Neutron Beta-Decay

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Hall C Summer Meeting
Jefferson Lab
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Outline:
- Beta-decay and its physics interest
- How to make neutrons
- Some beta-decay experiments

Shameless advertising

International Workshop: Ultracold Neutron (UCN) Sources and Experiments

September 13-14, 2007
TRIUMF, Vancouver, Canada
http://www.triumf.info/hosted/UCN

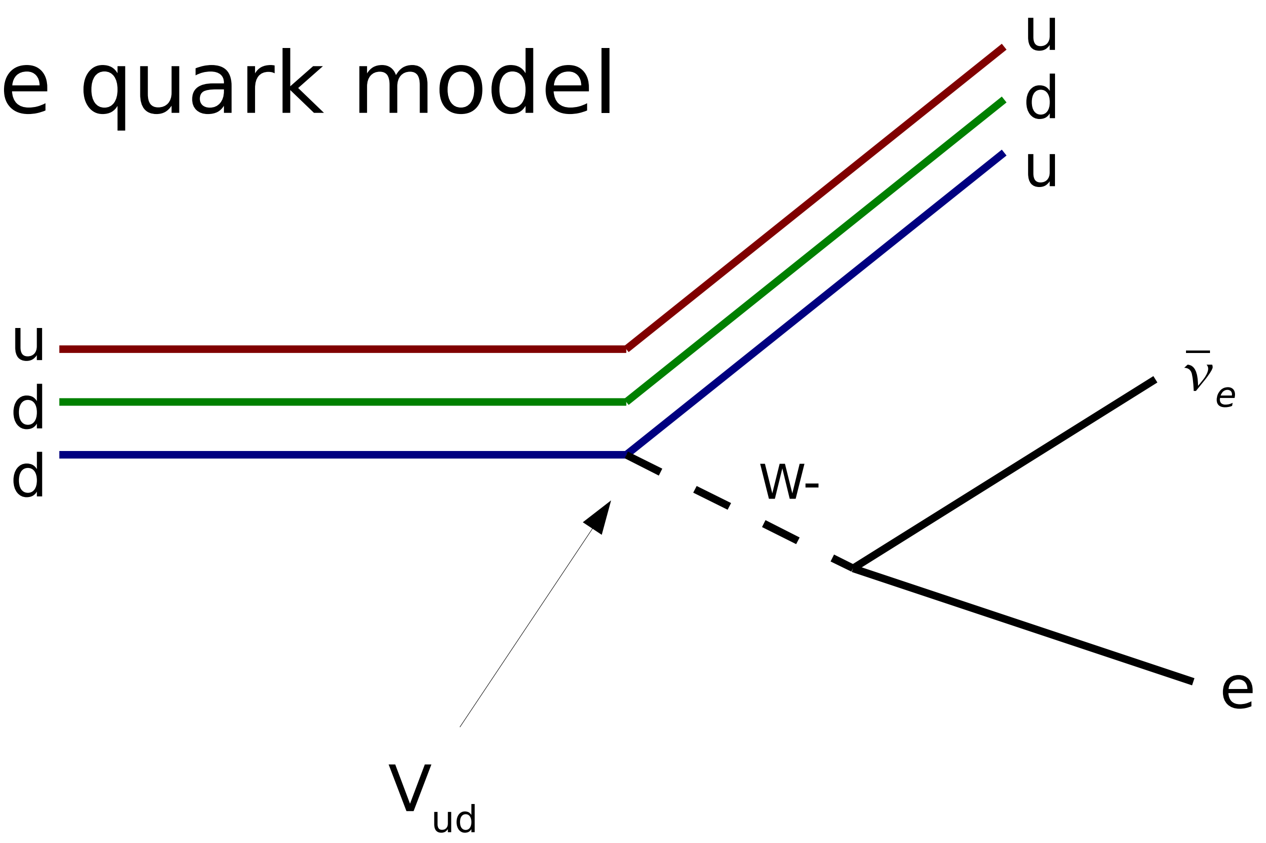
Registration is free, but please do register

~25 speakers from all over the world
ILL, FRM-II, NCSU, LANL, PSI, KEK, Mainz, UK...

Supported by TRIUMF and TUNL

Neutron Beta-Decay

In a naive quark model



Physics Interest in Neutron Beta-Decay

- Astrophysics: BBN
- Particle Physics: tests of the SM
  - V_{ud} and unitarity of the CKM matrix
  - searches for scalar and tensor currents
  - time reversal violation
  - related topics: recoil-order corrections, weak magnetism, neutron radiative decay

today, I'll focus mainly on CKM

Neutron Decay: What can be measured?

- Applying symmetries: (Jackson, Treiman, Wyld, 1957)

$$\frac{d^5W}{dE_\beta d\Omega_\beta d\Omega_\nu} \sim 1 + a_{\beta\nu}\frac{\vec{p}_\beta \cdot \vec{p}_\nu}{E_\beta E_\nu} + b\frac{m_e}{E_\beta} + \vec{\sigma}_n \cdot \left[A_\beta \frac{\vec{p}_\beta}{E_\beta} + B_\nu \frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_\beta \times \vec{p}_\nu}{E_\beta E_\nu}\right]$$

- Measure a, b, A, B, D, and τ, and then you know everything about neutron decay.
- However, each coefficient has a different physics interest!

Neutron Decay: Why measure it?

- In the standard model (V-A):

$$a = \frac{1-\lambda^2}{1+3\lambda^2}, \quad A = -2\frac{\lambda^2+\lambda}{1+3\lambda^2}, \quad B = 2\frac{\lambda^2-\lambda}{1+3\lambda^2}$$

where: $\lambda = G_A/G_V$

$$\tau = \frac{k}{G_V^2 + 3G_A^2}$$

Measure e.g. A (and/or a, B) and τ to solve for G_A and G_V

$$D = 0$$

Measure D to search for time-reversal violation

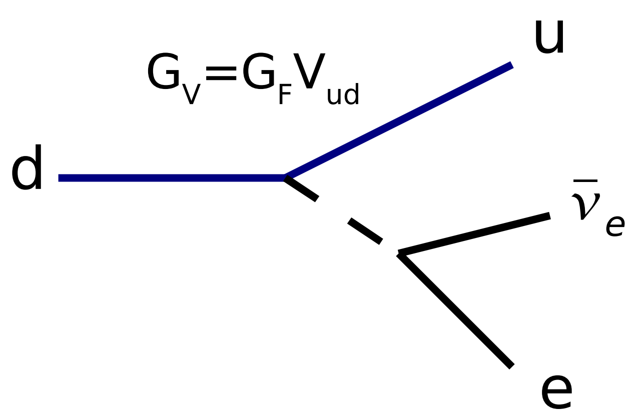
$$b = 0$$

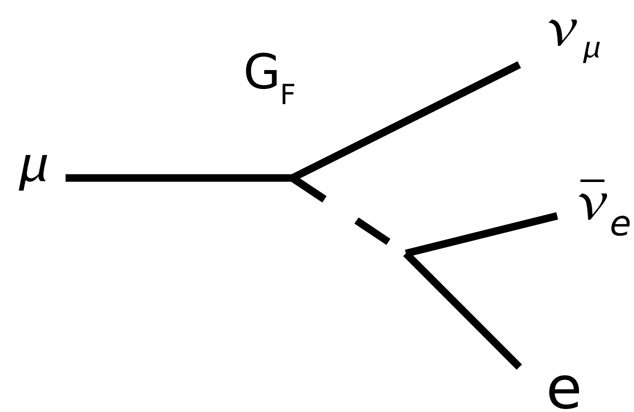
Measure b to search for scalar and/or tensor currents interfering with V-A amplitudes ("Fierz interference")

Why measure G_A and G_V?

