Research with Ultracold Neutrons at the Los Alamos Ultracold Neutron Source Facility

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for the UCNA collaboration

Highlights: Ultracold Neutron (UCN) Program at LANSCE 2007 - 2012

The solid deuterium UCN source in Area B:

- **First spallation-driven SD_2 source**
- Began production running for UCNA in 2007
- Steadily increased UCN densities to **values comparable to ILL's rotor source** (average polarized UCN densities > 1 UCN/cm^3)
- Maximum UCN density to date: ~2 UCN/cm^3 for UCNA, 58±6 UCN/cm^3 at the shield wall

UCNA:

- **First to use UCN for angular correlations measurements**
- Published 4.4% measurement of beta-asymmetry in 2009
- Published 1.4% measurement of beta-asymmetry in 2010
- Currently analyzing 2010/2011 data (~64M decays), targeting < 0.8%
- Experiment **still unique**, provides important cross-check to existing and planned cold neutron measurements

Research and Development in the UCN Program at LANSCE 2007 - 2012

UCNB:

- Experiment to use electron-proton coincidences to measure angular correlations in the UCNA spectrometer. Initial goal: neutrino-asymmetry at 0.1% level
- LDRD-funded R&D program produced **working prototype Si detectors, with "test bench" detection of low energy electrons and protons already demonstrated** (also has been critical for the Nab experiment)

Neutron lifetime with UCN:

- Hallbach array magnetic trap under construction (partially funded by LDRD). Initial goal: 1 s measurement

UCNb:

- "integrating box" measurement of beta-decay spectrum to place limits on scalar and tensor interactions.
- LDRD-funded R&D program produced prototype device.

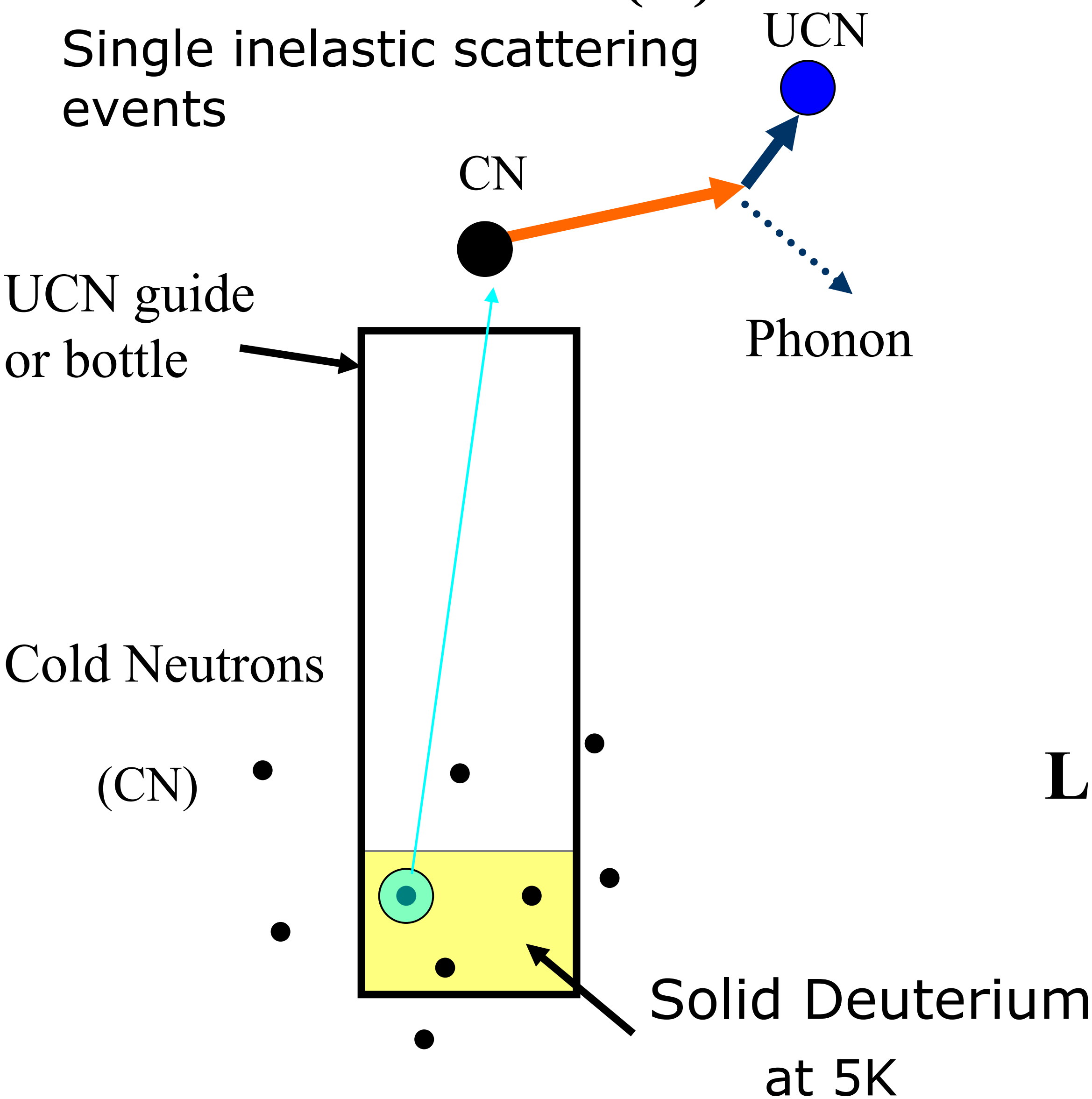
Outline:

- The solid deuterium UCN source in Area B
- UCNA – beta-asymmetry
- UCNB – angular correlations with Si detectors
- Lifetime – decay rate in Hallbach-array magnetic trap
  (see talk by C.-Y. Liu)
- Other projects and activities
  UCNb – beta-decay spectrum
  Support R&D - nEDM, UCN technology, nuclear forensics, surface physics,etc…
- Summary of Goals

The solid deuterium UCN source

UCN Production (R)

Single inelastic scattering events



UCN Loss (τ)

