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Title: The Standard Model and Beyond with Ultracold Neutrons

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The Standard Model and Beyond with Ultracold Neutrons

Leah Broussard

Los Alamos National Laboratory

September 25, 2014

Ultracold Neutrons

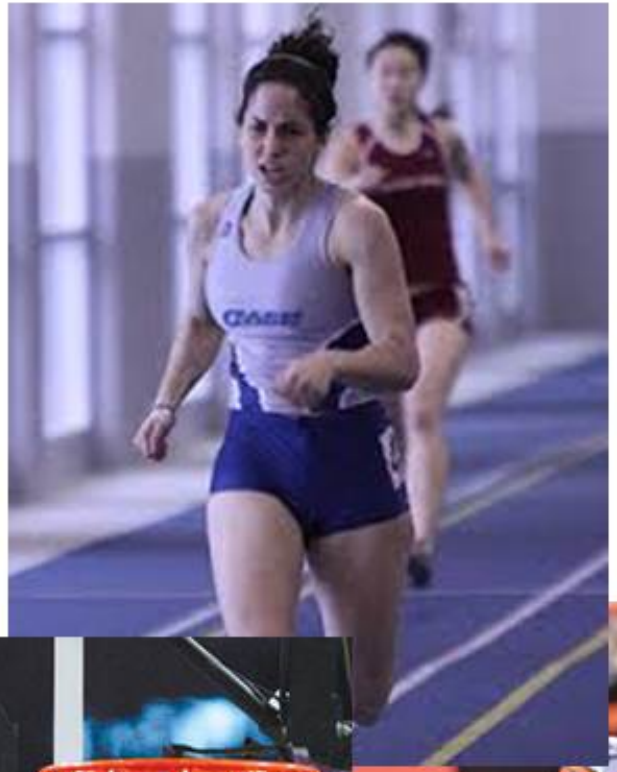
Class	Energy	Source
Fast	> 1 MeV	Fission reactions / Spallation
Slow	eV – keV	Moderation
Thermal	0.025 ev	Thermal equilibrium
Cold	μeV – meV	Cold moderation
Ultracold	≤ 300 neV	Downscattering

How cold is Ultracold?

- Temperature < 4 mK
- Velocity < 8 m/s
- Usain Bolt ~ 12 m/s

Sensitive to Lab-Accessible Potentials

- Gravitational ($V = mgh$): 100 neV / meter
- Magnetic ($V = -\vec{\mu} \cdot \vec{B}$): 60 neV / Tesla
- Material $\left(V = \frac{2\pi\hbar^2 Nb}{m}\right)$ $\begin{cases} {}^{58}\text{Ni}: & 335 \text{ neV} \\ \text{DLC}: & 250 \text{ neV} \\ \text{Cu}: & 170 \text{ neV} \end{cases}$



NBA

NBA
31
28

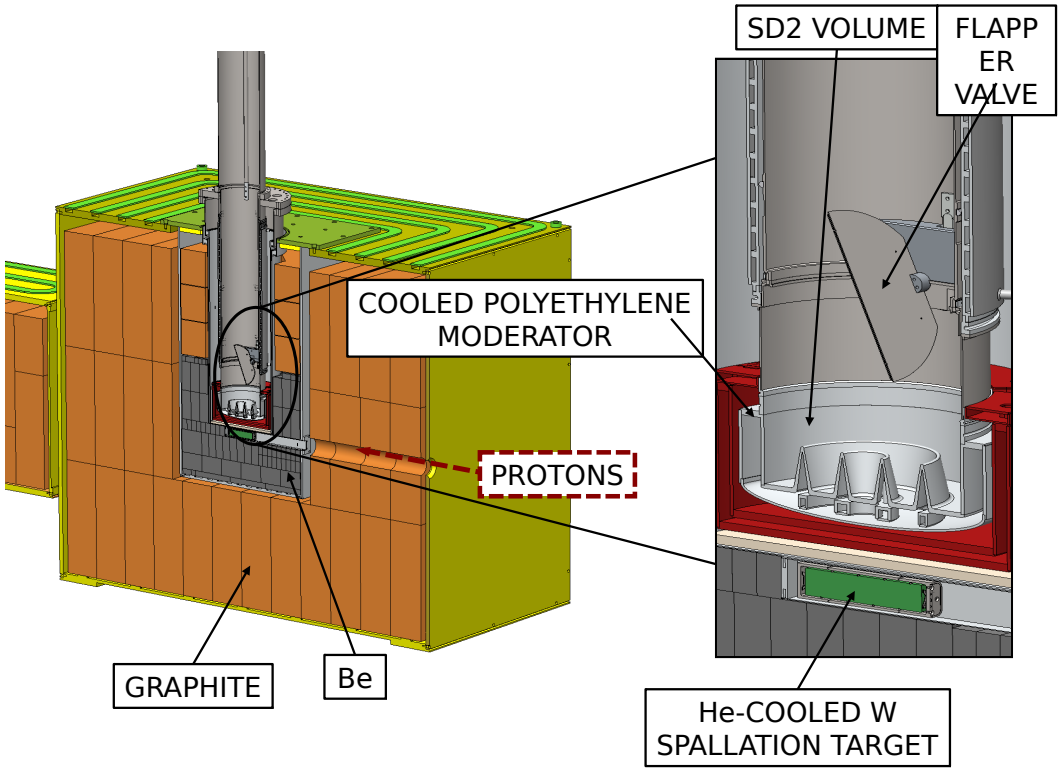
Ultracold Neutrons Live in Bottles

UCN video

LANSCE UCN Facility

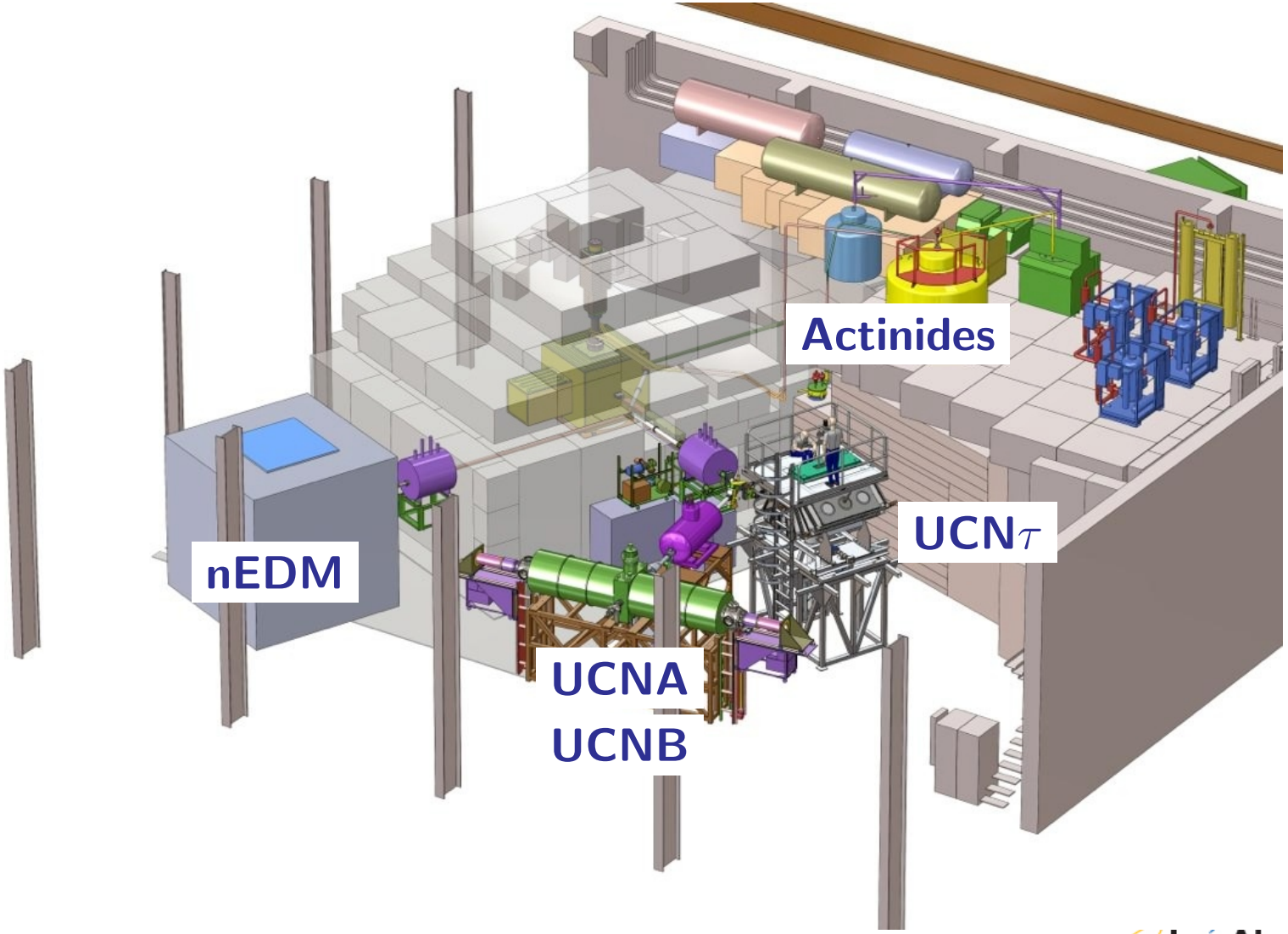
UCN Source[1]

- 800 MeV protons bombard a tungsten target to create spallation neutrons
- Neutrons are cooled in the polyethylene moderator and downscattered in a solid deuterium crystal to form UCN
- High densities observed: 50 UCN/cc at shield wall



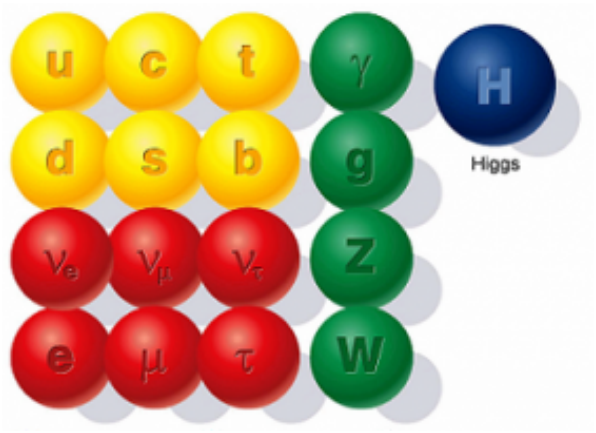
[1] Rev. Sci. Instrum. 84, 013304 (2013)

UCN Experimental Program



The Standard Model of Particle Physics

Standard Model is complete!