- G_A related to strong interaction modifications (QCD) to quark axial-vector electroweak interaction
- G_V is related to fundamental quark electroweak coupling (conserved vector current, CVC)

Universality (almost)





G_F precisely measured in muon decay (K. Giovanetti's talk)

CKM Matrix

- Weak eigenstates ≠ mass eigenstates

$$\begin{pmatrix} d_W \\ s_W \\ b_W \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{ct} \\ V_{bd} & V_{bs} & V_{bt} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

Note: this matrix must be unitary!

- A precise test of unitarity:

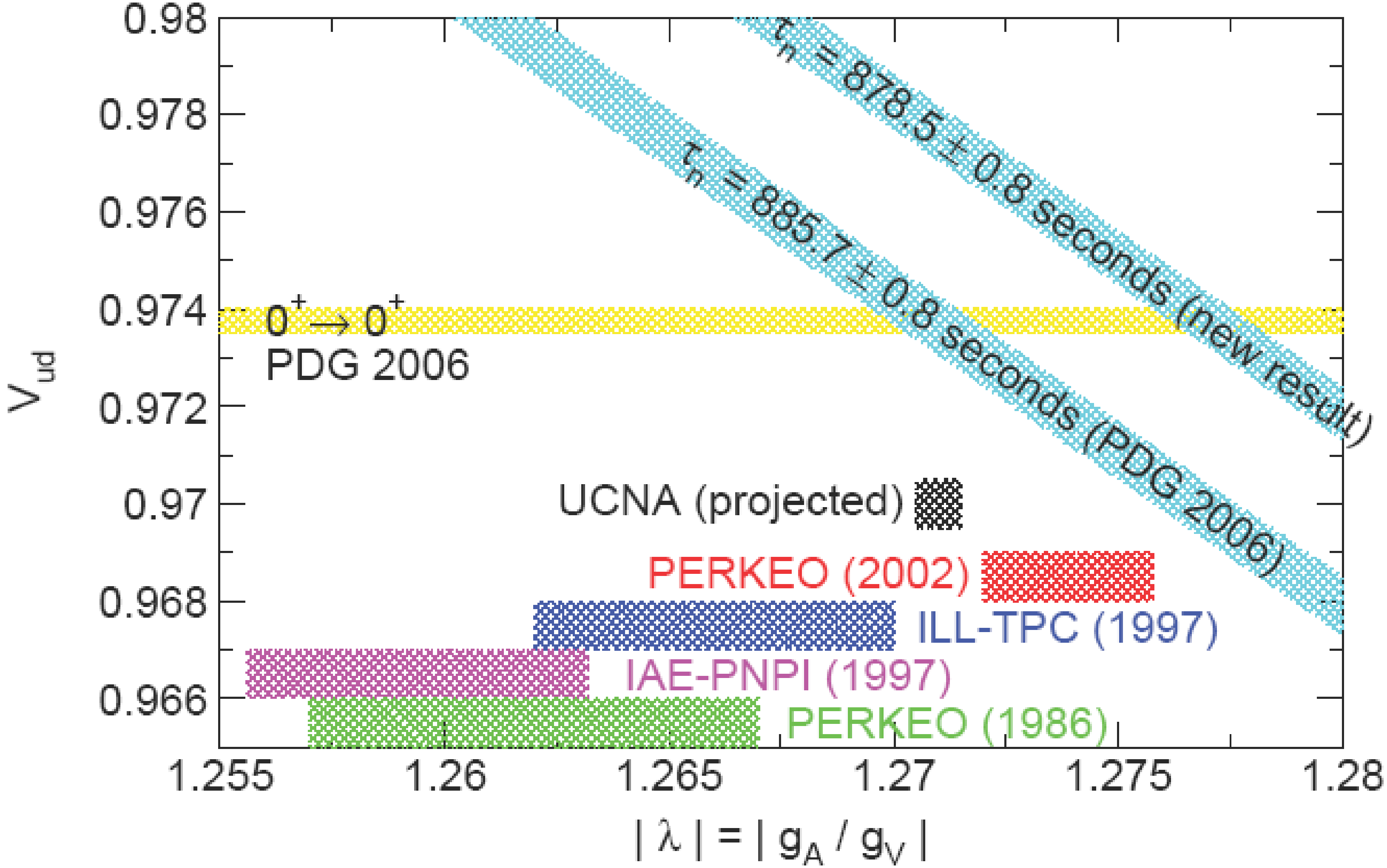
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 \overset{?}{=} 1$$

nuclear decay — kaon decay — B decay

- Status (2007):

$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9992 \pm 0.0005 \pm 0.0004 \pm 0.0008$

V_{ud} Status

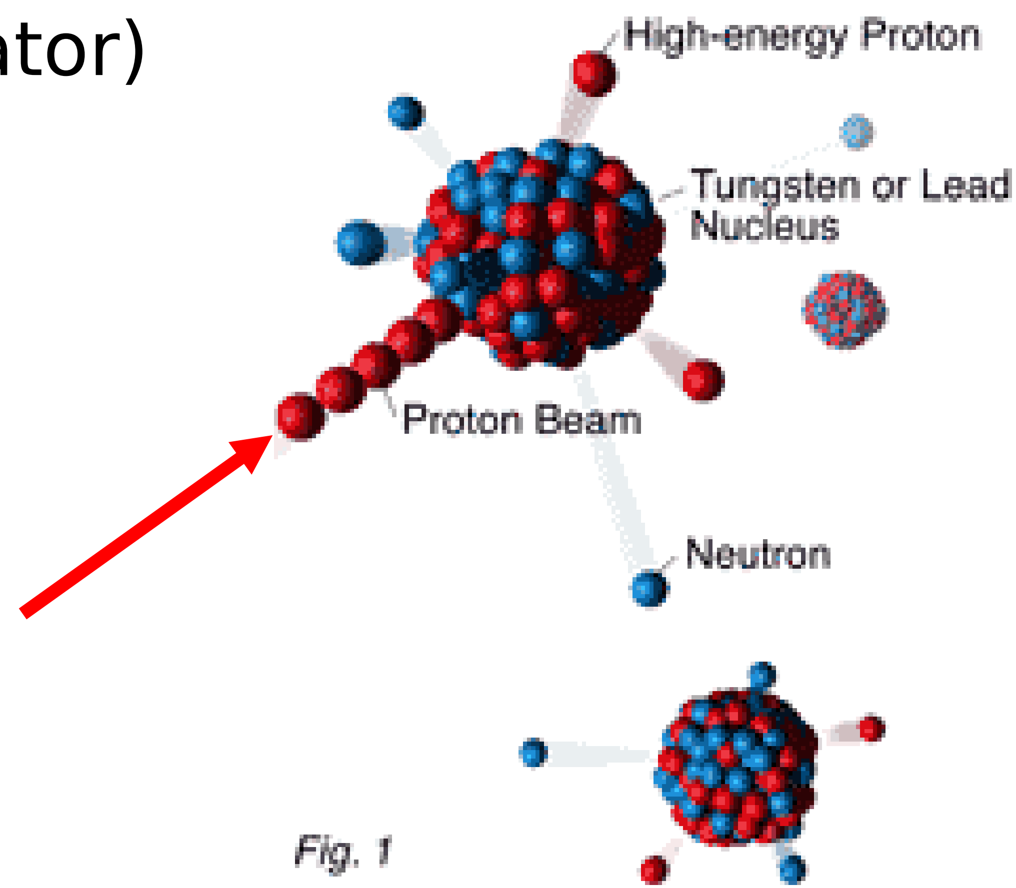


- The most recent, precise measurements of both A and tau disagree with all previous!
- We would like to improve this situation, and compete with nuclear beta-decay (nuclear structure uncertainties).