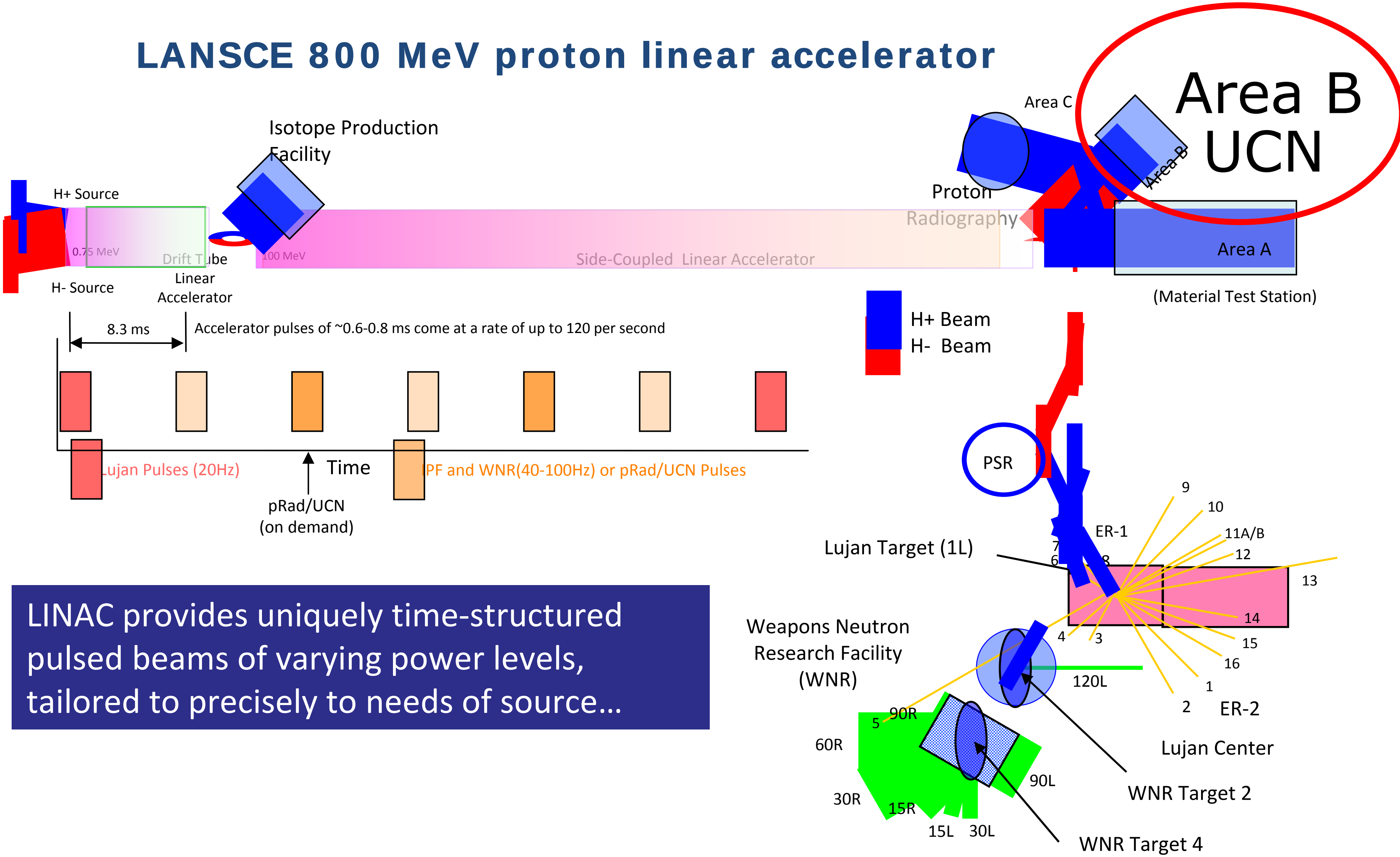
- upscatter on D_2 (para-D_2)
- upscatter on D_2 (phonons)
- absorption on D_2
- absorption on H

Limiting UCN Density

$$\rho = R\tau$$

Neutron Production

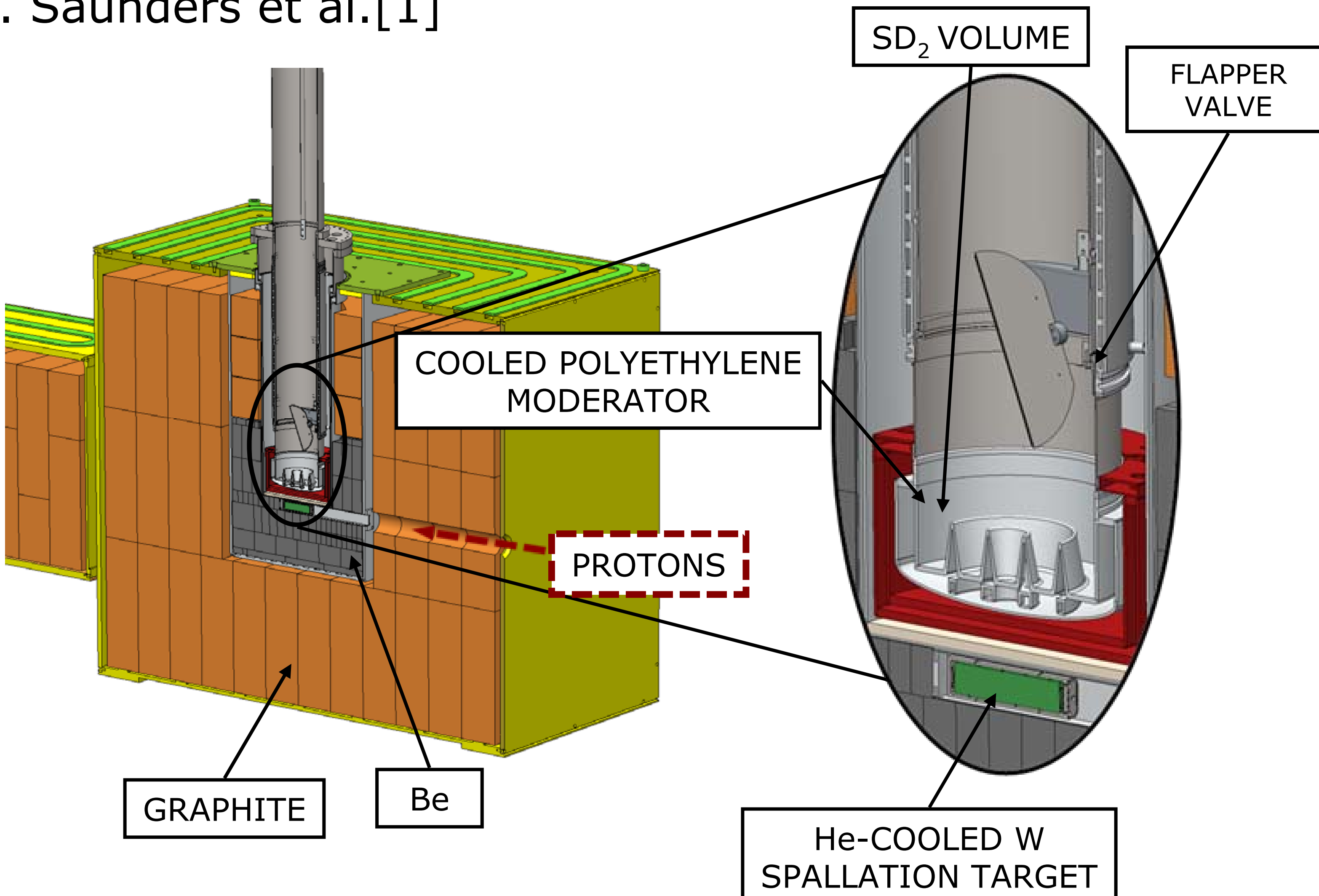
LANSCE 800 MeV proton linear accelerator