The Standard Model of Particle Physics

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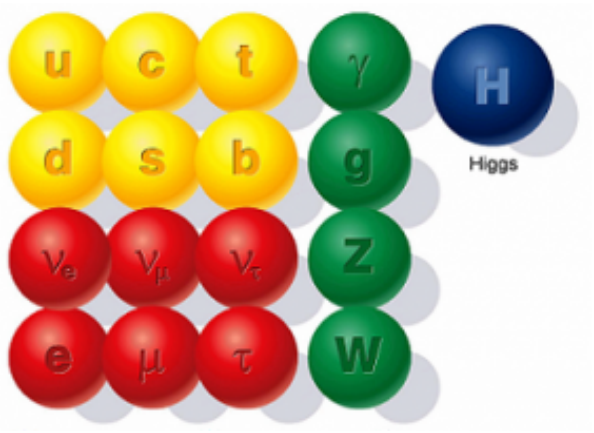
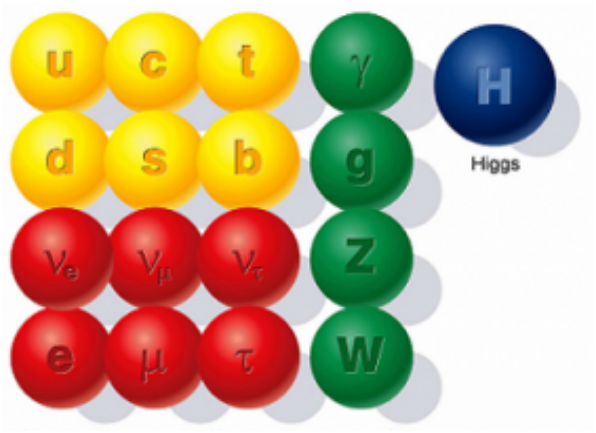


But...

- 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?

The Standard Model of Particle Physics

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?

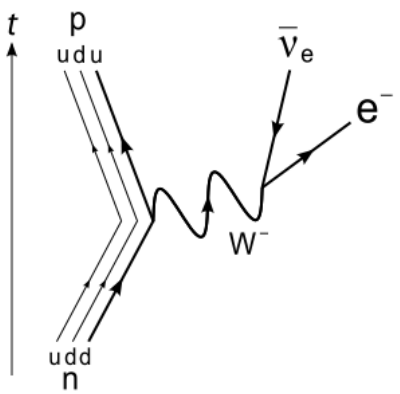
Are there more missing pieces?

- 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

The Weak Interaction

Described very well by the Standard Model

Example: β-decay



Quark Mixing (CKM)

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

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

Nuclear β-decay exhibits influence from Strong Force

- 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

The Neutron Beta Decay Alphabet

Experimental Observables

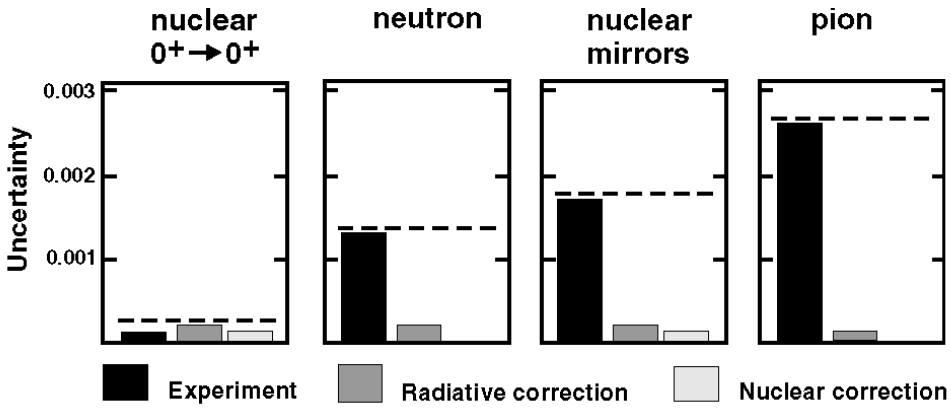
- Angular correlations polarized decay[1]:
  $\frac{dW}{dE_e d\Omega_e d\Omega_\nu} \propto p_e E_e (E_0 - E_e)^2 \left[1 + \mathbf{a}\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_e E_\nu} + \mathbf{b}\frac{m_e}{E_e} + \langle\vec{\sigma_n}\rangle \cdot \left(\mathbf{A}\frac{\vec{p_e}}{E_e} + \mathbf{B}\frac{\vec{p_\nu}}{E_\nu} + \mathbf{D}\frac{\vec{p_e}\times\vec{p_\nu}}{E_e E_\nu}\right)\right]$
- 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** + τ $\rightarrow$ **V**, **A** interactions
- **B**, **b** $\rightarrow$ **S**, **T** (BSM) interactions

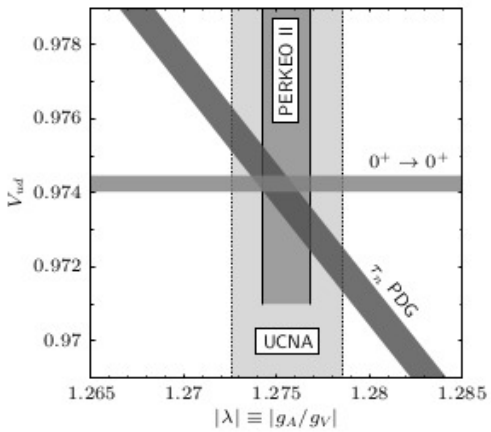
Test CKM Unitarity: Extract $\mathbf{V}_{ud}$

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

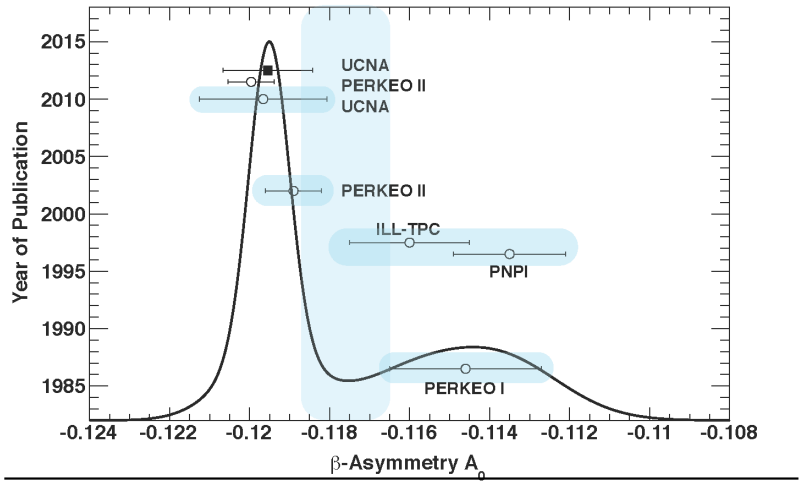
[1] Phys. Rev. C **106** 517 (1957)

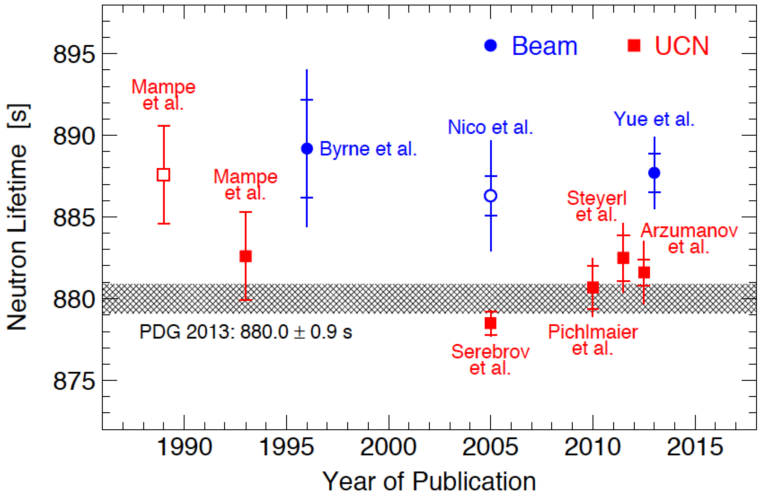
V_{ud} from Neutron Decay: A, a, and τ





- Superallowed Fermi $0^+ \to 0^+$ decays: V_{ud} at 0.02% level[1]
- 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





[1] *Ann. Phys.* **525** 443 (2013)

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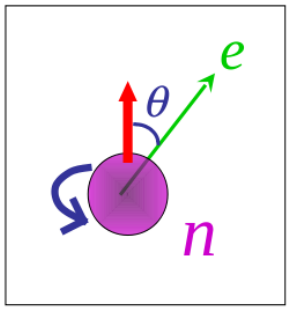
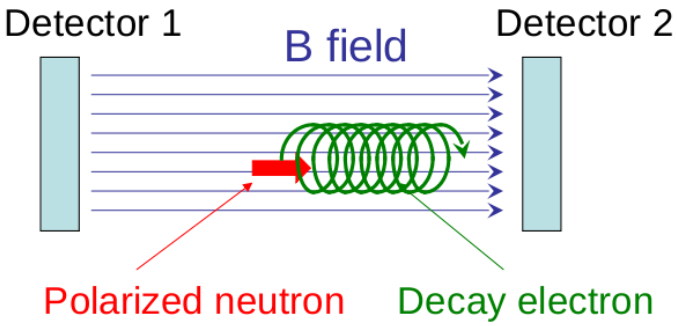
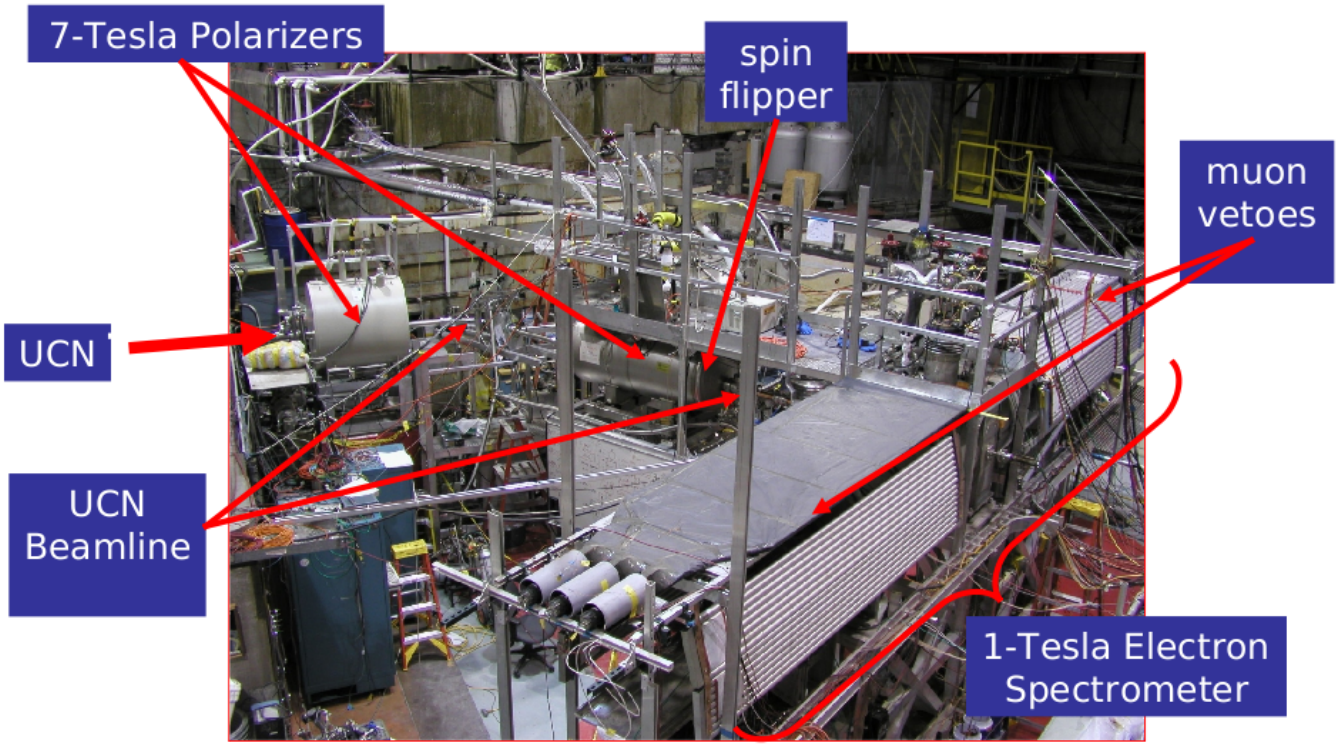
UCNA Experiment





