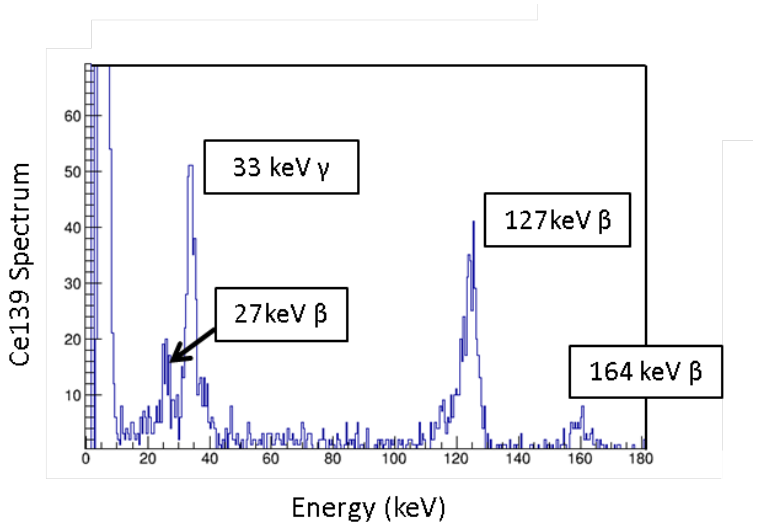


Detector mount biasable to -30 kV

UCNB/Nab Detector Development

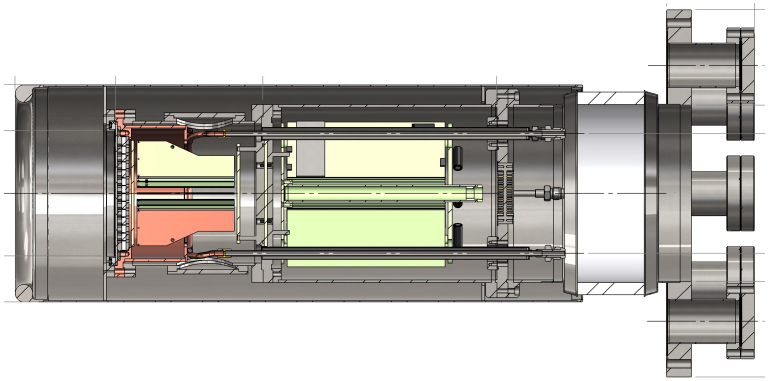
FY15 progress

- Specifications achieved with 24 ch prototype!
- 10 keV threshold, 2 keV (σ) resolution, 40 ns timing
- New data acquisition system from NI
- Multi-pixel p-β coincidences from n decay observed

