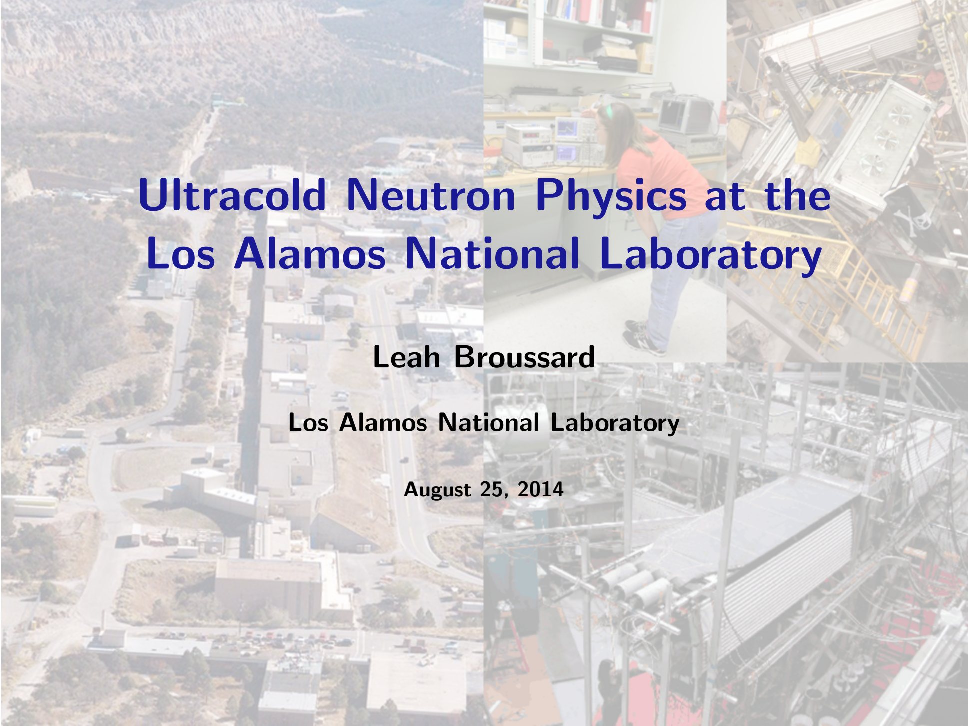


Ultracold Neutron Physics at the Los Alamos National Laboratory

Leah Broussard

Los Alamos National Laboratory

August 25, 2014

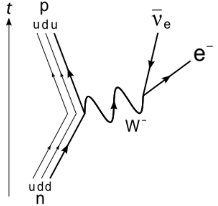
Precision Tests of the Standard Model

Neutron Decay Alphabet Soup

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

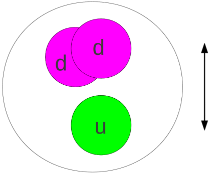
Decay Observables

- **A**, **a** + $\boldsymbol{\tau}$ → **V**, **A** interactions
- **B**, **b** → **S**, **T** (BSM) interactions
- **D** → **T**-invariance?
- (**b**, **D** = 0 in SM)



Fundamental Symmetries CP & T

- Weak force violates Parity (left-handed)
- Time?
- Charge-Parity?



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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 $\left(V = \frac{2\pi\hbar^2 Nb}{m}\right) \begin{cases} ^{58}\text{Ni}: & 335 \text{ neV} \\ \text{DLC}: & 250 \text{ neV} \\ \text{Cu}: & 170 \text{ neV} \end{cases}$

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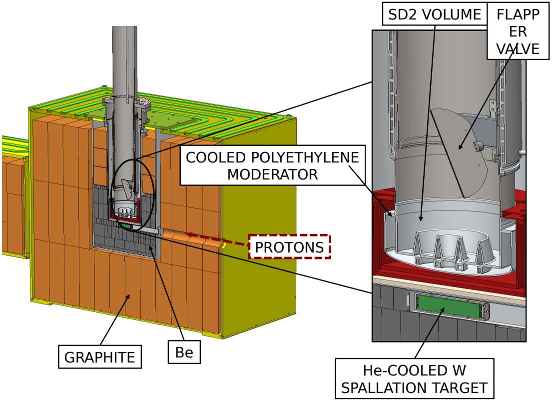
LANSCE UCN Facility