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

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



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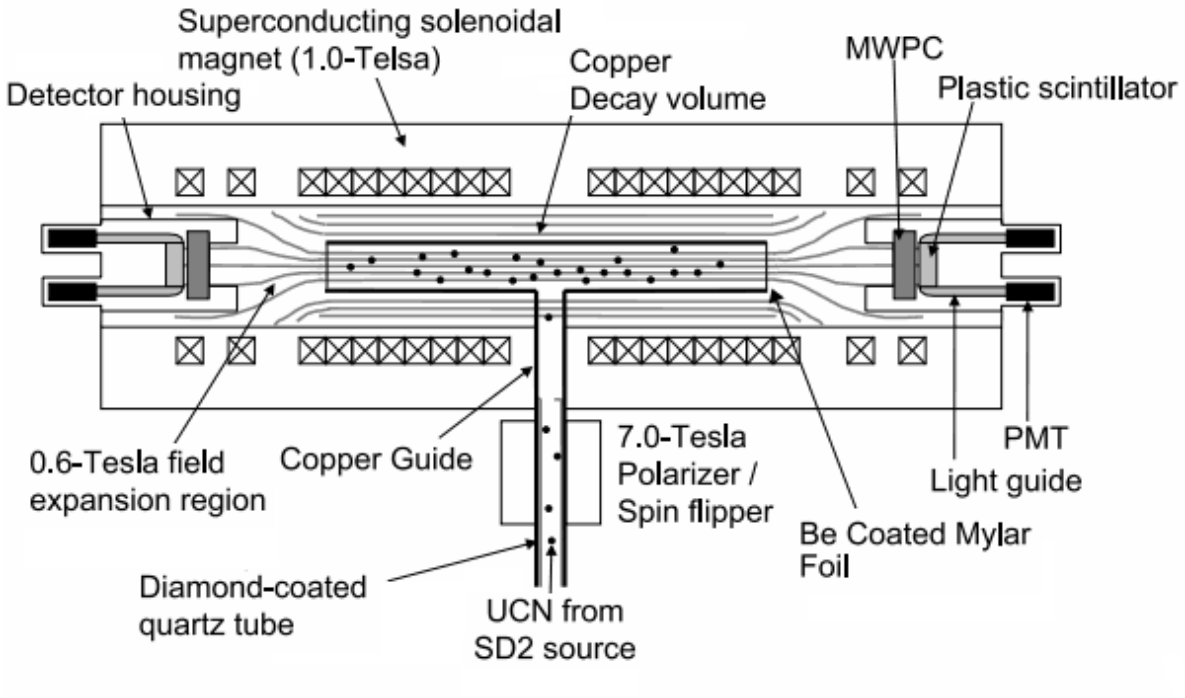
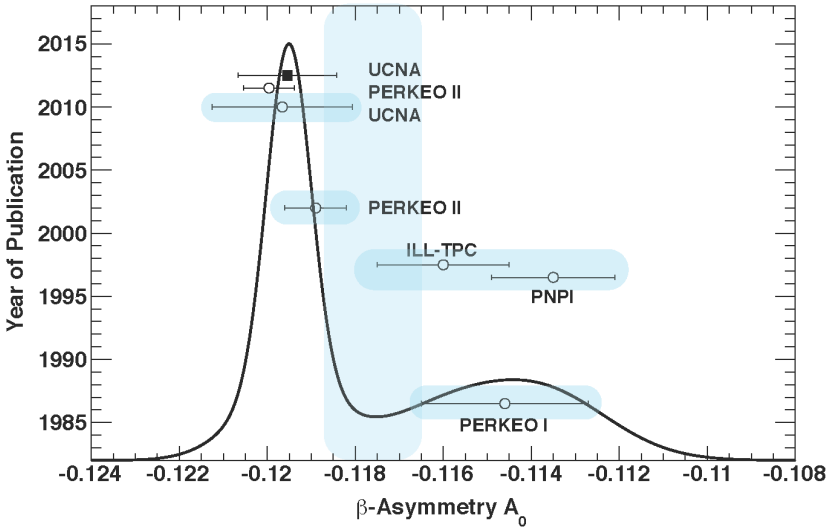
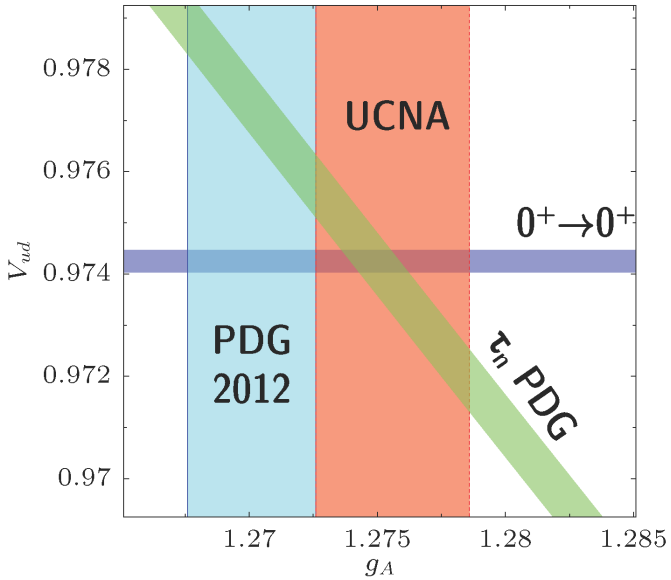


- Reduce backscatter: low Z, field expansion
- Plastic Scintillator: β energy
- MWPC: β position info, suppress backgrounds, backscatter reconstruction
- Super-ratio: cancel loading/detector efficiencies

$$S(E) = \frac{N(E)_1^+(N(E)_2^-}{N(E)_1^-(N(E)_2^+} \qquad A(E) = \frac{1-\sqrt{S(E)}}{1+\sqrt{S(E)}}$$

UCNA Results: 2010 data set



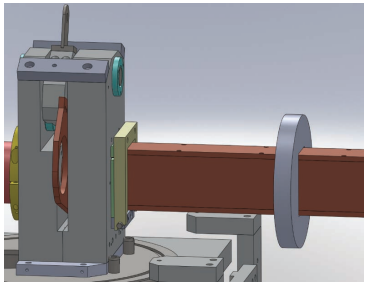


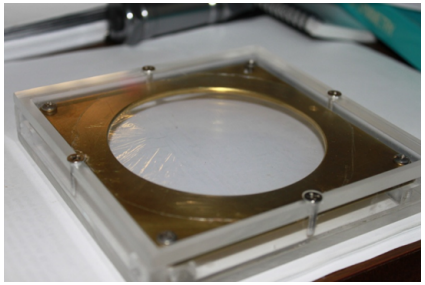
- Mendenhall et al. *Phys Rev C* **87** 032501(R) (2013)
- 20M β-decay events
- $A_0 = 0.11972(55)_{stat}(98)_{sys}$

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	





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The Neutron Lifetime τ

Beam of cold neutrons

- Count the dying

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

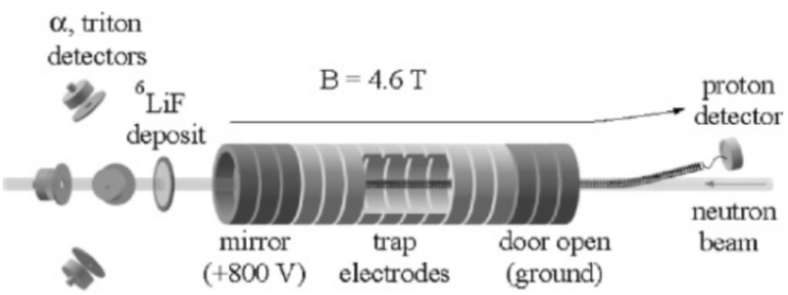
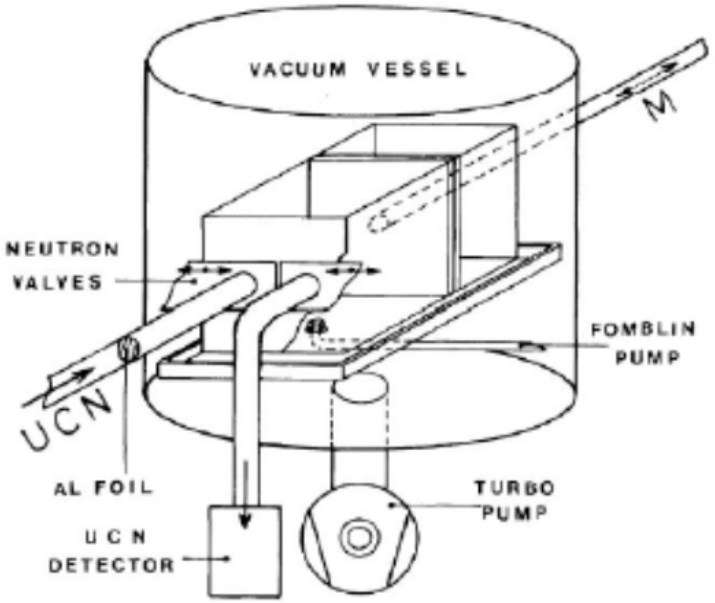


FIG. 2. Experimental method for measuring lifetime by counting neutrons and trapped protons.