LINAC provides uniquely time-structured pulsed beams of varying power levels, tailored to precisely to needs of source…

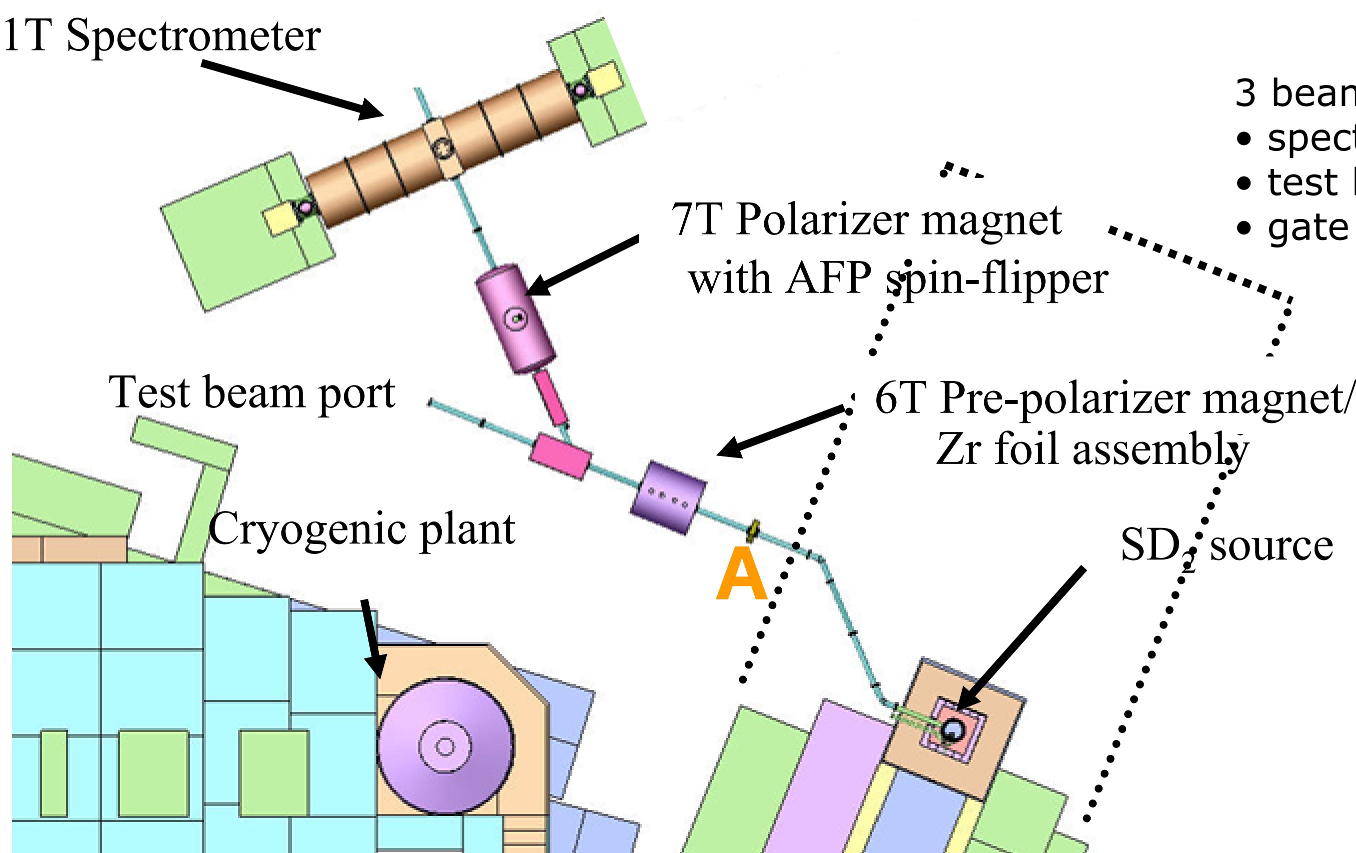
UCN now officially one of 5 primary facilities at LANSCE

Primary neutrons produced by spallation on W target
CN produced in cooled polyethylene moderator
UCN converter: 2l SD_2
(under "flapper" isolation valve)
Ref: A. Saunders et al.[1]



UCN Facility in Area B:

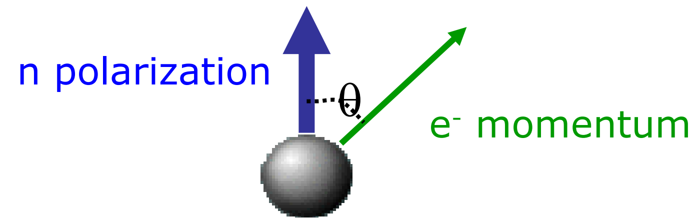
- **Only source of extracted UCN in US**
  (~45 faculty and staff doing UCN research in US)
- Running with 5 μA protons (administrative limit)
  $<\rho_{UCN}>$ (polarized) in spectrometer > 1 UCN/cm^3
  $<\rho_{UCN}>$ at shield wall (pt A) ~ 35 ± 6 UCN/cm^3
- Experimental area has capability to mount large scale experiments (such as UCNA)