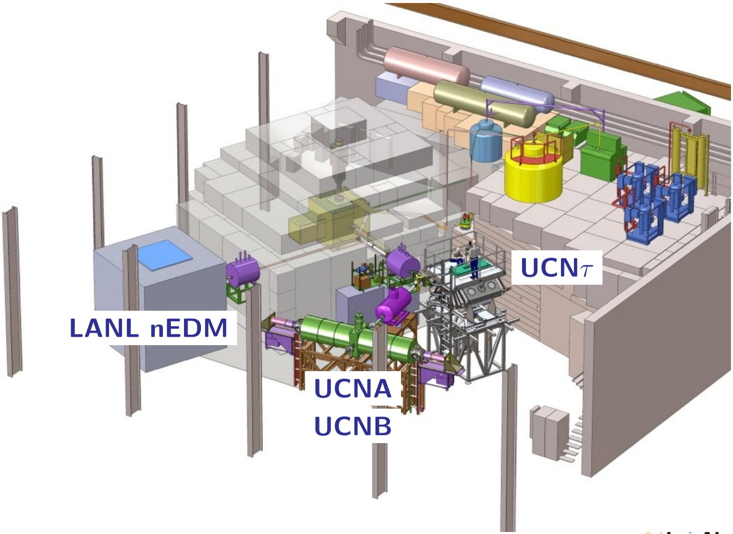
UCN Source[1]

- 800 MeV p + W → spallation; poly moderated CN + SD_2 → UCN
- 50 UCN/cc at shield wall



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

UCN Experimental Program



UCNA Collaboration

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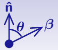
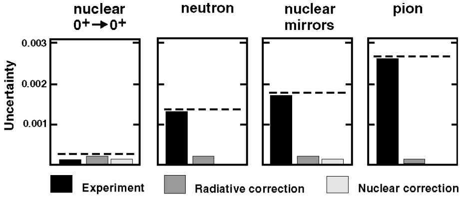
UCNA Motivation



β-asymmetry **A** in neutron decay

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

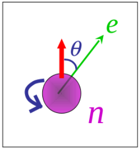
- $A_0 = -2\frac{\lambda(\lambda+1)}{1+3\lambda^2}$; Most sensitive to $\lambda = \frac{g_A}{g_V}$
- With τ_n: fix λ and extract CKM matrix element V_{ud}

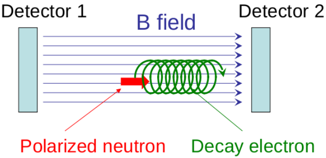


- $\frac{\delta A}{A} \sim 0.1\% + \delta\tau \sim 0.35\text{s} \rightarrow \text{V}_{ud}$ at 0.02% level
- Compare to: superallowed Fermi $0^+ \rightarrow 0^+$ decays: V_{ud} at 0.02% level[1]

[1] *Phys. Rev. C* **79** 055502 (2009), *Phys. Rev. C* **82** 065501 (2010)

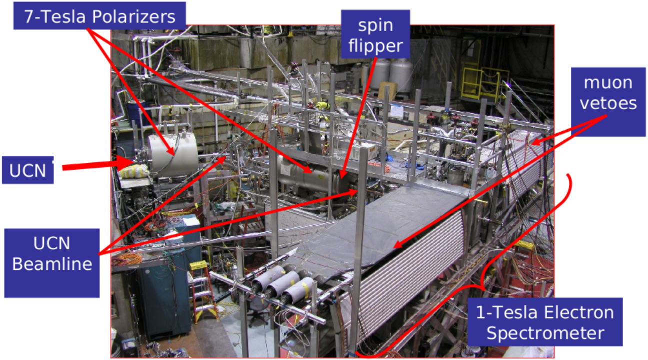
UCNA Experiment





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

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



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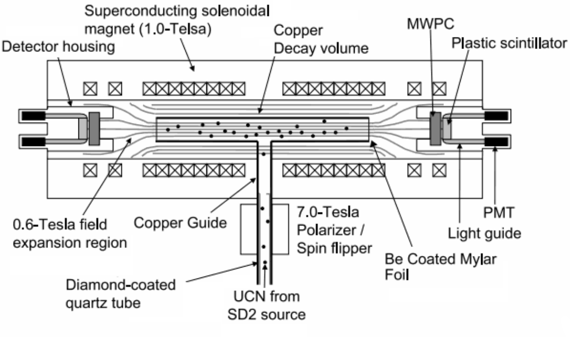
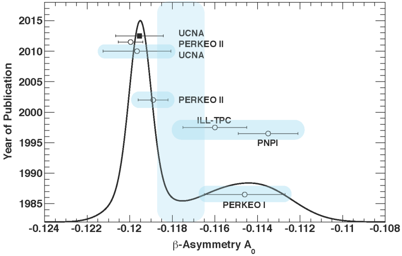
UCNA Experiment