Experiments

How to make (free) neutrons

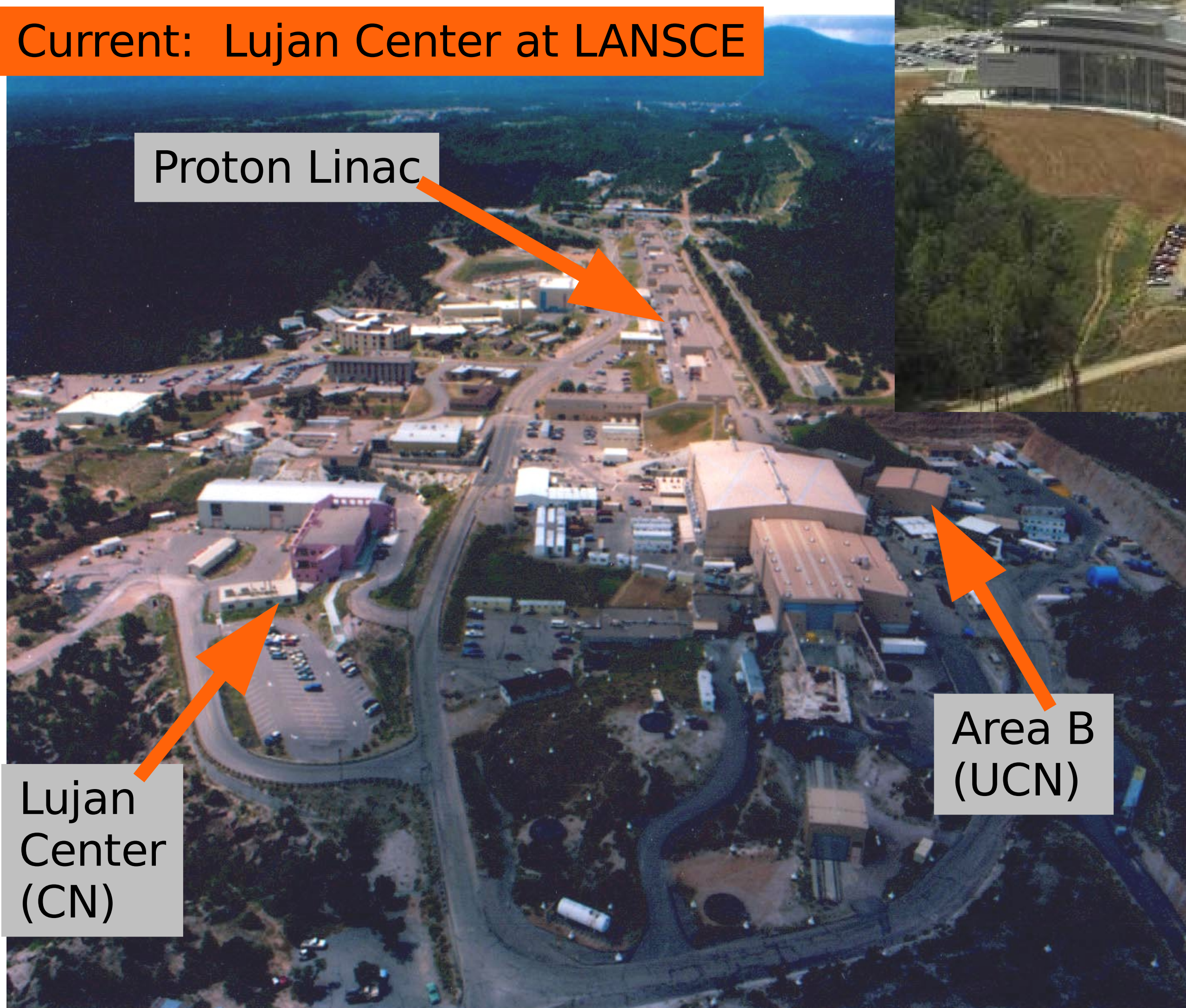
- Liberate them from nuclei
  - Fission (reactor)
  - Spallation (accelerator)



- Spallation produces 18 neutrons/proton at 1 GeV incident proton energy

- Spallation sources can be <u>pulsed</u> to reduce backgrounds

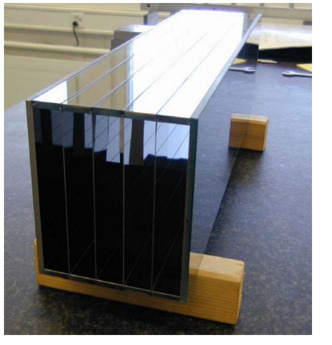
Spallation Sources in North America



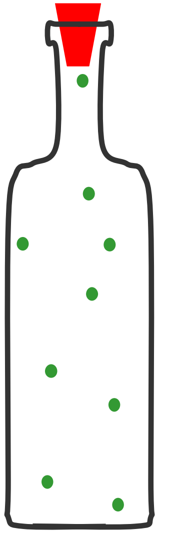
(also IPNS Argonne)

There are two kinds of neutrons in this world

- Cold neutrons (CN)
  - brought into thermal eqm with cold moderator
  - T = 25 K = 2 meV
  - small-angle neutron scattering



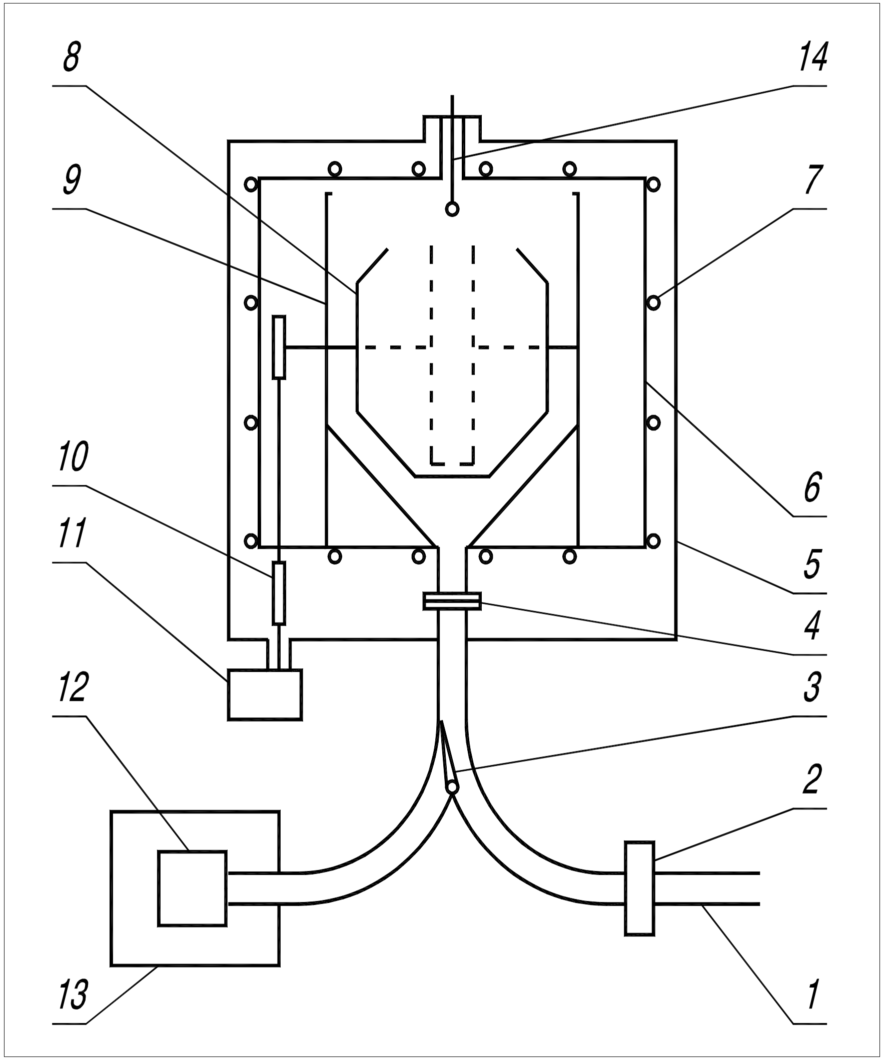
- Ultracold neutrons (UCN)
  - are so cold, critical angle is all angles
  - can be “bottled”
  - T < 4 mK = 300 neV



- Recent advances for both:
  - superthermal sources for UCN, SNS's for CN

Example Experiment: The most precise measurements of neutron lifetime

- Bring UCN into a bottle
- Close the bottle, wait
- Open the bottle and see how many come out
- Also, do many systematic checks, upscattering, (n,γ), in-trap monitoring, ...
- Dominant systematic: wall effects.