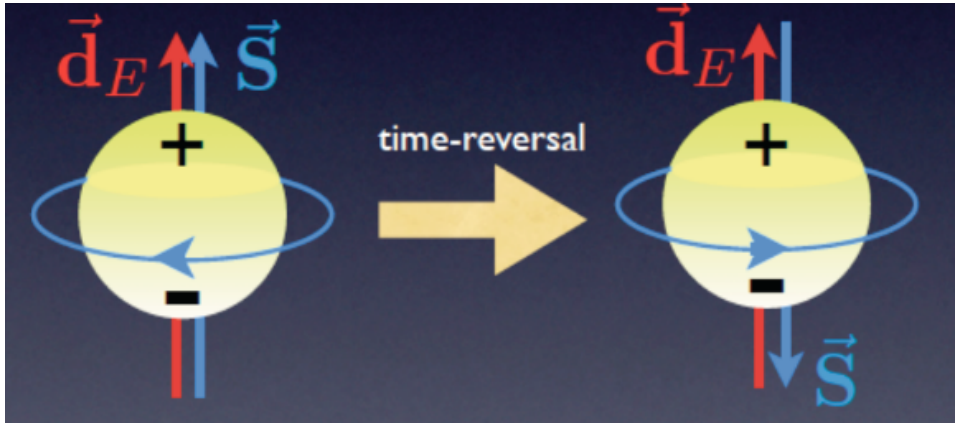


By FY16: full instrumentation

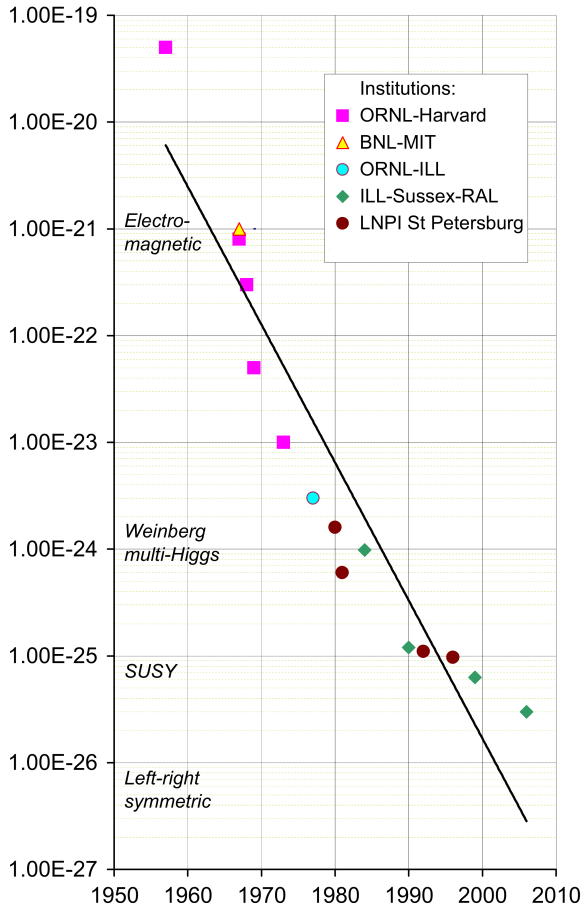
- Detector upgrade: new pogo-pin connectors
- 128 ch preamp instrumentation and testing
- Construct improved detector mount
- Begin commissioning of Nab experiment



Fundamental Symmetries and the neutron EDM



- EDM nonzero $\rightarrow$ T symmetry violation
- Matter-antimatter asymmetry? Source of CP violation?
- SM prediction: $d_n \sim 10^{-32} - 10^{-31}$ e-cm
- Current Limit: $d_n < 2.9 \times 10^{-26}$ e-cm (ILL)
- Constraints on EDM: best constraints on many BSM models (the "theory killer")
- EDM is DOE highest priority in "fundamental symmetries"