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!

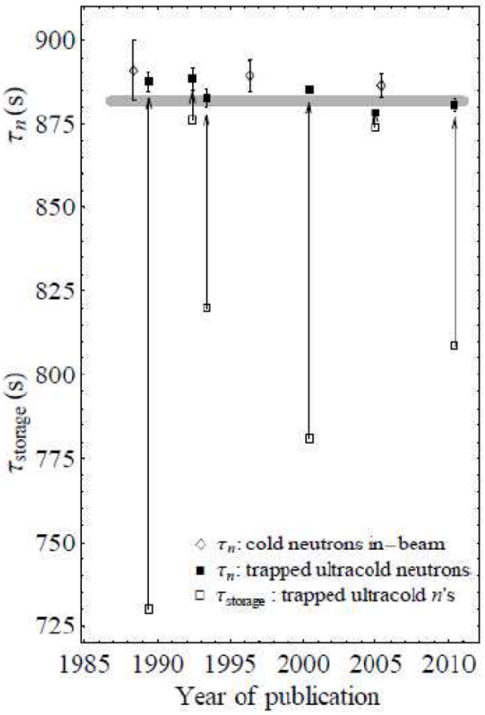
UCNτ Experiment

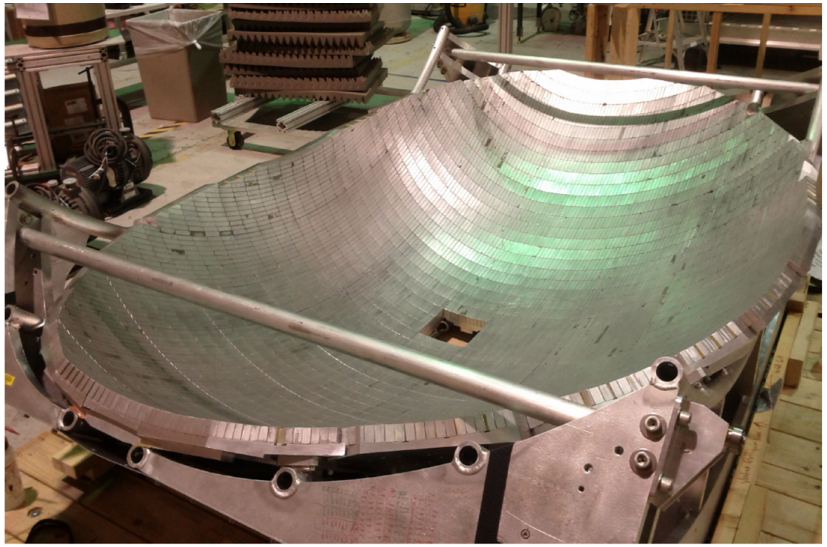
Material Bottles

- Extrapolate wall losses: large corrections!

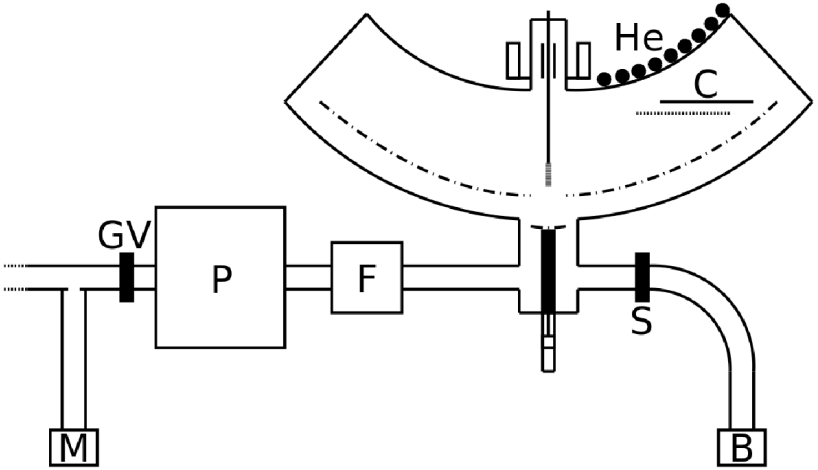
Magneto-gravitational Trap

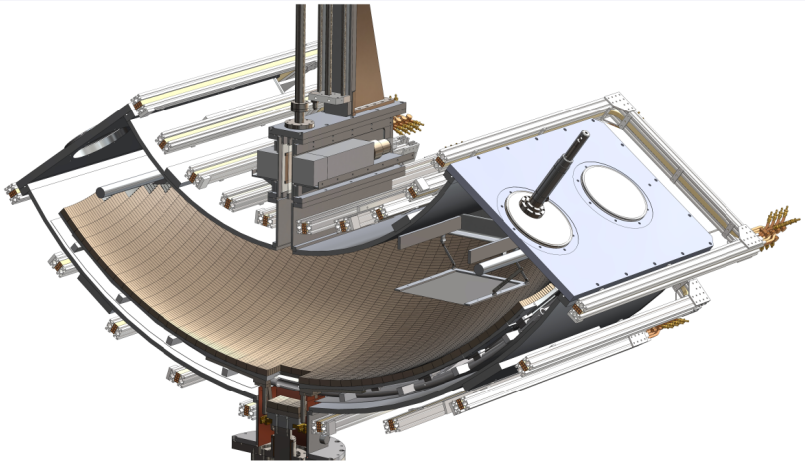
- World's largest permanent magnet array
- No material interactions!
- Asymmetric design: phase space mixing $\rightarrow$ no quasi-bound orbits



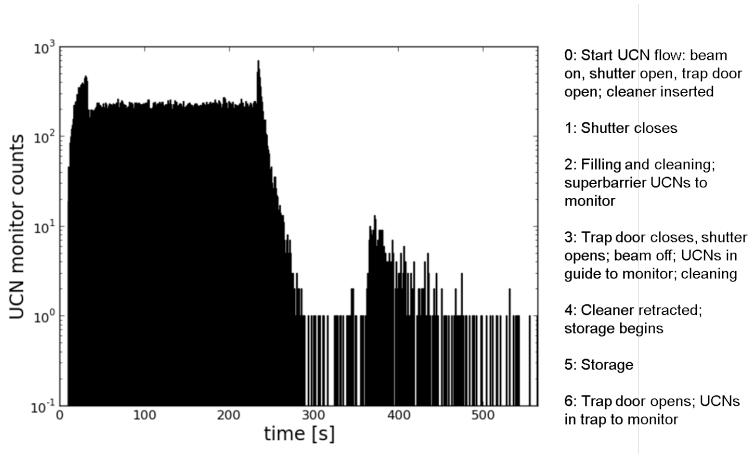


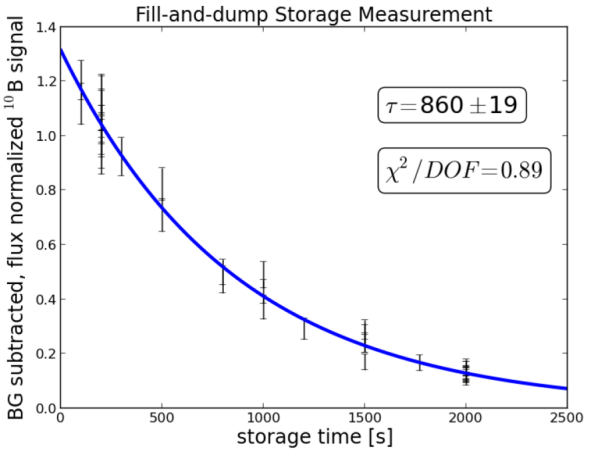
UCNτ Experiment





Ex-situ: fill and dump





Storage time $>$ 10 hours!

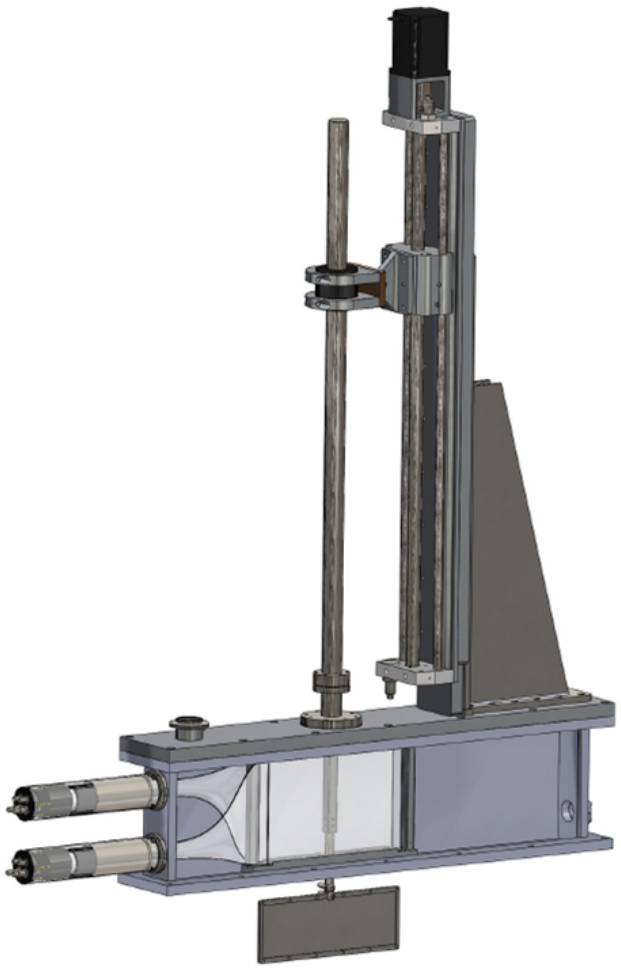
UCNτ Experiment

Improve precision with *in-situ* measurement

- Capture UCNs: $^{51}V(n,\gamma)^{52}V$
- Detect: $^{52}V \rightarrow^{52} Cr + \beta + \gamma$
- β scintillator + NaI γ detector assembly

UCN absorbed 10$\times$ faster than drained

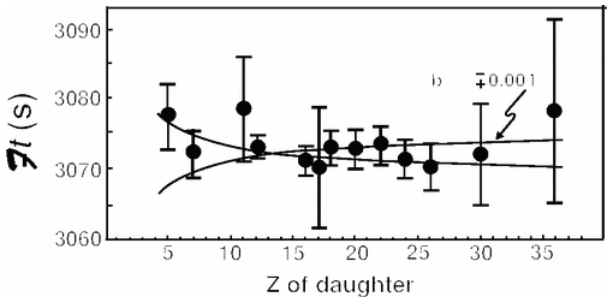
V foil absorber height: important systematic check



The Weak Interaction Beyond V-A: B and b

What can cause a scalar/tensor contribution?