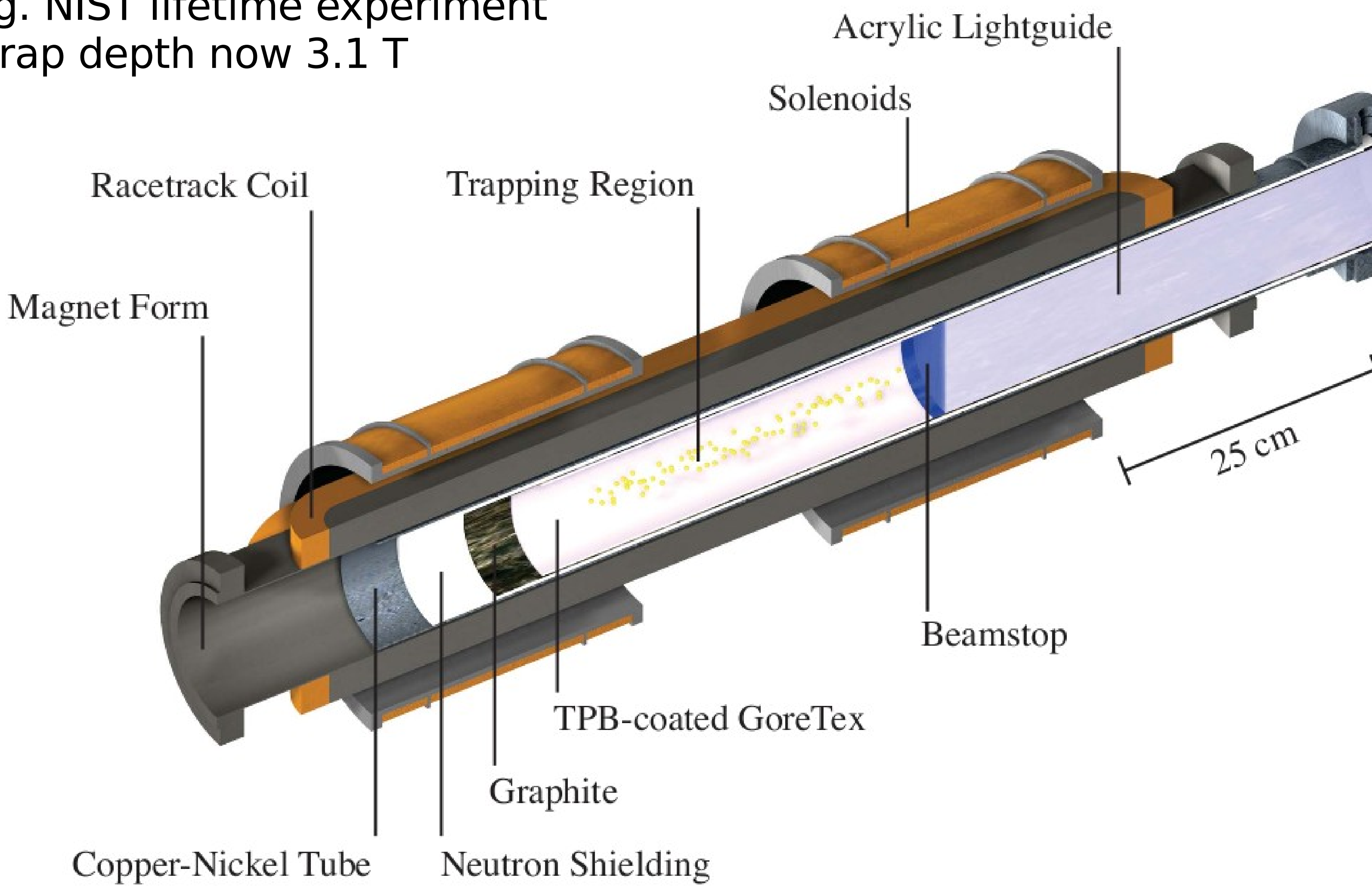
e.g. Serebrov et al's “Gravitrap”

V = mgh, h = 3 m gives V = 300 neV

Magnetic trap lifetime experiments

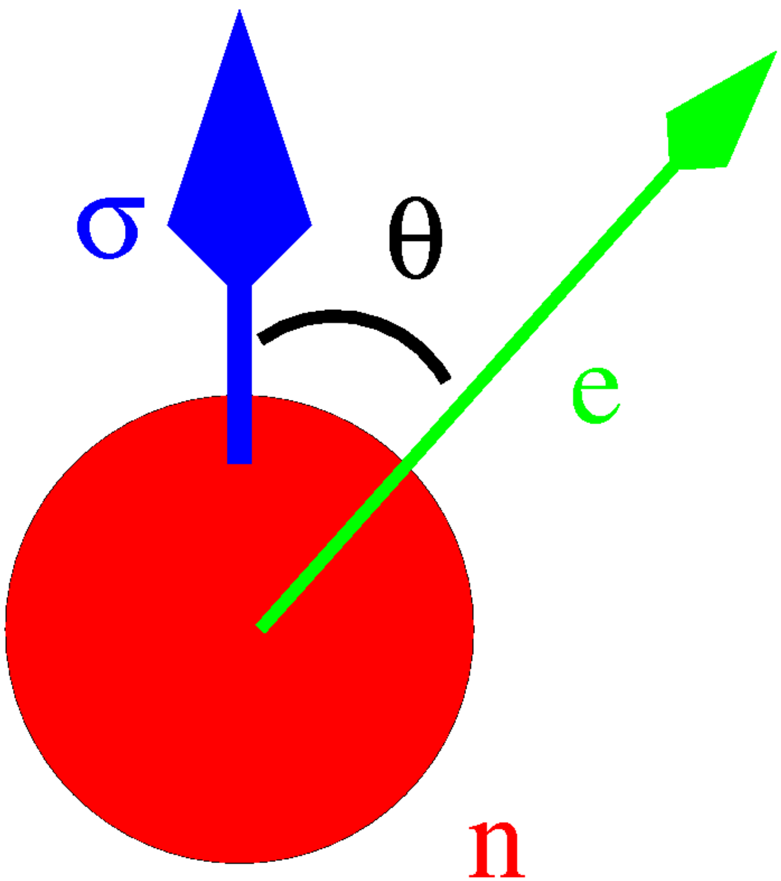
- Get rid of the walls! Trap using $V = -\mu \cdot B$