nEDM Collaboration

Los Alamos National Laboratory

J. Burkhart, S. Clayton, S. Currie, T. Ito, M. Makela, C. Morris, R. Pattie, J. Ramsey, A. Saunders, Z. Tang, T. Womack

Indiana University

E. Adamek, N. Callahan, C.-Y. Liu, J. Long, M. Snow

University of Kentucky

N. Nouri, B. Plaster

Yale University

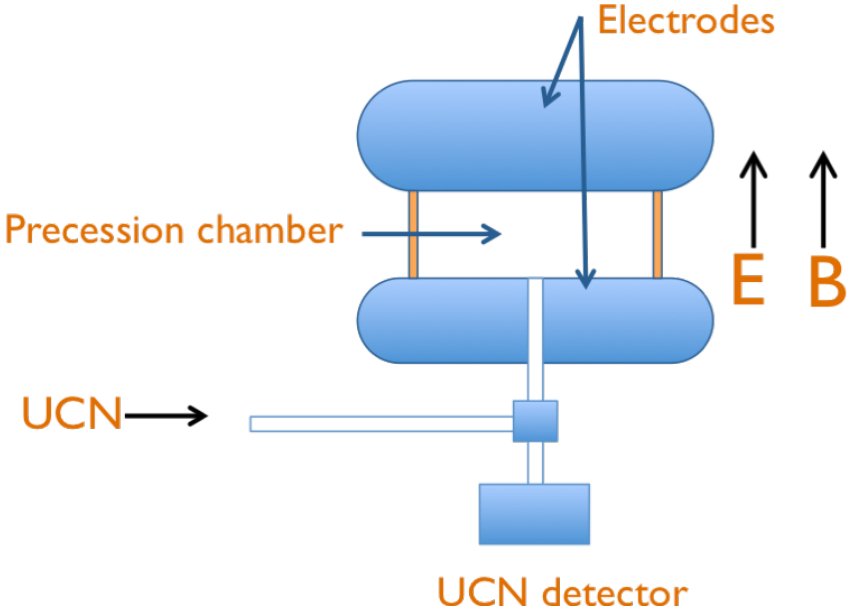
S. Lamoreaux

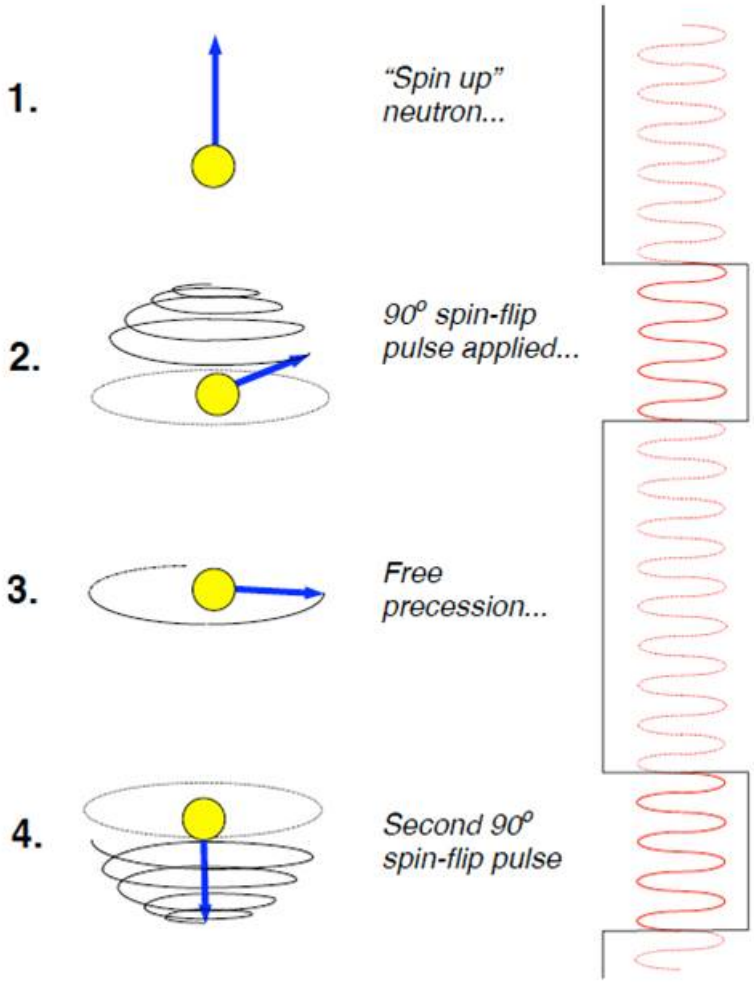
Joint Institute for Nuclear Research

E. Sharapov

nEDM Experiment

Experiment Principle





Keys to improving sensitivity

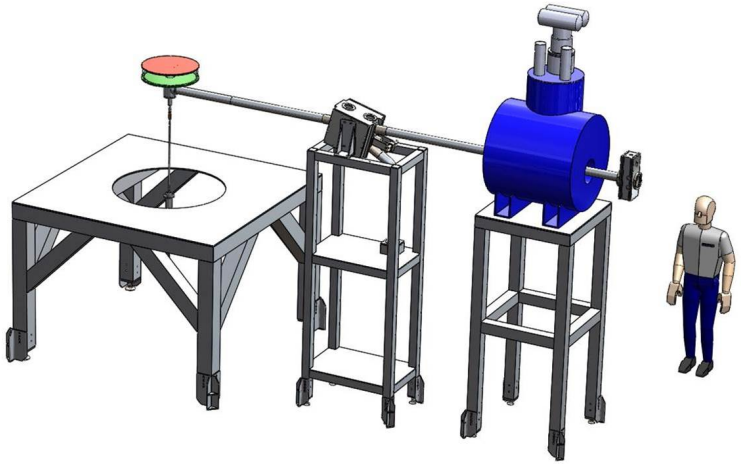
- $\delta d_n = \frac{\hbar}{2\alpha E T \sqrt{\rho_{UCN} V}}$
- Goal: $\rho_{UCN} \sim 100$ UCN/cc
- R&D to improve: E$\geq$10 kV/cm, T=130 s