3 beam ports:
- spectrometer port (UCNA,UCNB)
- test beam port (lifetime, nEDM)
- gate valve port (UCNb)

UCNA Experimental Approach: Motivation

Experiment to measure the beta-asymmetry in neutron decay:



$$R = R_o(1 + (v/c)\ P\ A(E)\ \cos\theta)$$

β-asymmetry = A(E) in angular distribution of e^-

$$A = A_o(1 + \Delta(E))$$

$\lambda = G_A/G_V$ $\quad A_o = -2\dfrac{\left(\lambda^2 - |\lambda|\right)}{1+3\lambda^2}, \quad \tau_n = \dfrac{\text{constant}}{1+3\lambda^2}$

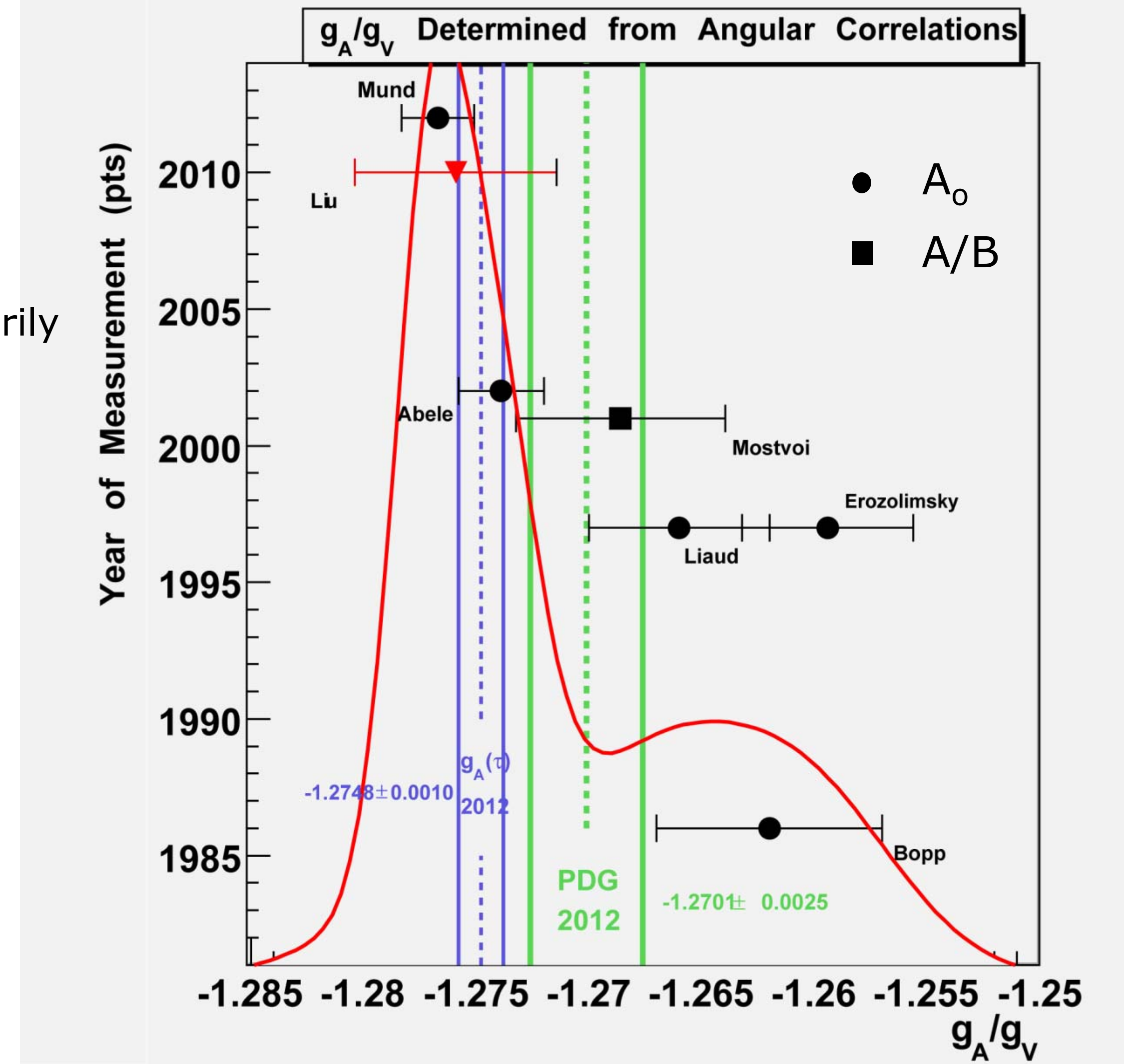
$\langle\Delta\rangle = \delta_{rec} + \delta_{rad}$

$= (0.0179 \pm 0.0003)_{rec} + (0.0010 \pm 0.0005)_{rad}$

(275 < E (keV) < 625)

Accidental cancellation also makes A_o very sensitive to $\lambda = g_A/g_V$

$\delta|\lambda|/|\lambda| \sim 0.24\delta|A_o|/|A_o|$



PDG λ

Derived primarily from A [2]

0.20%

PDG 2012: $\lambda = -1.2701 \pm 0.0025$, error scaled by 1.9

From PDG2012 τ: $\lambda = -1.2748 \pm 0.0010$, error scaled by 1.8

agree at 1.75 σ level

Impact

A <0.4% measurement from UCNA will improve the precision and confidence to which g_A is known (uncertainty comparable or better to reported measurements, with different systematics):