- SUSY, leptoquarks, ...
- Not yet observed at the LHC
- Need model independent extraction

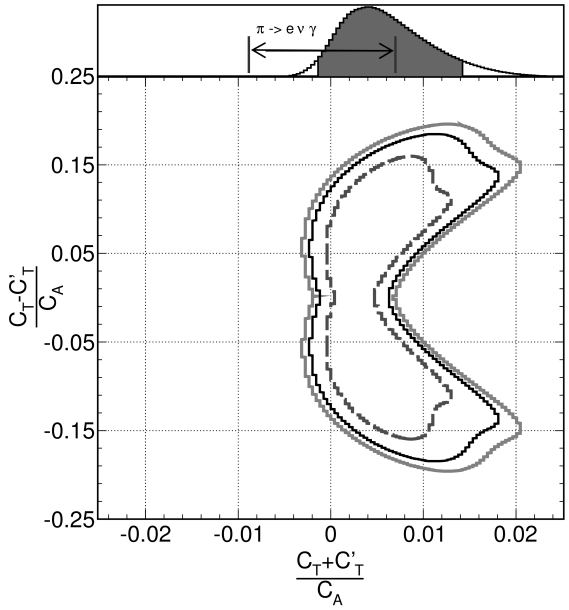


Current limits on Scalars

- From Superallowed Fermi $0^+ \to 0^+$ decays[1]
  $-1 \times 10^{-3} < C_S/C_V < 3 \times 10^{-3}$ (90% C.L.)

and Tensors

- From $\pi^+ \to e^+\nu\gamma$ (PIBETA)[2]
  $-2 \times 10^{-3} < C_T/C_A < 2 \times 10^{-3}$ (90% C.L.)
- From combined neutron/nuclear beta decay data[3]
  $0 < C_T/C_A < 4 \times 10^{-3}$ (90% C.L.)



[1] *Phys. Rev. C* **79** 055502 (2009)
[2] *Phys. Rev. Lett.* **103** 051802 (2009)
[3] arxiv:1306.2608v2 (2013)

BSM Scalar and Tensors in Neutron Decay

Access via b, B[1]

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

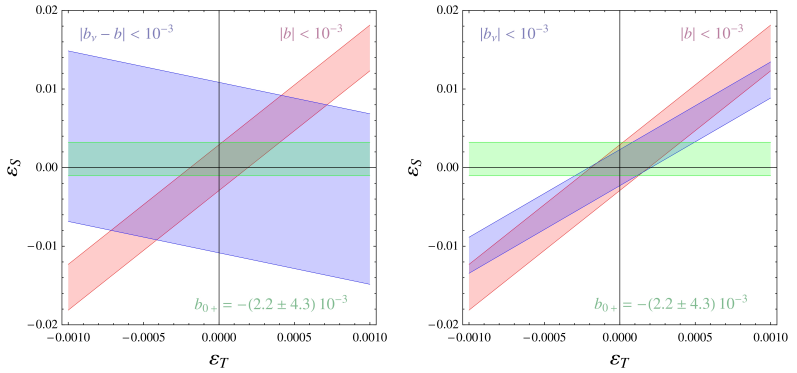
- $\bar{B}(E_e) = \frac{2\bar{\lambda}(1+\bar{\lambda})}{1+3\bar{\lambda}^2} + \frac{m_e}{E_e}(b_\nu^{SM} + \mathbf{b}_\nu^{\mathbf{BSM}}) + c_0 + c_1 \frac{E_e}{M_N}$
- $\bar{\lambda} = \lambda(1 - 2\epsilon_R)$; $c_{0,1}$: recoil corrections
- $\bar{b} = b^{SM} + \mathbf{b}^{\mathbf{BSM}}$

New 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

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North Carolina State University

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University of Kentucky

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University of Virginia

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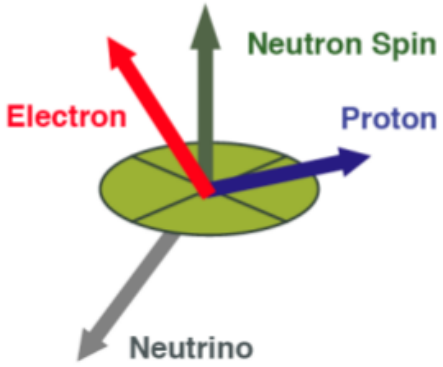
Virginia Tech

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

Experimentally Determining B

Classic Approach

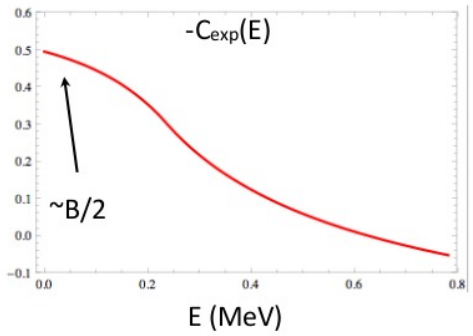
- Determine ν direction from e, p
- Count $N^{\beta p} = N^{\pm\pm}$ (β, p aligned vs. antialigned with σ_n)



$$B_{exp}(E) = \frac{N^{--}(E) - N^{++}(E)}{N^{--}(E) + N^{++}(E)}$$

$$C_{exp}(E) = \frac{(N^{++}(E) - N^{-+}(E)) - (N^{+-}(E) - N^{--}(E))}{(N^{++}(E) - N^{-+}(E)) + (N^{+-}(E) - N^{--}(E))}$$

- $\frac{\delta B}{B} = \frac{2.9}{\sqrt{N}}$: 0.1% in 1 month at 10Hz decay rate
- World average $B = 0.9807 \pm 0.0030(0.3\%)$



Isolating b_ν

Ratio of asymmetries[1]

- $r \equiv \frac{\beta_e E_e}{E_\nu}$ $\quad (r = 1 \text{ at } T_e = 236 \text{ keV})$

$$\alpha_p(E_e) = \frac{Q_{-\pm} - Q_{+\pm}}{Q_{-\pm} + Q_{+\pm}} = \begin{cases} \mathrm{P}\,\dfrac{\frac{2r}{3}A\beta_e + B\left(1-\frac{r^2}{3}\right)}{2\left(1+b\frac{m_e}{E_e}\right)} & \mathrm{r} < 1 \\ \mathrm{P}\,\dfrac{A\beta_e\left(1-\frac{1}{3r^2}\right)+\frac{2}{3r}B}{2\left(1+b\frac{m_e}{E_e}\right)} & \mathrm{r} > 1 \end{cases}$$

$$\alpha_e(E_e) = \frac{Q_{\pm-} - Q_{\pm+}}{Q_{\pm-} + Q_{\pm+}} = -\frac{1}{2\left(1+b\frac{m_e}{E_e}\right)} PA\beta_e$$

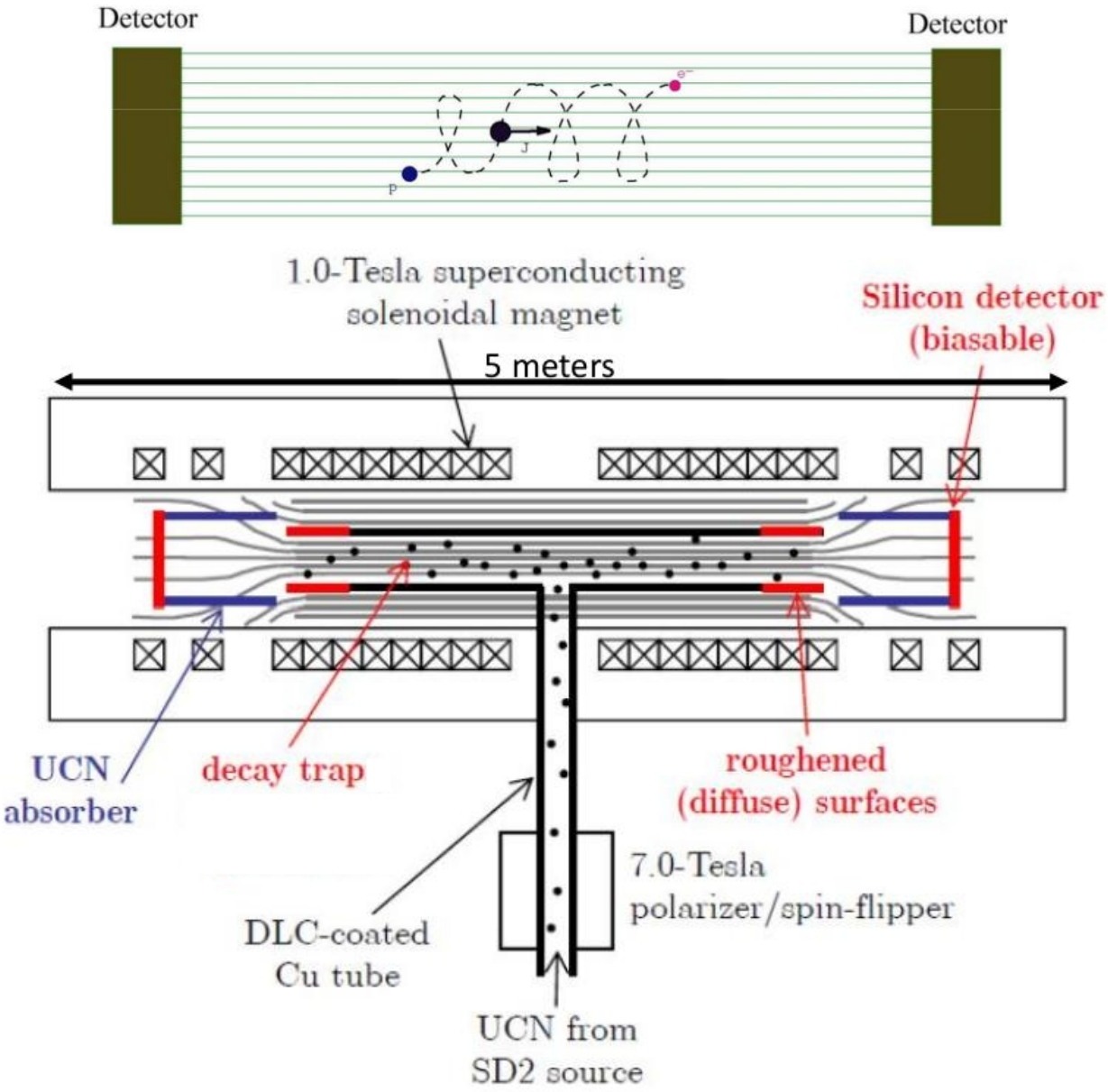
- Monte Carlo: $N = 10^8 \rightarrow$ probe b_ν at 3×10^{-3} level