nEDM FY15 Progress

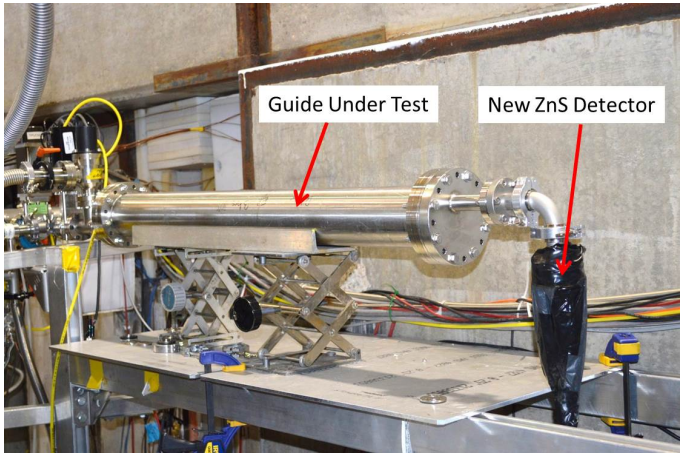
Small-scale HV test stand testing

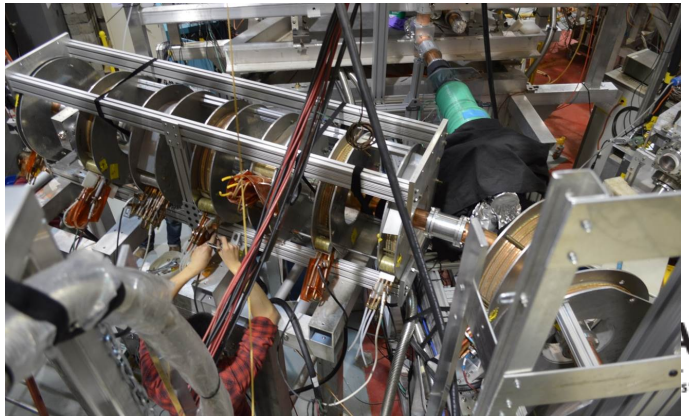
Upgraded UCN Source Fabrication

FY15 Goal: Prototype UCN Storage Cell



New UCN guide testing





nEDM UCN Density Improvements

UCN Source

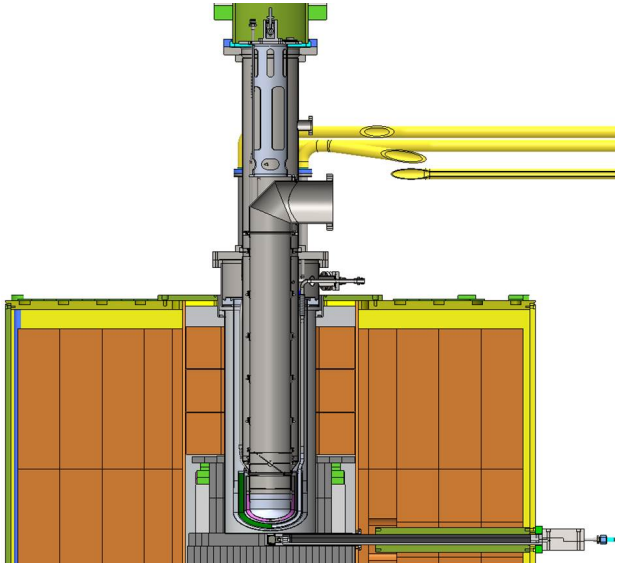
- Improved UCN source transition to guides
- Drive mechanism moved outside UCN volume
- Improvements to moderator cooling
- Geometry of source near W target

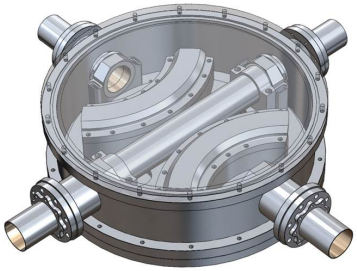
Proton Beam

- Improving high current operation safety, beam delivery

Transport to Experiment

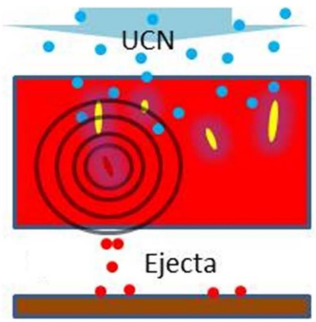
- Improve couplings, guide quality





Understanding Fission Fragment Damage

How do fission fragments (FF) damage material surface?



- FF: A$\sim$100, E$\sim$100 MeV, $\frac{v}{c} \sim 10\%$, 10 μm range