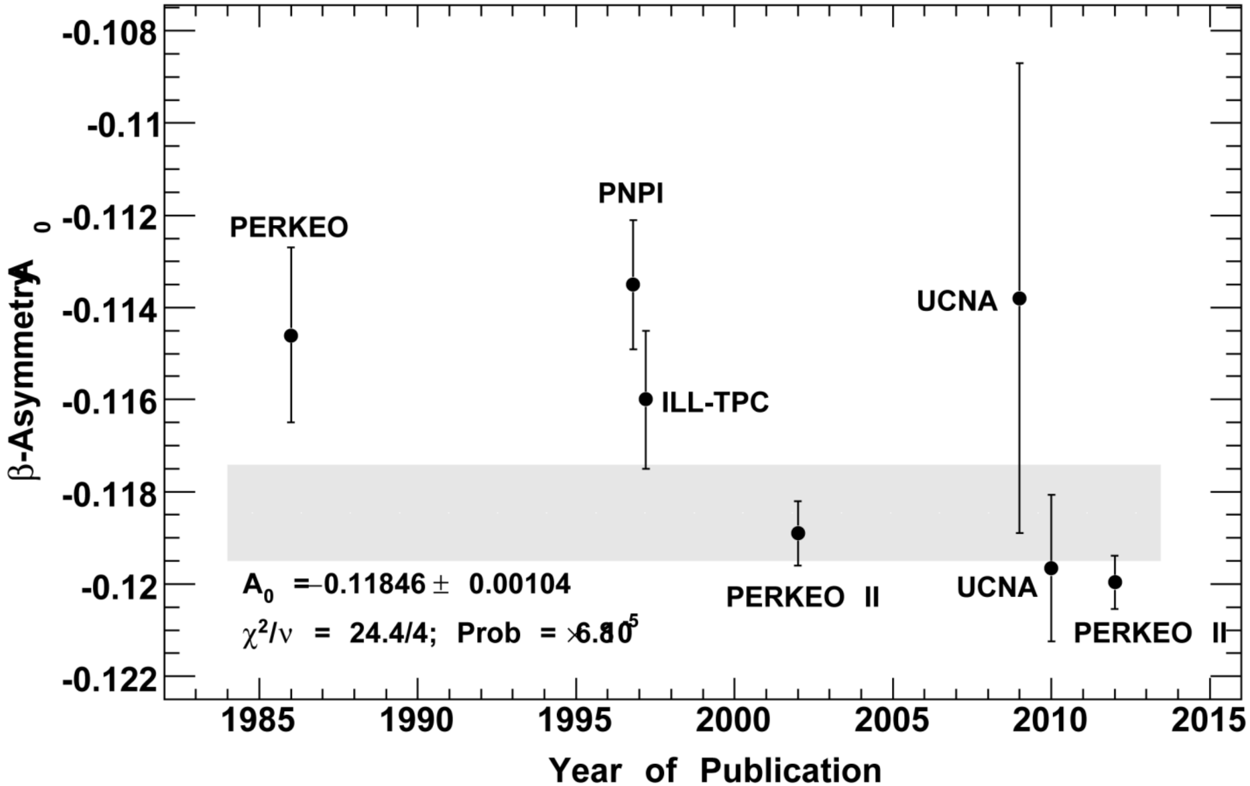
- g_A is a fundamental parameter for the charged weak current of the nucleon and defines a frontier for our understanding of this interaction

- g_A is a required input to (high precision) solar fusion models and other astrophysical processes[3], is a long-term target for high precision lattice calculations[4], plays a role in the reactor antineutrino anomaly[5], etc…

Neutron decay provides definitive value for g_A

Assuming τ available at 0.1s level, require δA/A ~ 0.1% to produce an uncertainty of ±0.00022 in V_{ud}, the current value from $0^+ \rightarrow 0^+$ decays – nuclear structure independent cross-check![6,7]

- V_{ud} critical input to unitarity test, one of the most stringent constraints on "chirality conserving" interactions such as V-A[8]:
  - 11 TeV lower bound on BSM mass scales. Better than Z-pole!
  - Constrains universality of supersymmetric models
  - 2-3 TeV lower bound on generic W^* from Kaluza-Klein theories



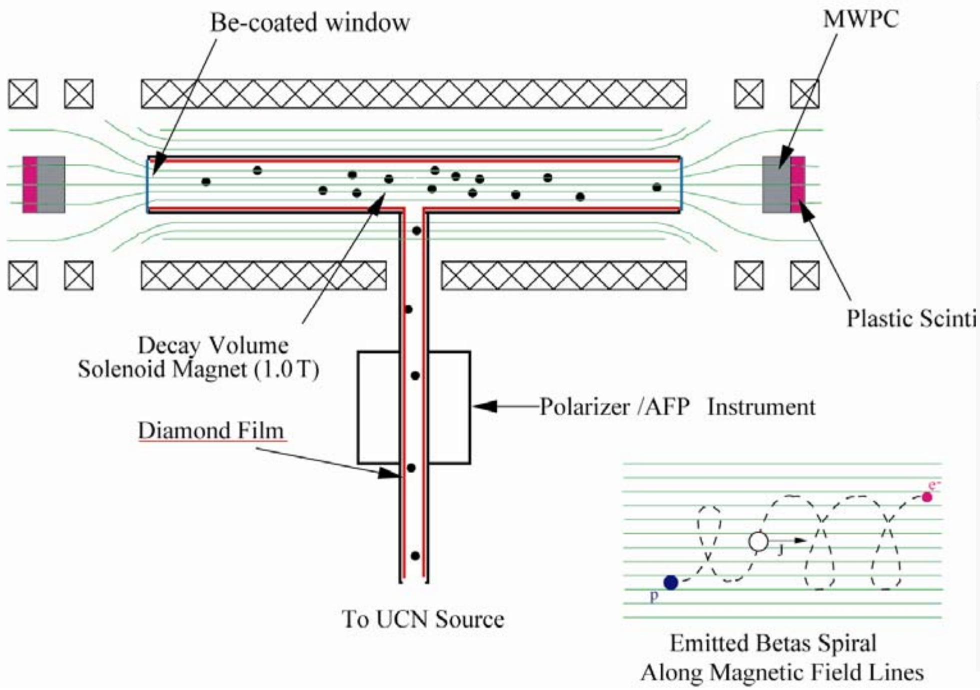
Accidental cancellation makes A_o small

A_o=-0.1176 ± 0.0011 (PDG 2012, expands error by 2.1)