Combined Fit

- $\mathrm{Q}^{\pm\pm}$: E_e, $\alpha_e(E_e)$, $\alpha_p(E_e)$
- Free parameters: λ, b, b_ν, normalization
- Use ϵ_S, ϵ_T dependence: $b = b_\nu + x$, $x = [-0.0005, 0.0003]$
- Monte Carlo: $N = 10^8 \rightarrow \lambda \sim 0.09\%$, $b \sim 2.2 \times 10^{-3}$, $b_\nu \sim 2.2 \times 10^{-3}$

[1] B. Plaster, S. K. L. Sjue, A. R. Young, *in prep* (2014)

UCNB Experiment: Overview



UCNB Experiment

CHALLENGE: Detecting protons and betas in coincidence

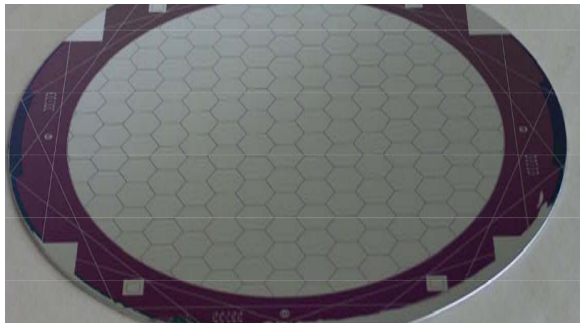
Protons

- max E $<$ 800 eV
- slow timing: 10 μs to 1 ms after decay
- Very low energy: detector deadlayer and noise important

Electrons

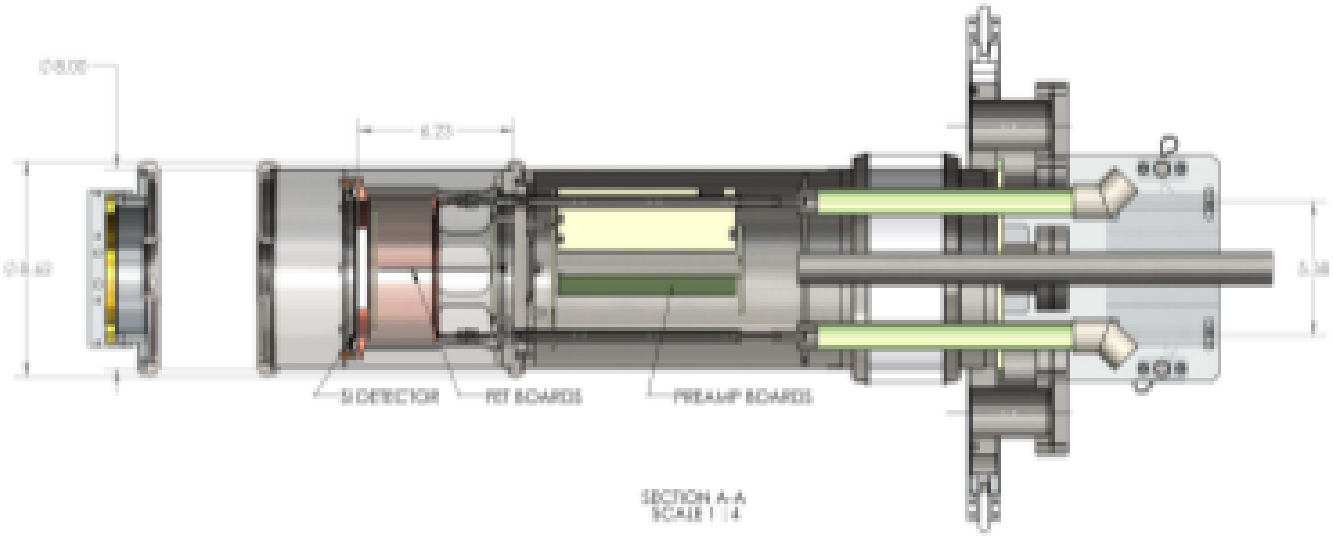
- max E $\approx$ 800 keV
- fast timing: 10 ns
- problem: backscattering $\rightarrow$ partial energy signal, direction

State of the art Si detectors



- 2 mm thick, 12 cm diameter active area
- Thin ($\sim$ 100 nm) deadlayer
- 128 pixels
- Characterization: Salas-Bacci *NIM A* (2014)

UCNB Experiment: Mount and Electrodes

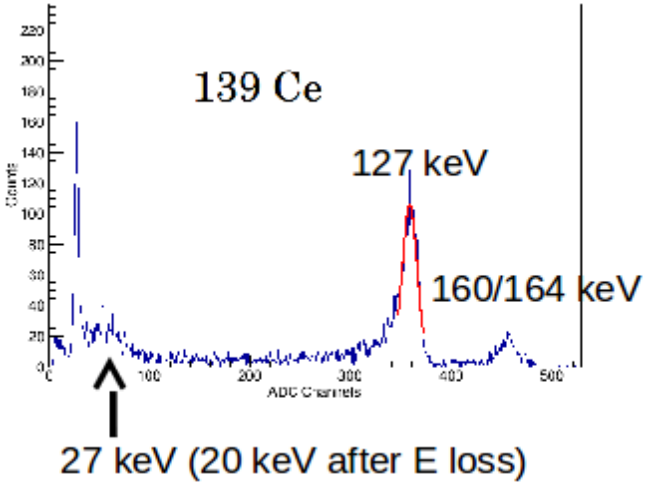


- Re-entrant into spectrometer vacuum: detector located at 0.6 T flat region
- Detector-FET assembly in vacuum, rest of preamp in air
- Full DAQ biased: detector, preamps, digitizers
- Stable operation at 1 T and -30 kV for ∼100 hours

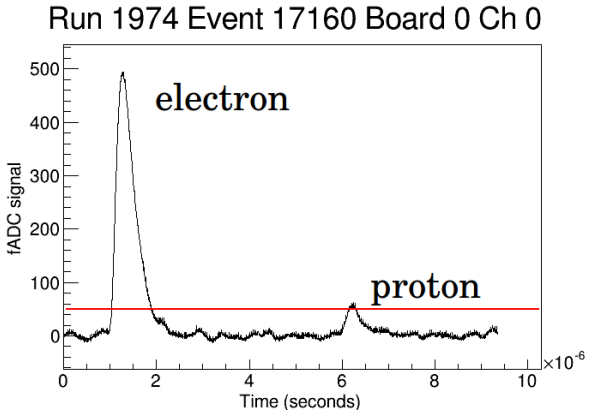
UCNB: Current Status

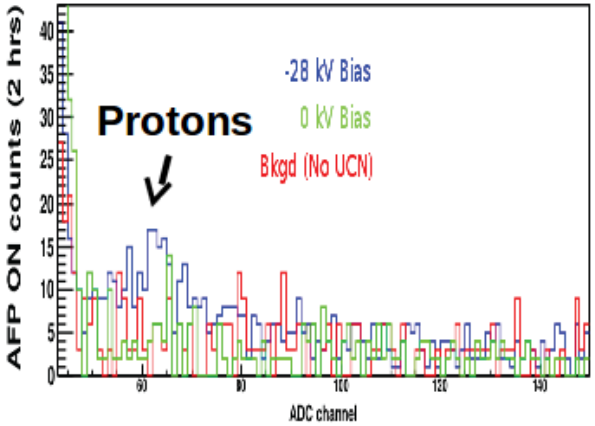
Preamplifiers

- 8-ch: <15 keV noise demonstrated, $\sim$ 3 keV energy resolution
- 24-ch: Now 20 ns rise time
- Successful demonstration with β-decay (Fall 2014) $\rightarrow$ assemble 128 ch model

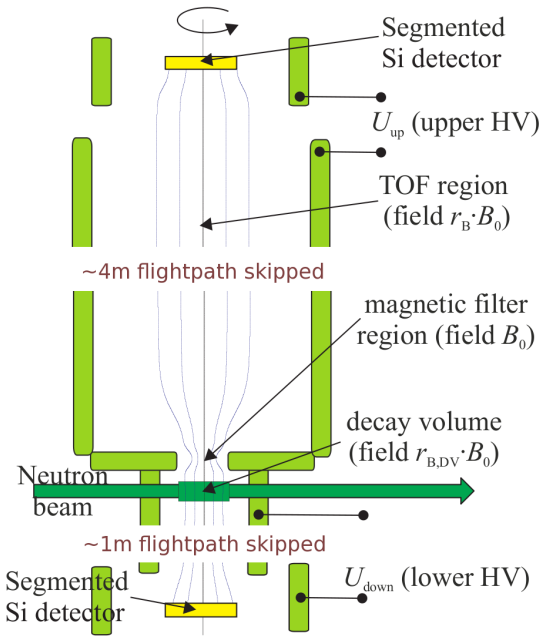


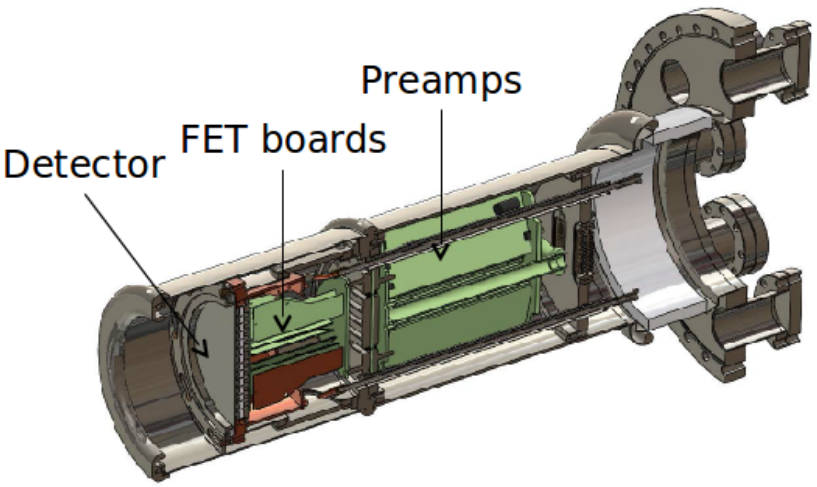
Neutron beta-decay proton-electron coincidences detected