- Energy transfer very difficult to model
- FF passing through surface: micron-scale defects, material ejection (sputtering)

Sputtering not well quantified

- Previous yield measurements: significant disagreement
- Dependence on sample surface characteristics?
- No information on fission location

Interesting questions

- Yield, angular distrubtion, energy, mass of ejected material (atoms, particulates) and material damage characteristics as a function of fission depth
- Dependence on sample properties/surface conditions

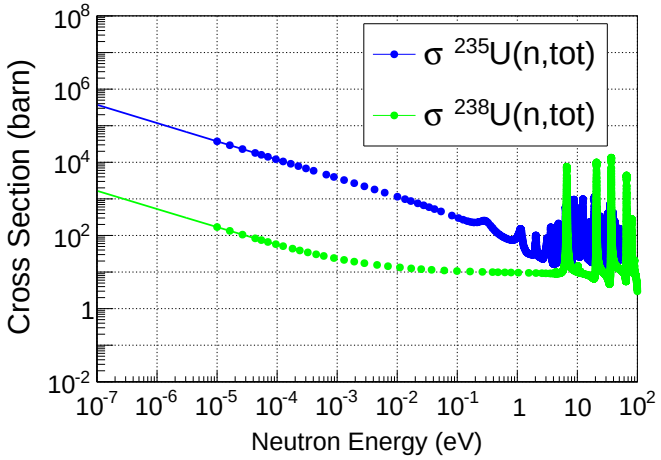
UCNS: Controlling the fission location

Uncharted energy regime

- UCN energy < 300 neV
- $\sigma \sim \frac{1}{v}$: very high predicted cross sections

UCN interact near surface

- Expected ranges
  - 80-150 μm in DU
  - 10-120 μm in LEU
  - < 1 μm in HEU
  - < 1 μm in ^{239}Pu
  - FF: $\sim$10 μm