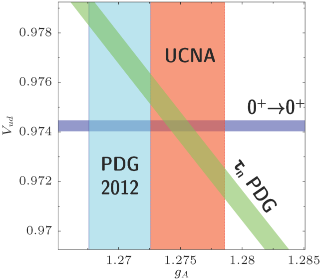


- Reduce backscatter: low Z, field expansion
- Plastic Scintillator: β energy
- MWPC: β position info, suppress backgrounds, backscatter reconstruction
- Super-ratio: cancel loading/detector efficiencies

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

UCNA Results: 2010 data set



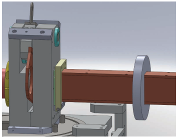


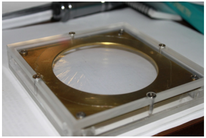
- Mendenhall et al. *Phys Rev C* **87** 032501(R) (2013)
- 20M β-decay events
- $A_0 = 0.11972(55)_{stat}(98)_{sys}$

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	





UCNB Collaboration

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University of Virginia

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Virginia Tech

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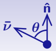
UCNB Motivation

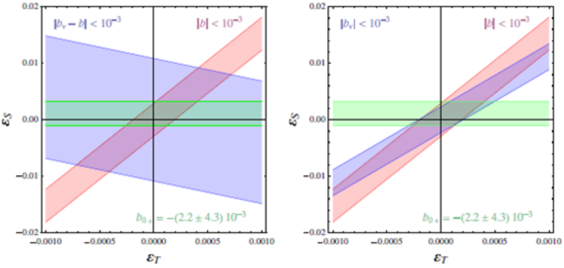


ν-Asymmetry **B** in neutron decay

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

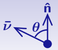
- SM: $B = 2\frac{\lambda(\lambda-1)}{1+3\lambda^2}$ (much less sensitive to λ than A, a)
- BSM[1]: $B \propto B_0 + \frac{m_e}{E_e}\left(b_\nu^{BSM} - b^{BSM}\right)$

10^{-3} level precision:



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

UCNB Experiment



Classic Approach

- Count $N^{\beta p} = N^{\pm\pm} =$ aligned vs. antialigned with σ_n
- $B_{exp}(E) = \frac{N^{--}(E) - N^{++}(E)}{N^{--}(E) + N^{++}(E)}$
- $\frac{\delta B}{B} = \frac{2.9}{\sqrt{N}}$: 0.1% in 1 month at 10Hz decay rate
- Cold neutron beam experiments: $B = 0.9807 \pm 0.0030 (0.3\%)$

Isolating b_ν: Ratio of asymmetries[1]

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

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

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

- Ratio $\frac{\alpha_p}{\alpha_e}$: Remove dependence on b term
- $N = 10^8 \rightarrow b_\nu \sim 10^{-3}$: order of magnitude improved sensitivity

[1] B. Plaster, *in prep* (2014)

UCNB Experiment

CHALLENGE: Detecting protons and betas in coincidence

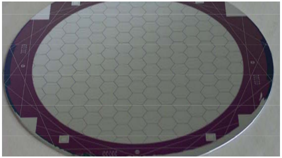
Protons

- 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)

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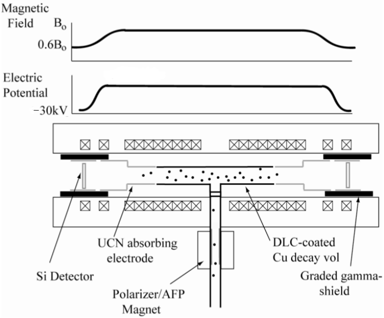
UCNB Experiment



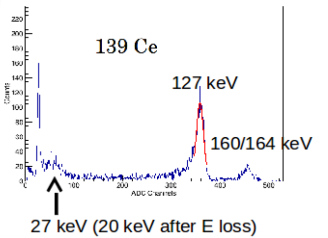
System Requirements

- Installed in existing UCNA spectrometer (1 T field)
- Detectors biased -30kV to accelerate protons
- Fast timing to resolve electron backscatter
- Fast, low noise, 128-ch preamps