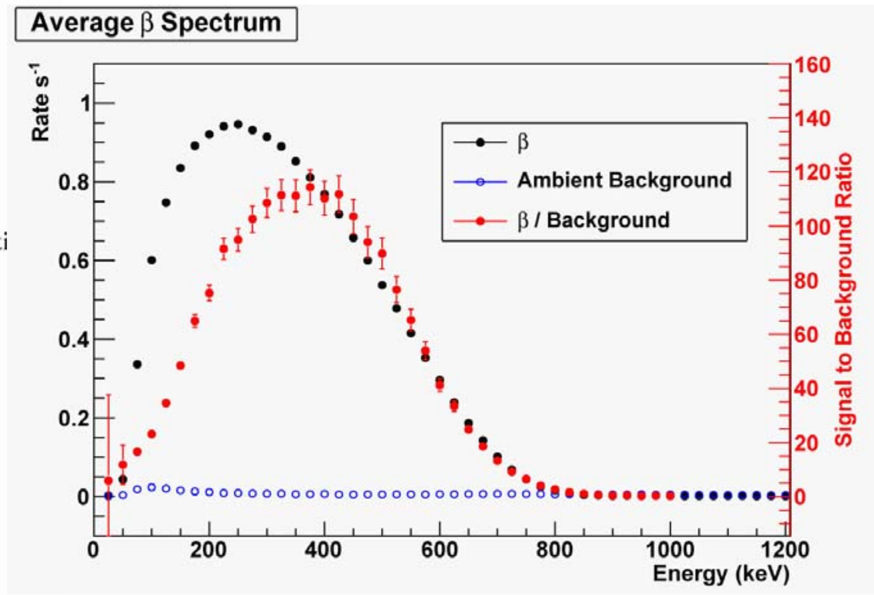
Expanded error suggests inconsistent assessment of systematic errors in some of cold neutron beams experiments

UCNA Goal at LANL: sub-0.4% measurement with complementary systematic errors to existing and planned cold neutron experiments

UCNA: Experimental Approach



2010 Beta-decay spectrum and ambient backgrounds



Unique aspects of the UCNA experiment:

- **UCN provide a unique handle on neutron-related systematic errors:**
  "Ballistic" polarization of neutrons with very high precision
  Very low neutron-generated backgrounds also possible
- **Scintillator + MWPC detector package**
  MWPC/scintillator coincidence to greatly reduce backgrounds
  Improved position-dependent det response, fiducial volume and backscatter

UCNA Accomplishments:

Year	Statistics	δA/A	Published
2007	0.8 M	4.4%	2009 (PRL)[9]
2008/2009	30 M	1.4%	2010 (PRL)[10], 2012 (PRC)[11]
2010/2011	64 M	In prep.	In prep.

Reaching ultimate limit acknowledged **as high priority** for neutron community by 2011 NSAC neutron subcommittee (priority #2)

Immediate Goals:

- From available data: Sub-0.8% measurement
- At LANL: Sub-0.4% measurement

Most precise measurement to date (PERKEO II) – 0.48% δA/A

PDG 2012 average – 0.94% δA/A

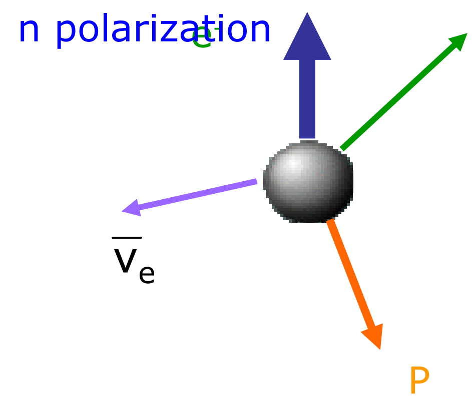
UCNB

$$d\Gamma \propto F(E_e)\left[1 + b\frac{m_e}{E_e} + \left(B_0 + B_1\frac{m_e}{E_e}\right)\frac{\vec{\sigma}_n\cdot\vec{p}_\nu}{E_\nu} + \cdots\right]$$

"Fierz interference term"

Energy-dependent component of "antineutrino asymmetry" (B)

$$B = 2\frac{|\lambda|^2 - \mathrm{Re}(\lambda)}{1+3|\lambda|^2} = 0.9807 \pm 0.0030 \quad \text{(PDG 2010)}$$



Sensitive to complementary BSM physics to the β-asymmetry, *e.g*. B1 from scalar and tensor interactions

Examine in a model-independent framework…real progress made understanding nucleon matrix elements! [12,13]

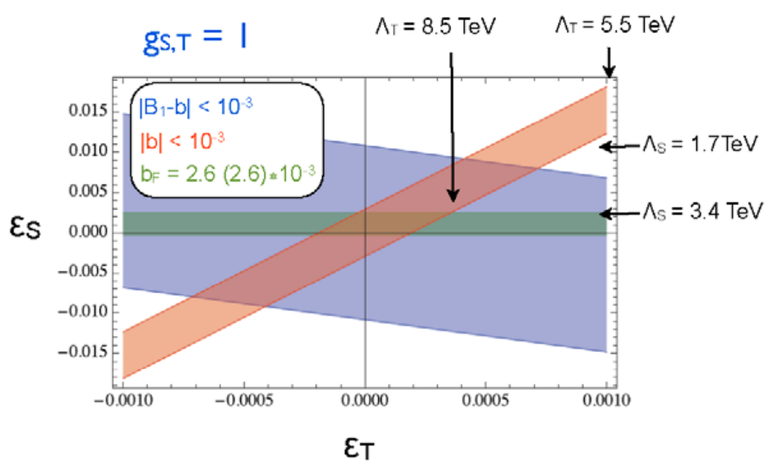
Focus on couplings to (e,ν_e): Cirigliano *et al.* (2010)

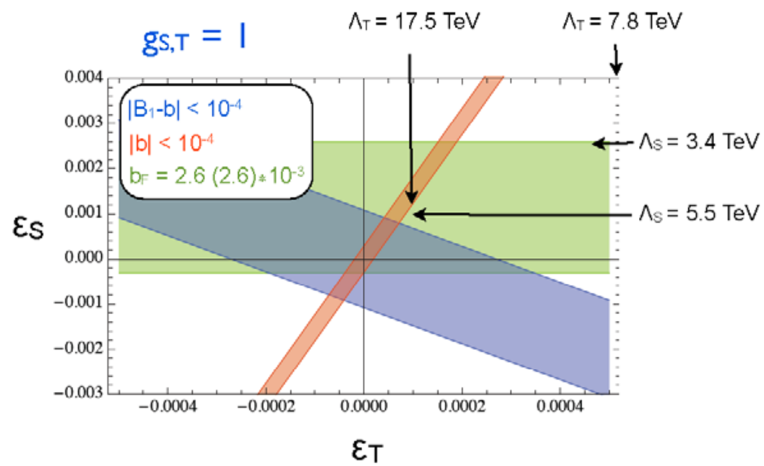
Working to linear order in deviations from the SM (interference of A_{SM} and A_{BSM}) only ε_S and ε_T contribute to b and B_1

$$b = f_b\,(\varepsilon_{S,T} * g_{S,T}) \qquad B_1 = f_B\,(\varepsilon_{S,T} * g_{S,T})$$

$$g_S \sim \langle p|\bar{u}d|n\rangle$$
$$g_T \sim \langle p|\bar{u}\sigma_{\mu\nu}d|n\rangle$$