e.g. NIST lifetime experiment
- trap depth now 3.1 T



$V = -\mu \cdot B$, B = 7 T gives V = 300 neV

Experimental Method to Measure A



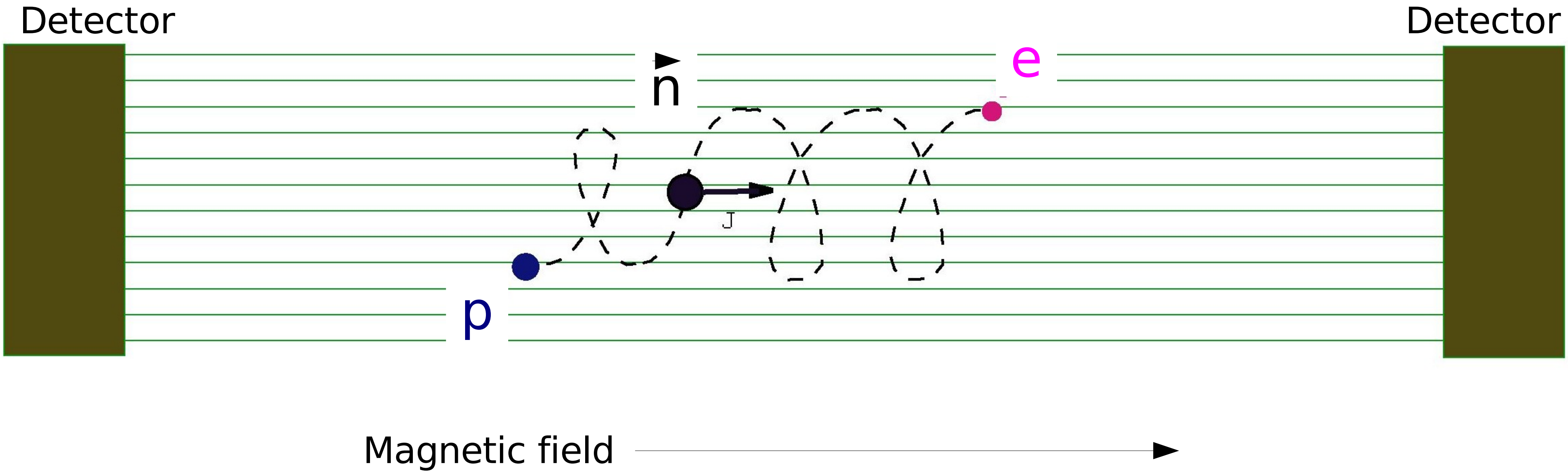
$$dW = \left[1 + \beta P A \cos\theta\right] d\Gamma\left(E\right)$$

$$A_{\text{exp}}\left(E\right) = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} \approx \frac{1}{2} A \beta P$$

Endpoint energy 782 keV

Focus electrons onto detectors using a strong (1 T) magnetic field

How to Measure a Beta-Asymmetry



$$A_{\exp}(E) = \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} \approx \frac{1}{2} A \beta P$$

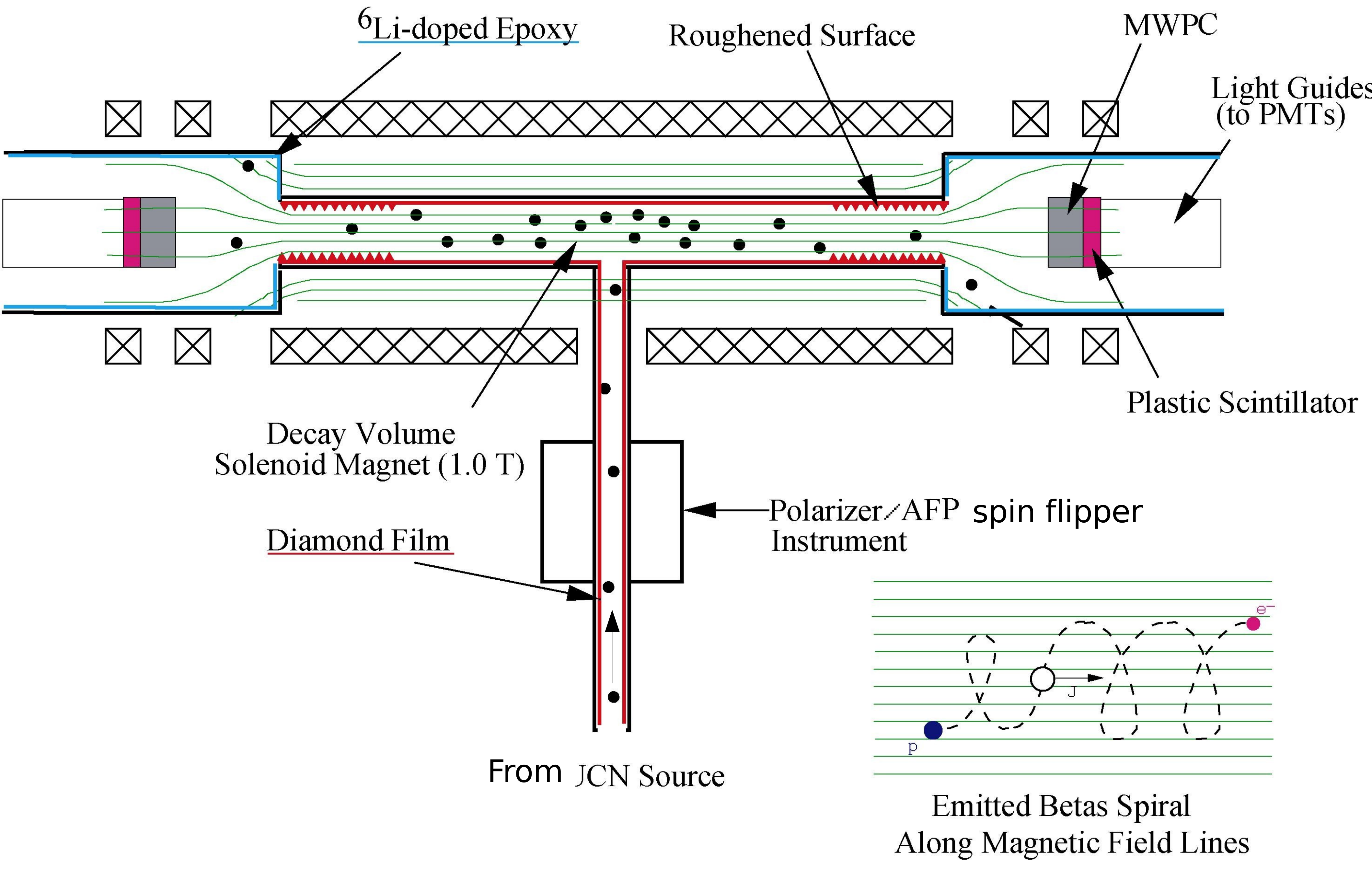
Desired Improvements in A

- Previous A measurements done with cold neutron beams from reactors, and used supermirror polarizers.

Using UCN, expect:

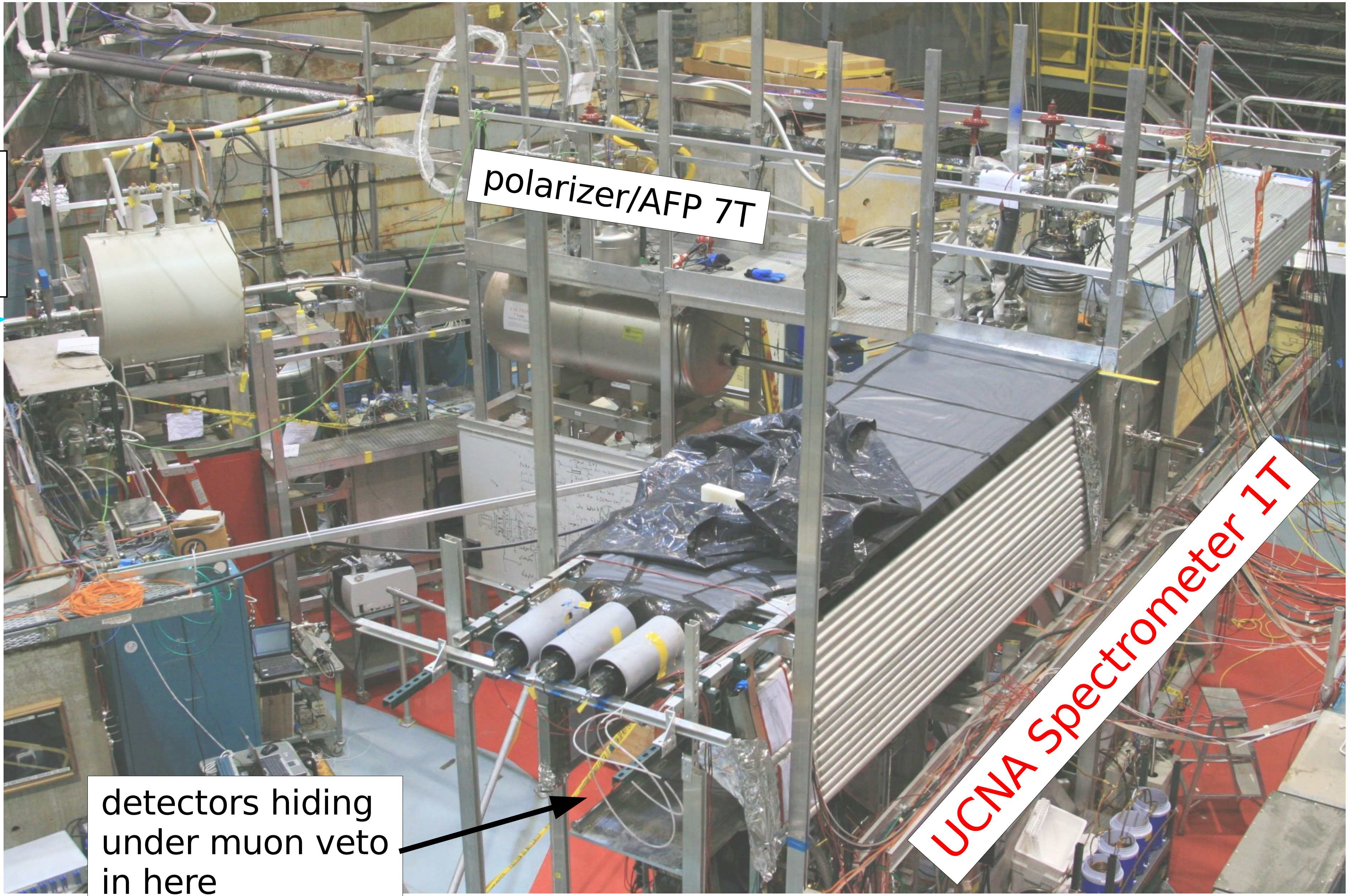
- reduced backgrounds
  - pulsed spallation source, low loss UCN transport over meters
- higher neutron polarization:
  - UCN 100% polarized by passage through strong B field

UCNA Experiment Schematic



UCNA in Area B at LANSCE

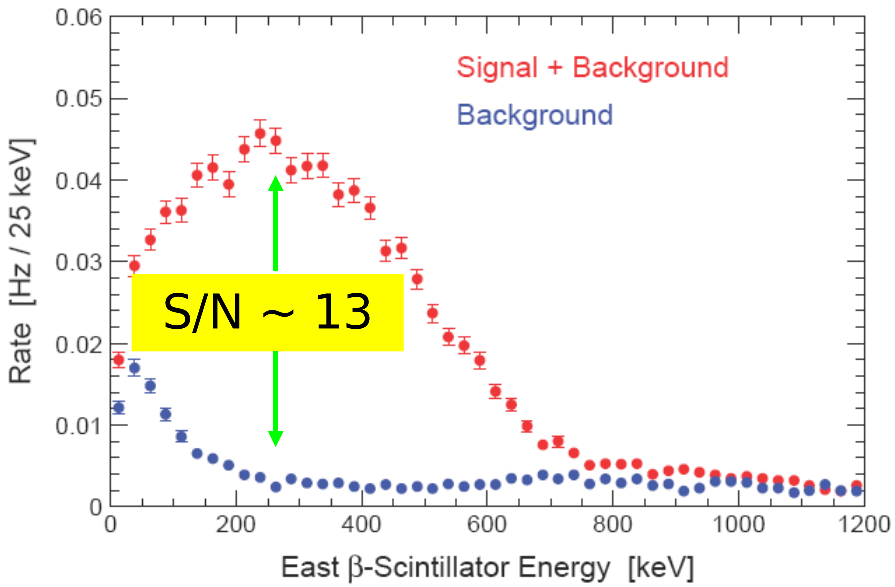
UCN from Source

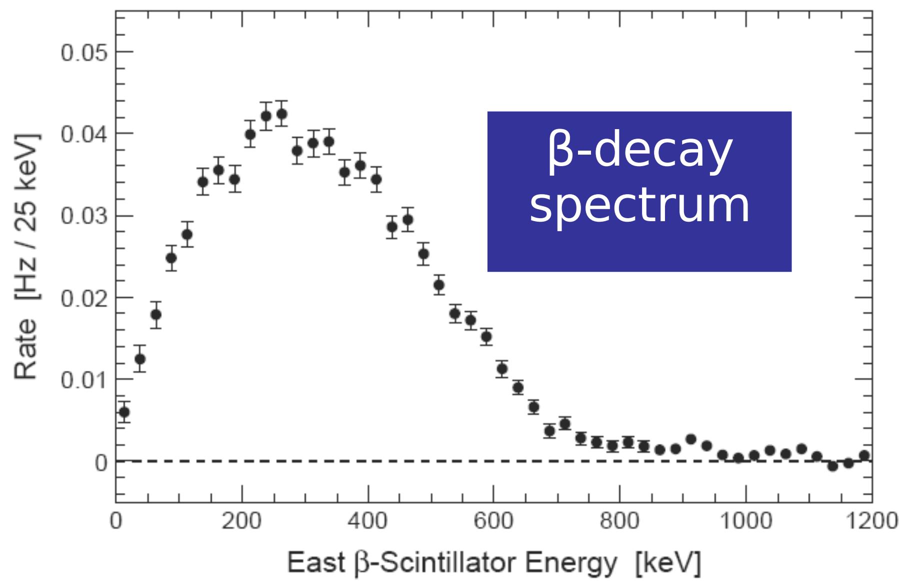


note: we have a dedicated spallation source of UCN

detectors hiding under muon veto in here

Measurement of Beta-Spectrum in UCNA





thanks, B. Plaster

- in PERKEO 2, S/N at 300 keV was ~6.
- S/N in UCNA might be increased if S can be increased

Experimental Parameters of UCNA

- Goal precision: $\Delta A/A = 0.2\%$
  - collection of 2×10^{8} decays
- UCN polarization > 99.9% determined to 0.1%