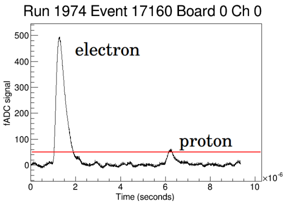
UCNB: Current Status

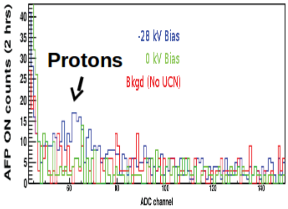
Preamplifiers

- 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



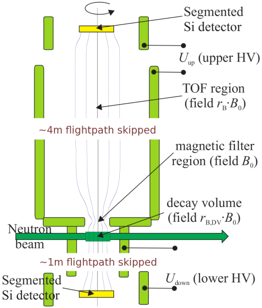
Neutron beta-decay proton-electron coincidences detected

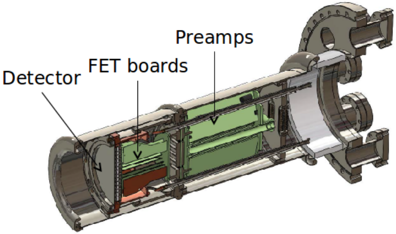




Stable operation at 1 T and -30 kV for $\sim$100 hours

UCNB partnership with Nab



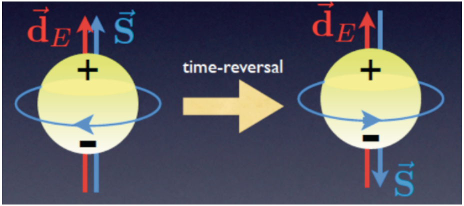


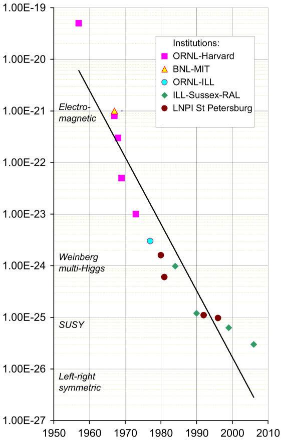
- Planned for Spallation Neutron Source at Oak Ridge National Laboratory

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

- 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





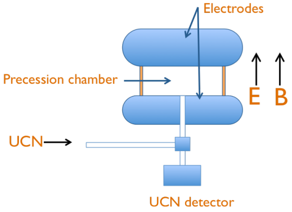
Why EDM

- 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

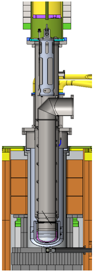
- Improved UCN source transition to guides
- Drive mechanism moved outside UCN volume
- Improvements to moderator cooling
- Geometry of source near W target

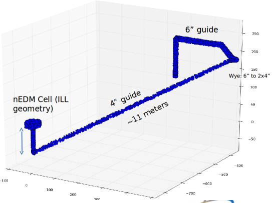
Proton Beam

- 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





UCNτ

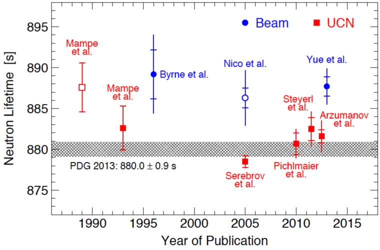
Beam vs. Bottle

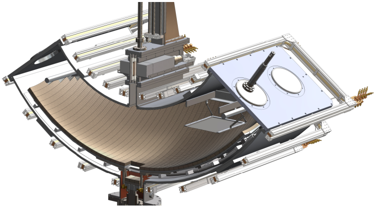
- Beam experiments: neutron flux?
- UCN bottle experiments: loss in the walls?

Magneto-gravitational Trap

- World's largest permanent magnet array

See A. Saunders talk next!





UCN Experimental Program

UCNA 2011/2012 analysis and future gains

- Uncertainty table: DNP 2014
- Unblinding: Winter 2014
- Confirm rate gains: Fall 2014

UCNB development (with Nab)

- Fall 2014: Test of new 24 ch preamps, new DAQ
- Fall 2014: Measure β-decay spectrum, detector systematics
- Spring 2015: Fabrication of 128 ch preamps, mount, new detector connectors

LANL nEDM

- Fall 2014: Finalize new source design and begin fabrication
- Fall 2014: construct and test HV prototype chamber
- Summer 2015: Install new source

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