UCNB partnership with Nab



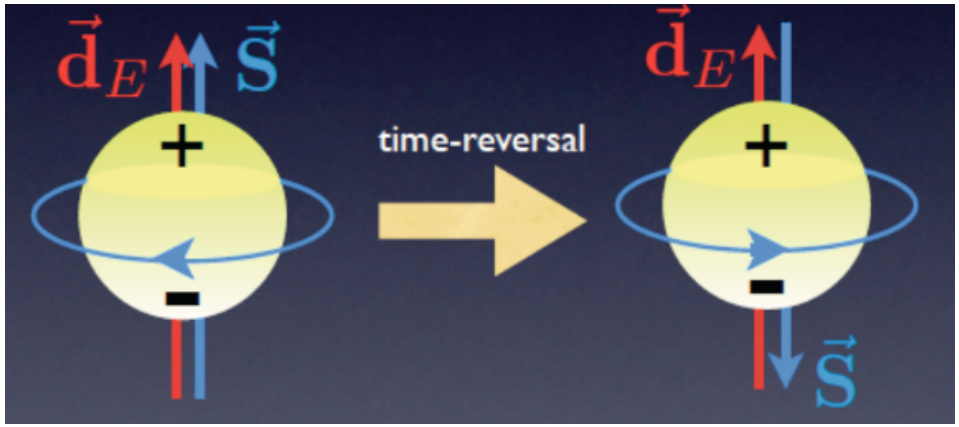


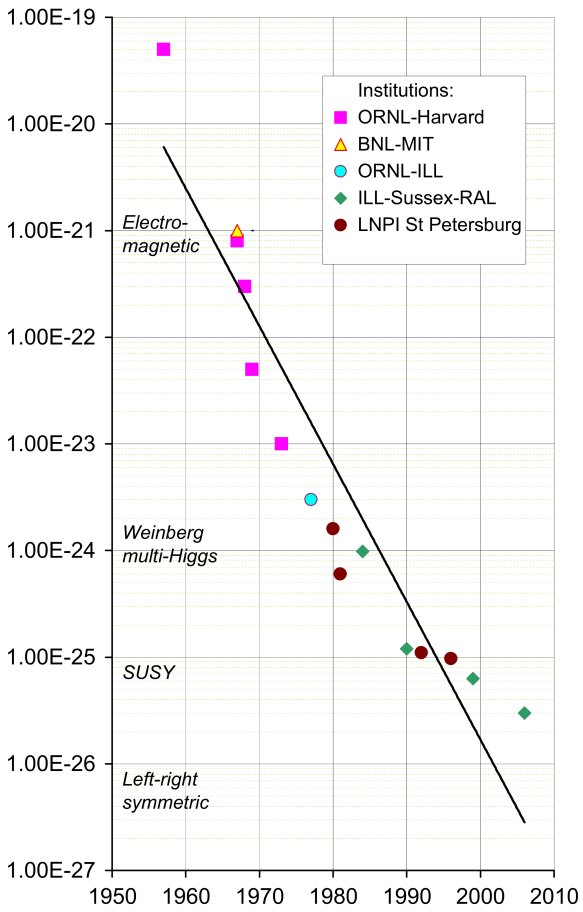
- Planned for Spallation Neutron Source at Oak Ridge National Laboratory

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

- Will measure **a** (similar sensitivity to λ as **A**) and **b** (zero in SM)
- No polarized neutron requirement
- Same detector/preamp technology

New effort to measure nEDM at LANL





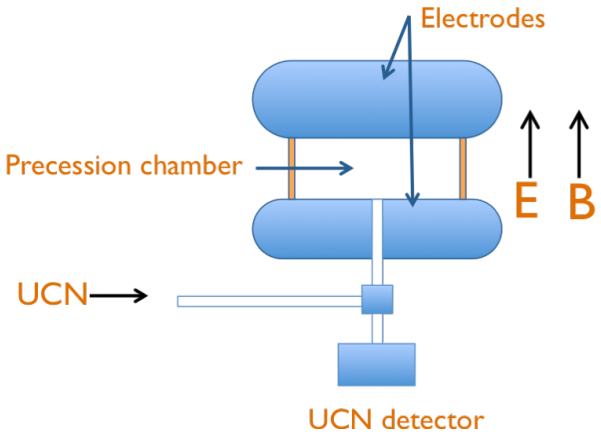
Why EDM

- 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

New effort to measure nEDM at LANL

Room temperature EDM

- Ramsey's separated oscillatory field method (similar to most precise result at ILL)
- EDM $\rightarrow$ frequency shift when $\vec{E}$-field reversed
- Goal: $\delta d_n \sim 10^{-27}$ e-cm
- ILL result: $\sim$1 UCN/cc
- Requirement for improvement: 100 UCN/cc



LANL nEDM UCN Density Improvements

UCN Source

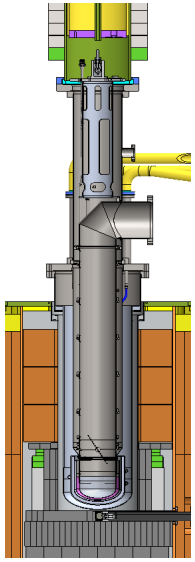
- Improved UCN source transition to guides
- Drive mechanism moved outside UCN volume
- Improvements to moderator cooling
- Geometry of source near W target

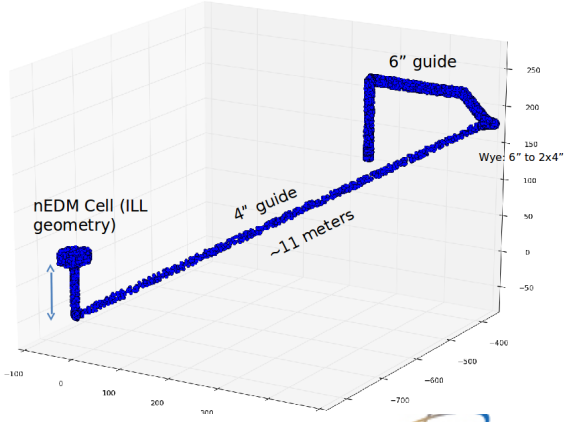
Proton Beam

- High current bursts every 30 s (presently every 5 s): Limit loss in SD_2

Transport to Experiment

- Current geometry suboptimal: Improve couplings, guide quality

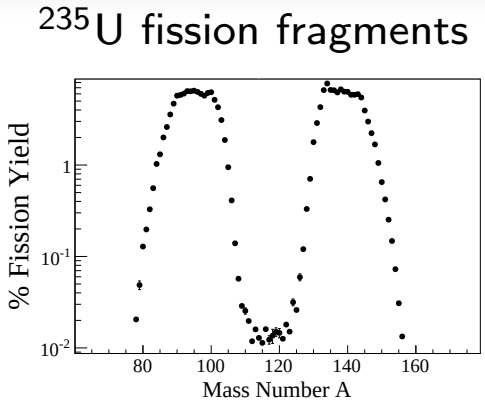




Studies of Actinides

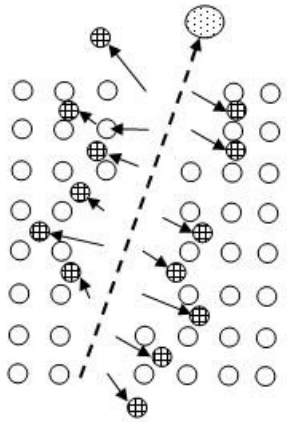
Typically 2 fragments emitted

- A$\sim$100, E$\sim$100 MeV, $\frac{v}{c} \sim 10\%$
- Range$\sim$10 μm



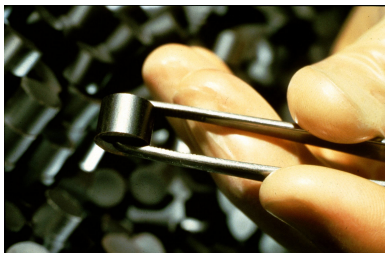
How does fission age material?

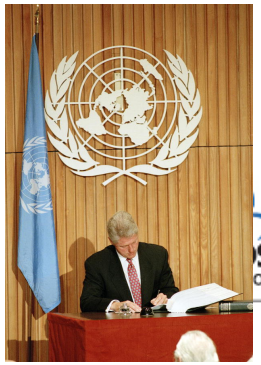
- Very energetic, heavy, charged particles
- How is energy deposited in material?
- Damage to the material?
- Near material surface: ejection of matter
- Differentiate between theoretical models



Why study nuclear material aging?

- Nuclear fuels
- Stockpile stewardship
- Lifetime of materials in space





Inducing Fission with Ultracold Neutrons

Experimental evidence

- Many previous measurements of sputtered atoms per fission
- **Significant disagreement in yield, distribution!**
- Key to differentiating models

New Technique for understanding sputtering

- Induce fission using Ultracold Neutrons
- Excellent control of neutron energy
- Very sensitive probe of fission as function of depth

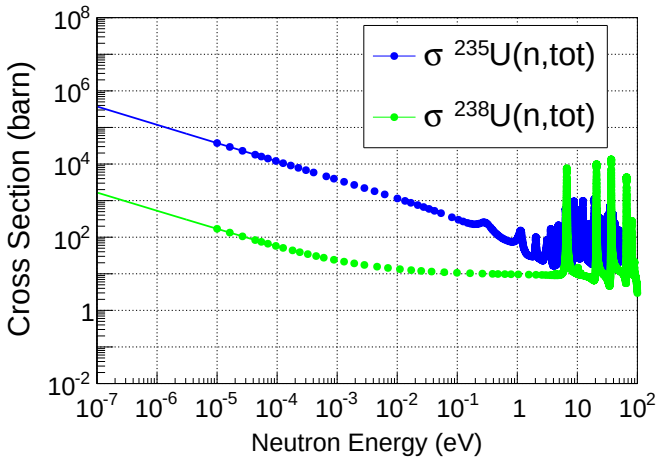
LANL: Unique Position for work

- LANSCE: one of world's brightest sources of UCN
- Expertise in fabrication and analysis of actinide targets

Predictions for UCN-induced Fission in Uranium

Uncharted energy regime

- 3 orders of magnitude lower than ever explored
- Very high theoretical cross section $\sigma \sim \frac{1}{v}$
- 300 neV UCN: 2.16×10^5 barn