- Constraints on ε_S and ε_T from proposed experiments vs other measurements ($0^+ \to 0^+$; $\pi \to e\nu\gamma$ and collider not competitive)
- Recall: $G_F * \varepsilon_{S,T} = (1/\Lambda_{S,T})^2$



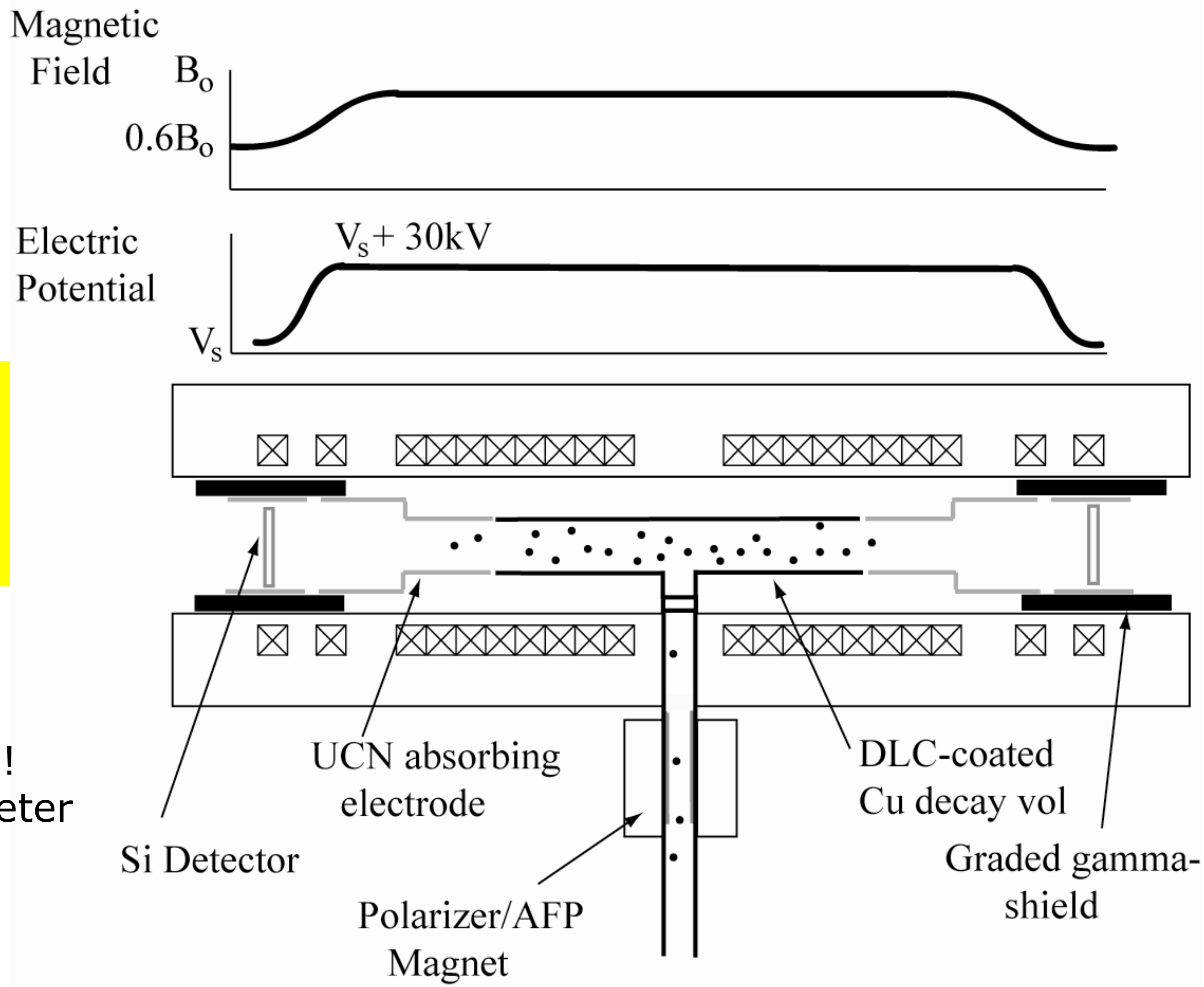


- Already 10^{-3} measurements probe multi-TeV scale; stringent constraint on existence of scalar and tensor BSM interactions

$$\frac{\delta B}{B} = \frac{2.9}{\sqrt{N}}$$

Target: 0.1%

Not statistics limited!
Use UCNA spectrometer



Experimental strategy is similar to that carried out by PERKEO II, measure same-hemisphere electron-proton coincidences:

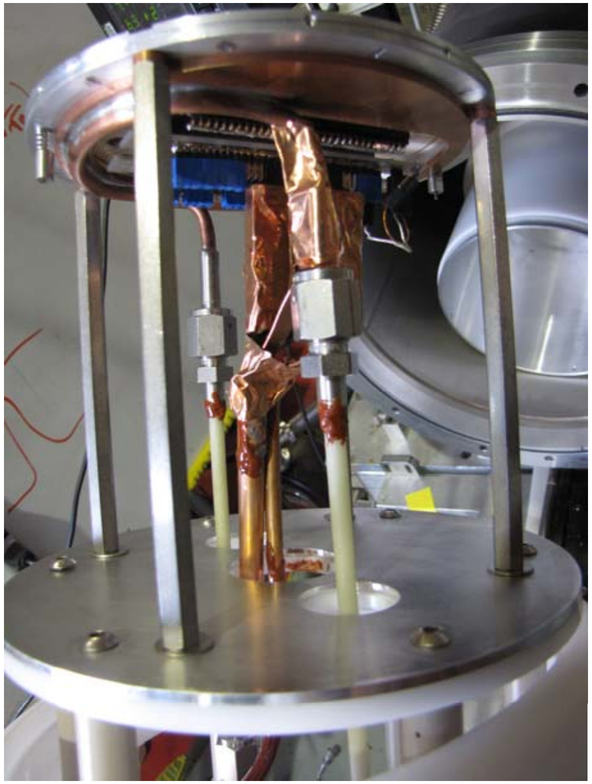
$$B_{exp} = \frac{N^{--}(E) - N^{++}(E)}{N^{--}(E) + N^{++}(E)}$$