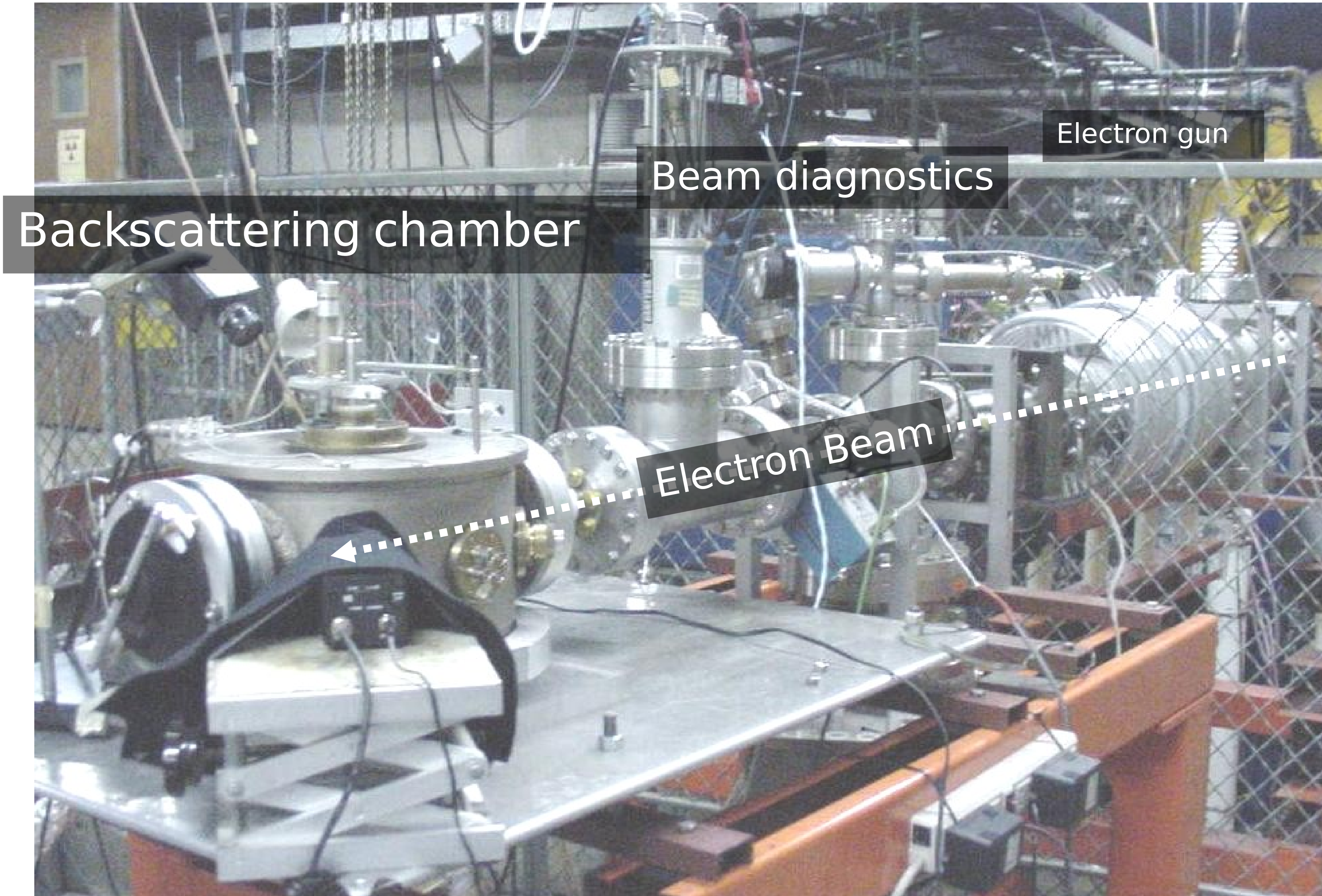
Dominant systematic corrections

Systematic Effect	Size of correction	Uncertainty
UCN Polarization	1×10^{-3}	1×10^{-4}
Wall depolarization	9×10^{-4}	1×10^{-4}
UCN spin alignment	1×10^{-4}	1×10^{-4}
Backscattering	1×10^{-3}	2×10^{-4}
Field nonuniformity	1×10^{-4}	2×10^{-5}
Detector response	3×10^{-4}	3×10^{-4}
Detector linearity	6×10^{-5}	6×10^{-5}
Total	1.7×10^{-3}	4.2×10^{-4}

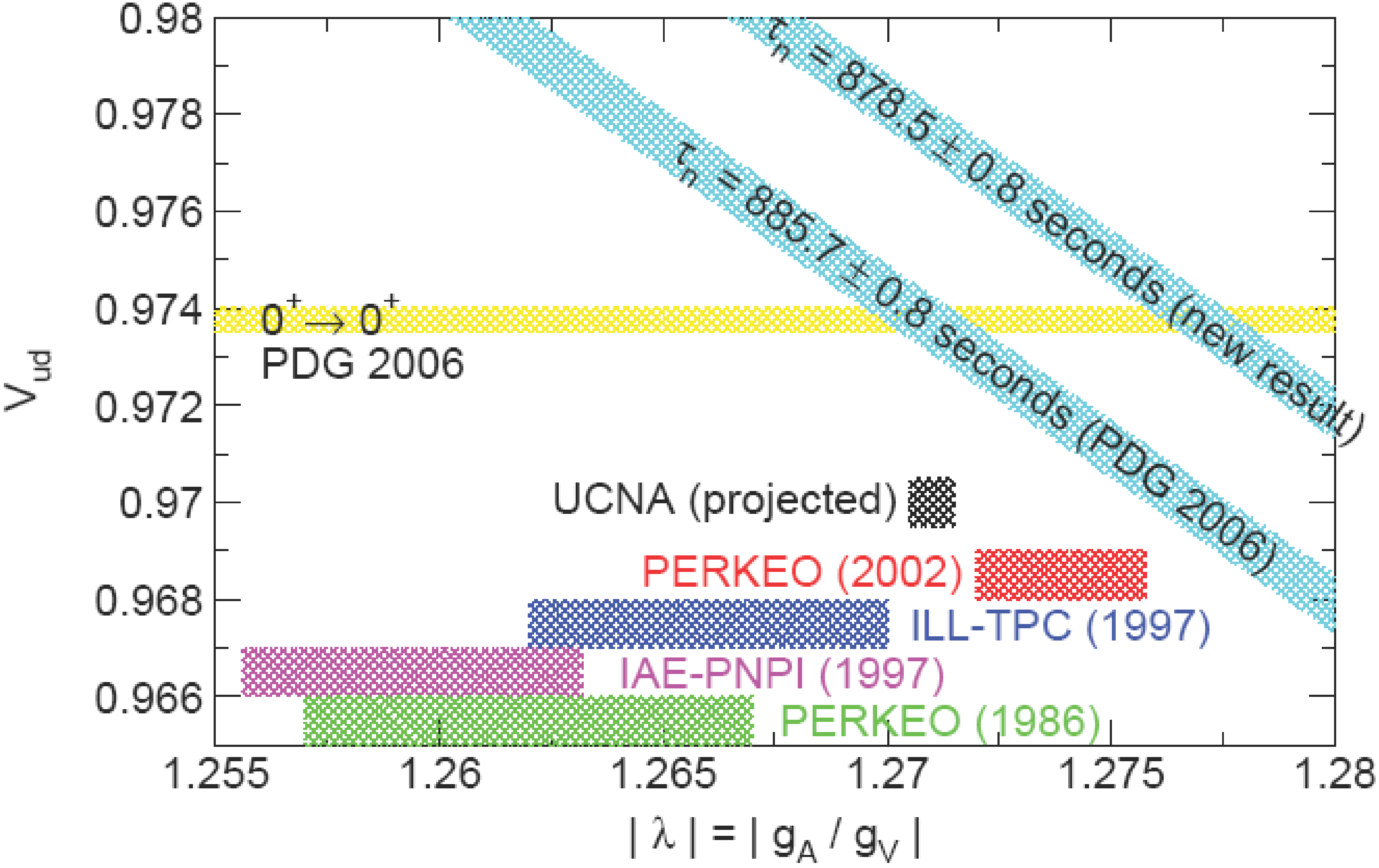
Extensive detector calibration scheme and new measurements of electron backscattering

T.M. Ito et al,
NIM A 571, 676 (2007)
J.W. Martin et al,
PRC 73, 015501 (2006)
J.W. Martin et al,
PRC 68, 055503 (2003)
J. Yuan et al,
NIM A (2001)