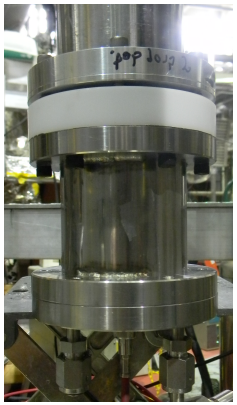
Control depth of fission event

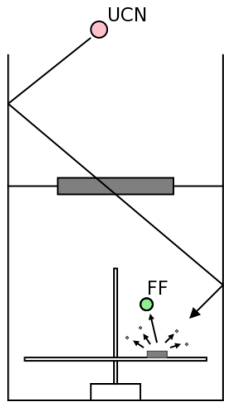
Range of UCN in uranium (μm)						
	DU	NatU	SEU	LEU	HEU	VHEU
$\%^{235}$U	0.2	0.7	2	5	20	100
200 neV	118	66	312	13	4	0.8
300 neV	144	81	38	17	4.5	0.9
400 neV	191	101	45	20	5	1

First Observations of Fission from UCN

Detection chamber

- Cylindrical ion chamber



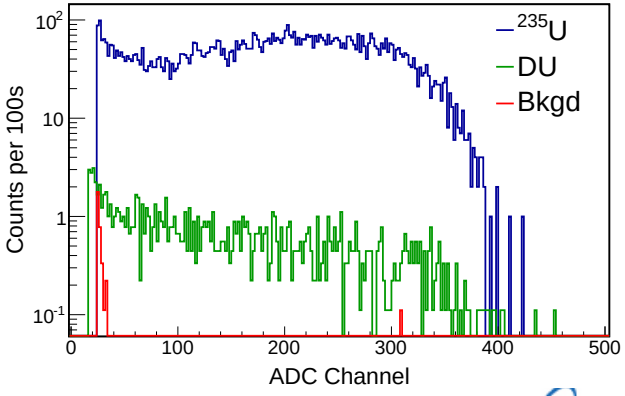


^{238}U

- 2.25 cm diameter, 1 mm thick disk of DU ($\sim 0.2\%$ ^{235}U)
- Rate: $(1.3 \pm 0.8) \times 10^{-4}$ fission/UCN

^{235}U

- 2.2 cm diameter, 1 mm thick disk of HEU ($> 80\%$ ^{235}U)
- Rate: $(1.90 \pm 0.02) \times 10^{-2}$ fission/UCN



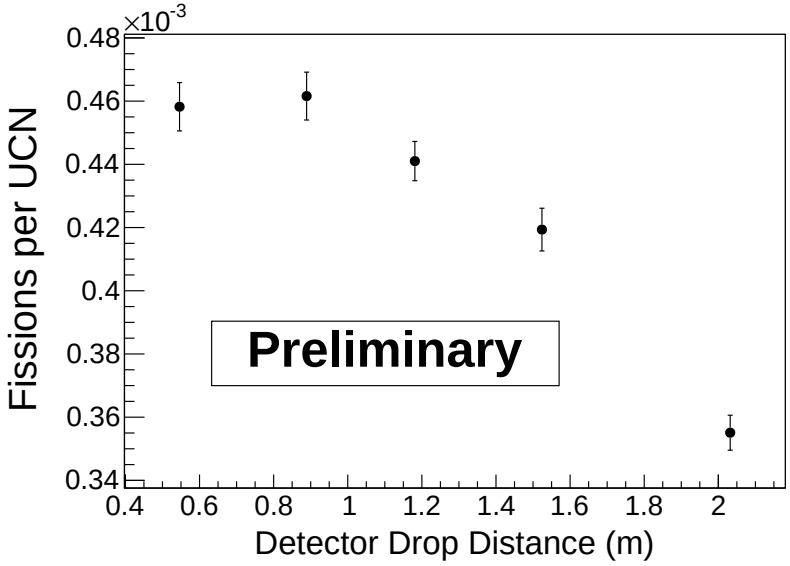
UCN-energy dependence of fission rates

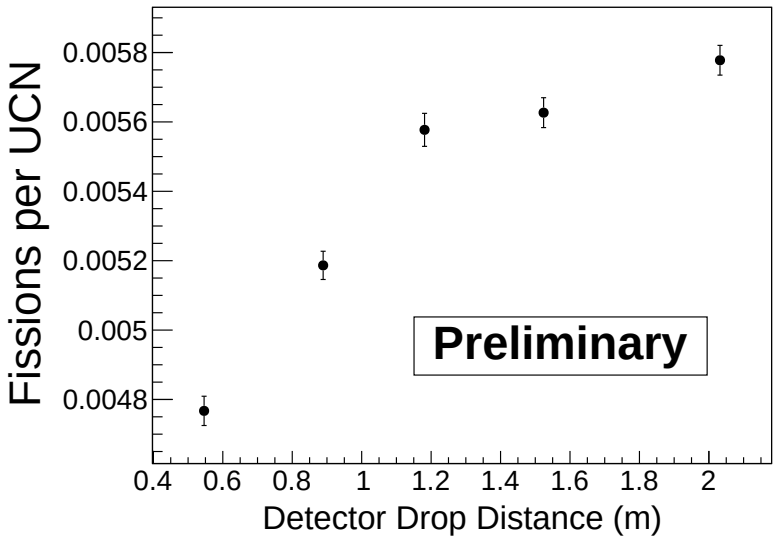
DU sample

- Electropolished, 2.25 cm diameter, 1 mm thick disk
- Measured fission rate decreases with UCN energy

^{235}U sample

- Thin sample: 30 μg heavily oxidized ^{235}U on tape
- Measured fission rate increases as UCN energy increases

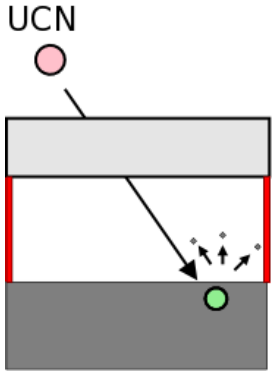




Sputtering from UCN-induced fission

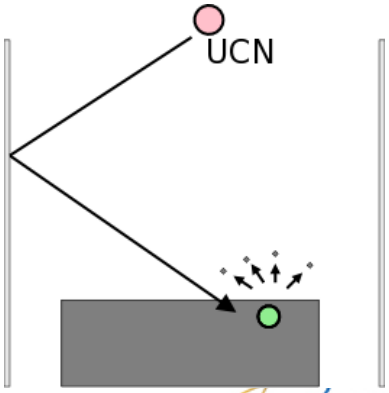
Exposure to Silicon wafer

- 1" diameter, 475 μm thick, polished wafer
- Exposed to 2.2 cm diameter, 1 mm thick electropolished DU disk
- 3×10^7 total UCN in chamber
- 0.18 μg ^{238}U collected on wafer
- Analyze with scanning probe microscopy



Exposure to Ni cylindrical foil

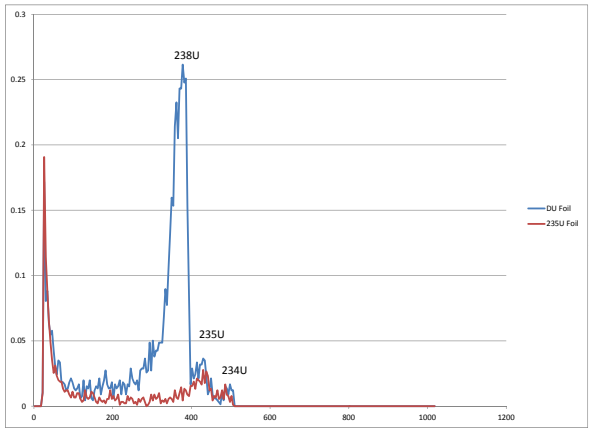
- 0.005" Ni foil, 1.15" diameter, 2.835" height
- UCN bottle: Ni material potential $\sim$ 300 neV
- Exposed to DU disk and 30 μg ^{235}U thin sample



Sputtering on Nickel foil

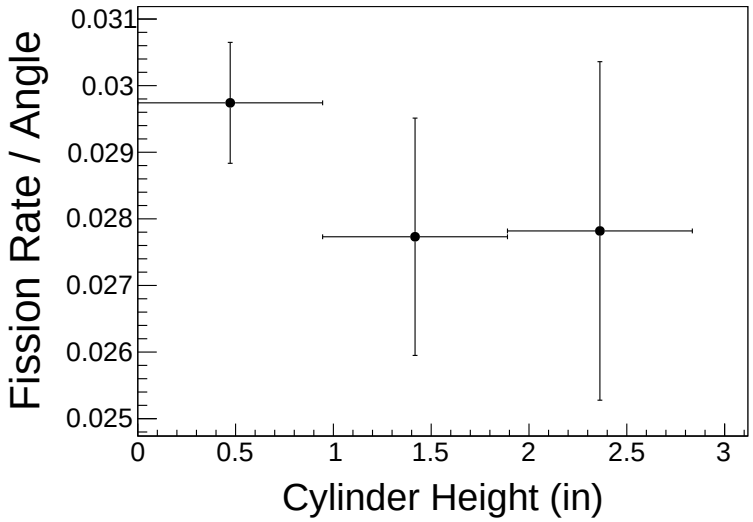
Expose to DU disk and HEU film

- Each sample exposed to $\sim 10^8$ UCN
- Determine yield from α decay rate in ion chamber
- Can distinguish α's from ^{238}U, ^{235}U decay



Angular distribution

- Mask vertical sections of foil
- Results from DU foil
- Distribution $\sim$ isotropic



UCN Experimental Program

UCNA

- Expect to announce unblinded result end of this year

UCNB

- This fall: Detector characterization with $\sim$35 pixels
- Next year: Full instrumentation of 128 pixels

UCNτ

- Moving to a 1 second accuracy measurement possibly this year

nEDM

- This fall: construct and test HV prototype chamber
- Next year: Install and test new source

Actinide Studies

- Install new beamline
- Continue detailed fission and sputtering characterizations

Opportunities for Students at LANL

Student Programs

- Undergraduate summer internships
- Post Baccalaureate programs (one year appointment)
- Post master's program (one year appointment)
- Graduate Research Assistants

Postdoctoral Program

- Postdoctoral Research Associates (2+1 year appointments)
- Director's, Agnew, Metropolis, Intelligence-Community Fellowships
- Distinguished Postdoctoral Fellowships (Oppenheimer, Feynman, Reines, Curie)

Seaborg Institute

- Research in nuclear science, especially actinides
- Nuclear Forensics Undergraduate Summer School
- Seaborg Student Research Fellowships
- Seaborg Postdoctoral Fellowship

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