(use super-ratio)

Highly segmented, thick Si detectors being instrumented for prototype experiment

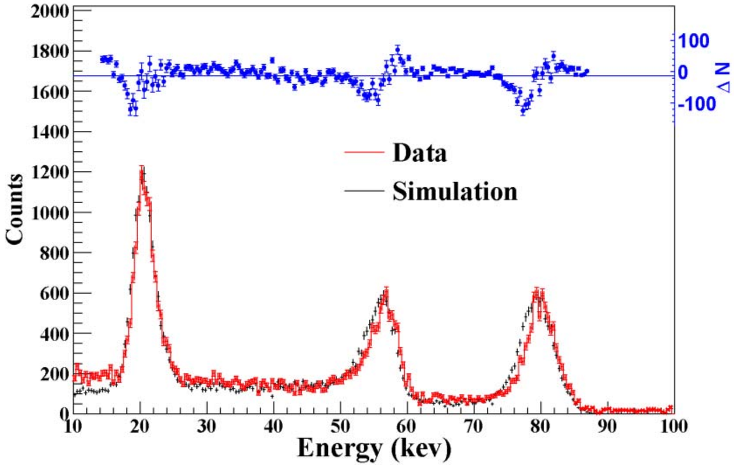
6” wafer, 1.5 mm thick, 127 full pixels

~100 nm deadlayer

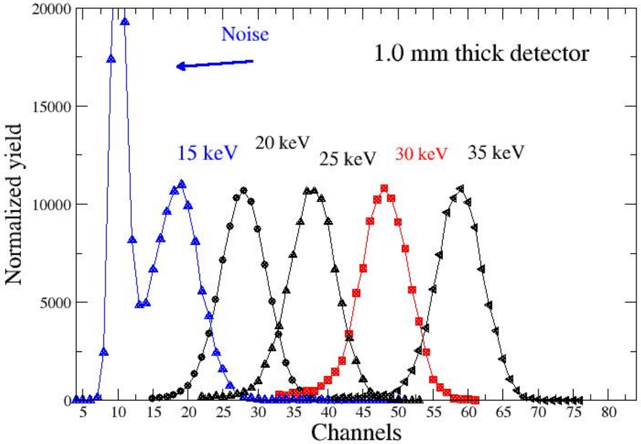


A prototype mount showing HV standoffs, cooling and coupling to 8-ch FET cards

^{109}Cd γ,e$^-$ response



Low E protons



Full detector arrays being prepared for test runs in 2012

Detector R&D also relevant for Nab

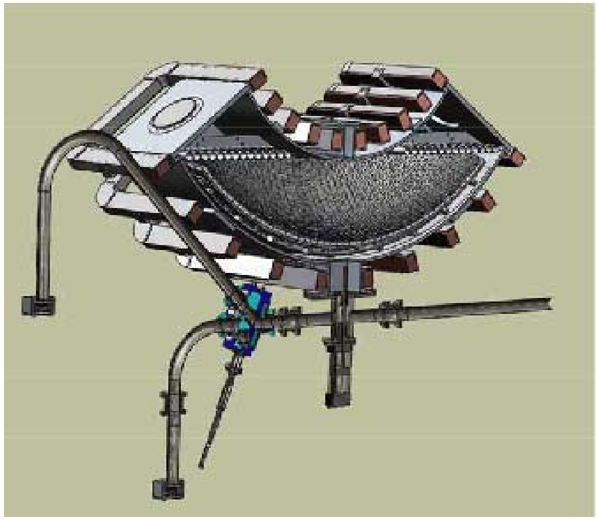
Lifetime with Magnetically Trapped UCN

Target: essentially negligible wall-losses through storage of low-field seeking UCN in magnetic trap; detect UCN without relying on transport to UCN detector

First attempt with VCN: 877 ± 10 s (toroidal sextupole[14])
First attempt with UCN: 833^{+74}_{-63} s (NIST Ioffe trap[15])
Most precise: 878.2 ± 1.6 s (permanent magnets and UCN[16])

Key systematic effects:
- marginally trapped neutrons
- marginally stable trajectories
- background subtraction (for real time counting)

Status:
- prototype under construction
- workshop to develop strategy towards 0.1s sensitivity planned for fall, 2012
- see Chen-Yu Liu's talk in this session!

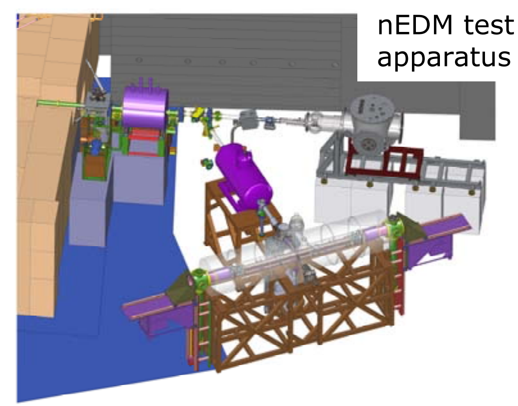


LANL lifetime

Other Projects and Activities

- UCNb:
  - “integrating box” runs parasitically with high rate at gate valve port
  - immediate goal is first direct limit on Fierz term (b) at ~1% level, improve by up to order of magnitude in future

- nEDM:
  - Performed on test beam port
  - Storage cell measurements to develop appropriate technology for full experiment



- Guide and source development

Summary of Goals

- UCN source
  - Proton beamline and source operation improvements planned to push average operation of source to our current maximum (~2 UCN/cm^3 in UCNA)
  - Work with LANSCE to push operational limits from 5 μA to 10 μA (another factor of two in UCN production, now approved for the 2012 run!!)
  - Requires roughly 660k/year to operate (over present levels)
- UCNA
  - Obtain below 0.4% uncertainty with current source capability (0.2% ultimate limit)
- UCNB
  - Immediate goal: test prototype detector arrays in spectrometer
  - Push for physics measurement at 0.1% level ASAP (2013?), final version may require ~500k one time capital investment
- Lifetime
  - Use planning process of workshop in October to formulate proposal

UCN program at LANL has produced a unique resource for the community and the opportunity for excellent science!

UCNA Collaboration

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Technical publications for UCNA can be found at:
http://neutron.physics.ncsu.edu/UCNA_NSAC