A small accelerator to measure backscattering and to calibrate detectors

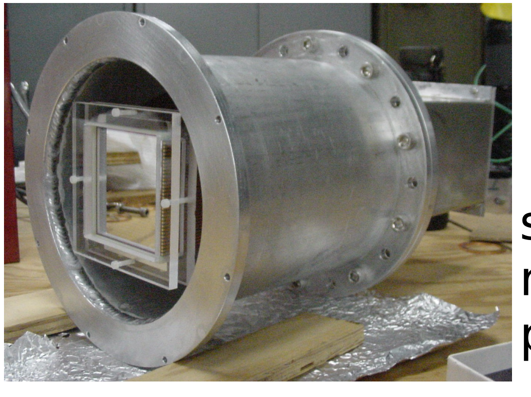


Projected Impact of UCNA



UCNA Schedule

- Up to now:
  - UCN production and transport (new technology)
  - Successful run with neutrons into beta-spectrometer
- This year: goal of Delta A/A = 1%
- Next year: 0.2%
- Future:
  - other correlations and recoil-order corrections (proton detectors and silicon detectors)



silicon prototype ready to mount in place of scintillator

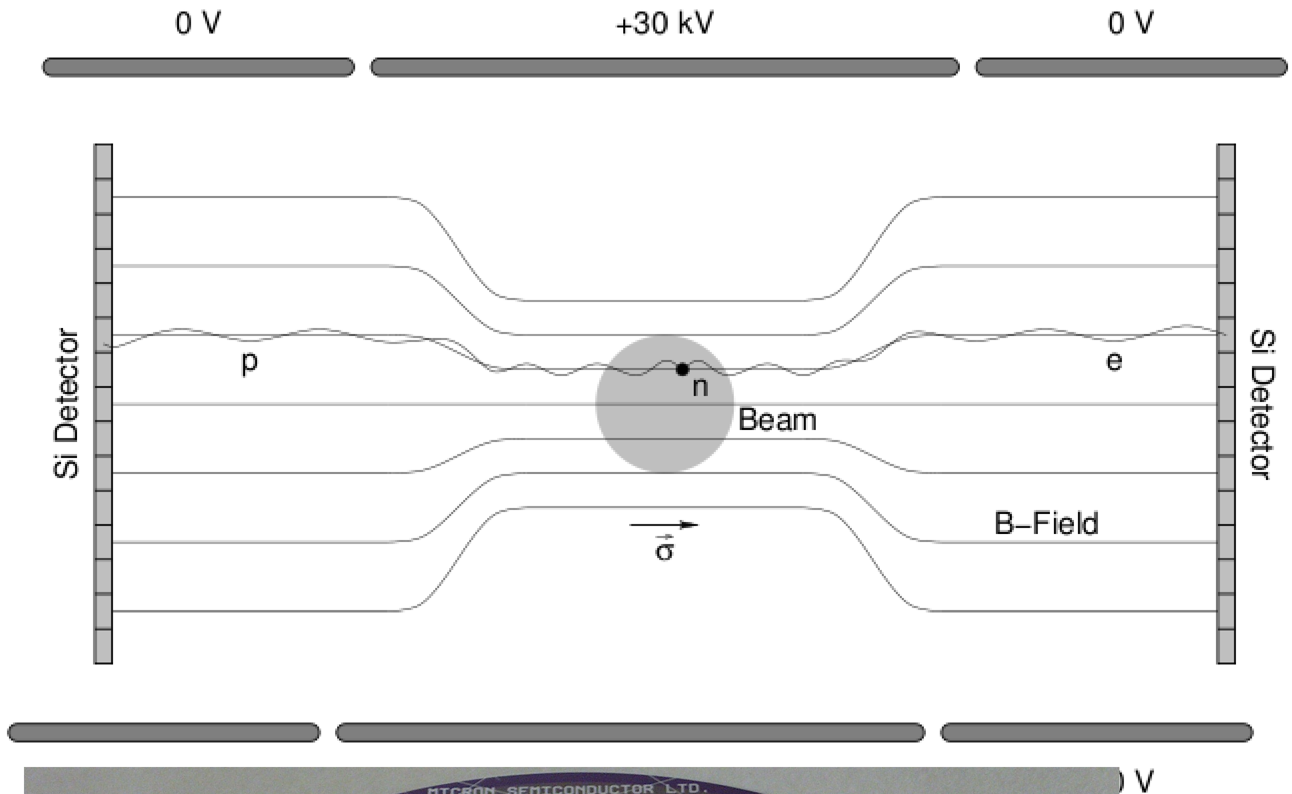
Beyond UCNA

- Previous A measurements done with cold neutron beams from reactors, and used supermirror polarizers.

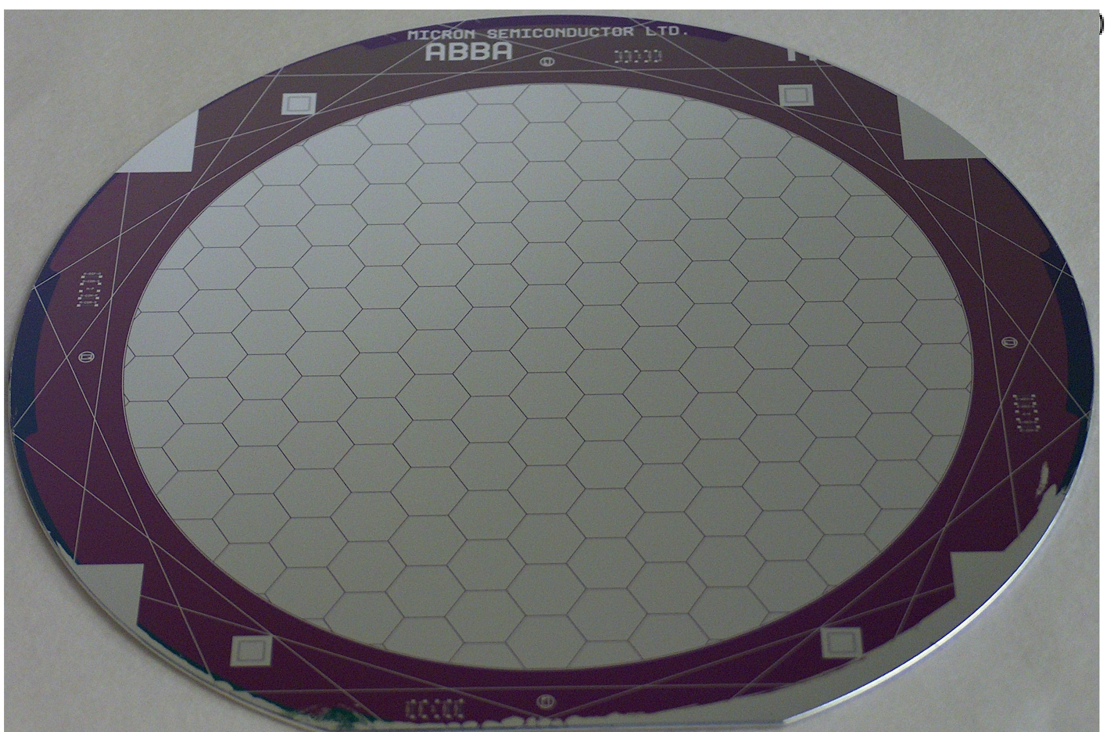
Using SNS CN, expect:

- reduced backgrounds
  - pulsed spallation source, transport CN far down a beam pipe from source
- better understood neutron polarization:
  - 3He polarizer, or supermirror
  - TOF tricks

Nab/abBA program at SNS: measure coefficients with improved accuracy



abBA schematic



abBA detector development

a 6”, 2 mm thick disk of silicon

Goal: Delta A/A = 0.1%
Challenge: Polarimetry

Conclusions

- Neutron decay is important
- Neutron experiments are fun
- New neutron sources coming online
- Very active field
  - e.g. at least six ongoing efforts on tau
  - similar number of angular correlation measurements (at least three on big A)
- Expect results soon!