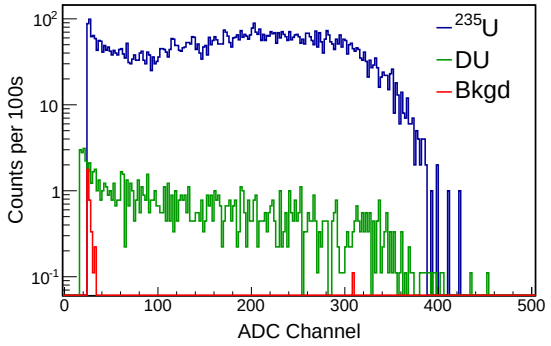


Vary UCN range (=fission location) using UCN energy, material composition/enrichment

UCNS Demonstration: control fission location

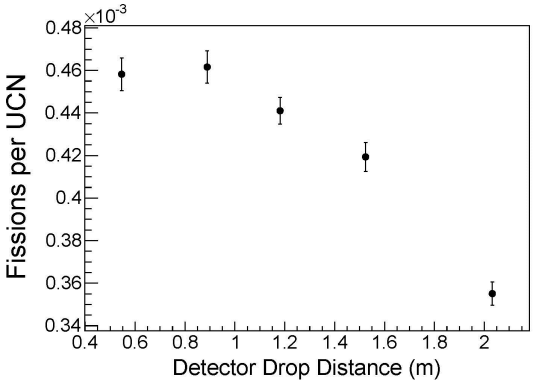
Adjust enrichment

- Similar sized disks of DU/HEU exposed to 2 kHz UCN
- FF Rate in DU: 0.5 ± 0.3 fission/s
- FF Rate in HEU: 70.9 ± 0.8 fission/s



Adjust UCN energy

- UCN penetration in DU $\sim$100 μm scale $\rightarrow$ fission distance from surface
- Compare to FF range $\sim$10 μm
- UCN energy increases $\sim$100 neV/m



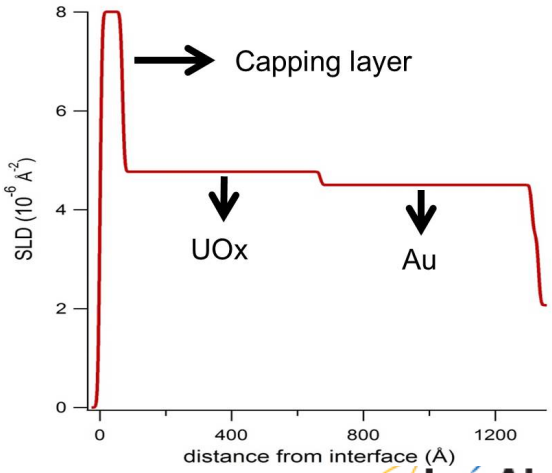
UCNS: FY15 Progress

Facility improvements

- Dedicated, parasitic beamline now commissioned
- Area B: Material Balance Area for sample use/storage

Developing technologies for uniform sample development

- Taking advantage of other LANSCE facilities (Asterix) for characterizations



New limits on cross sections

- DU $\sigma_{tot} < 5 \times 10^4$ barn
- HEU $\sigma_{tot} < 9 \times 10^5$ barn
- Consistent with theoretical predictions

Future of the UCN facility

Continue to increase UCN production

- nEDM source/transport improvements (funded): $\times \sim$2–3
- New diagnostics for improved proton beam tune (0.2M$): $\times \sim$2
- Low-loss UCN guides (0.3M$): $\times \sim$2–3
- Duty factor from pRAD beam kicker/shield wall (3M$) : $\times \sim$2

Expanding Multi-User Facility

- Consideration: implement PAC process for beamtime allocation

Physics output

- UCNA analysis underway, improved UCN rates allow future push to even lower uncertainties
- UCNτ 1 s precision measurement will shed light on current discrepancy in neutron lifetime
- UCNB detection system will enable broad suite of future correlation measurements (A, B, b, b_ν)
- nEDM expected to improve limit on EDM by order of magnitude
- UCNS represents new class of applied research for stockpile stewardship