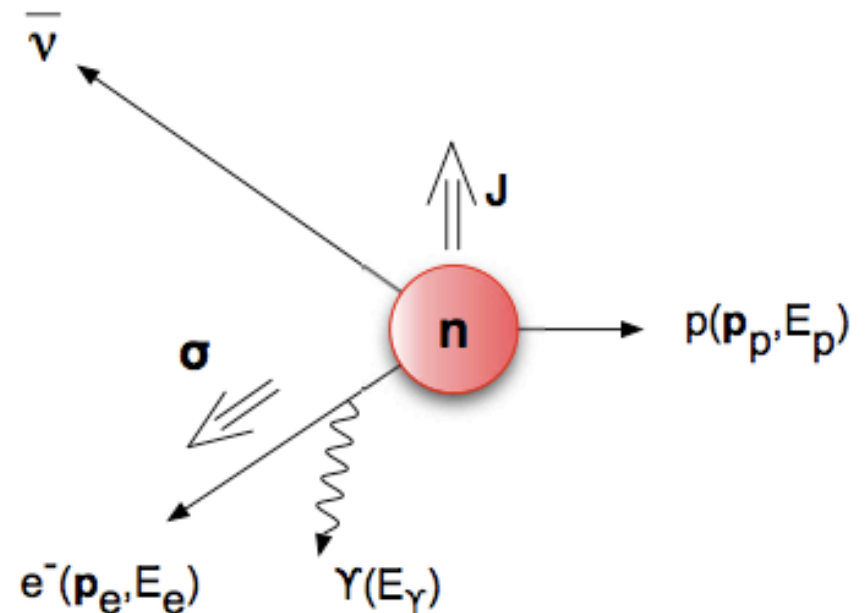


Nuclear Physics with Slow Neutrons

- (Very) brief history of the neutron
- Overview of low-energy neutron physics
- A little about cold and ultracold neutrons
- Lifetime and Correlations
- EDM/T-reversal

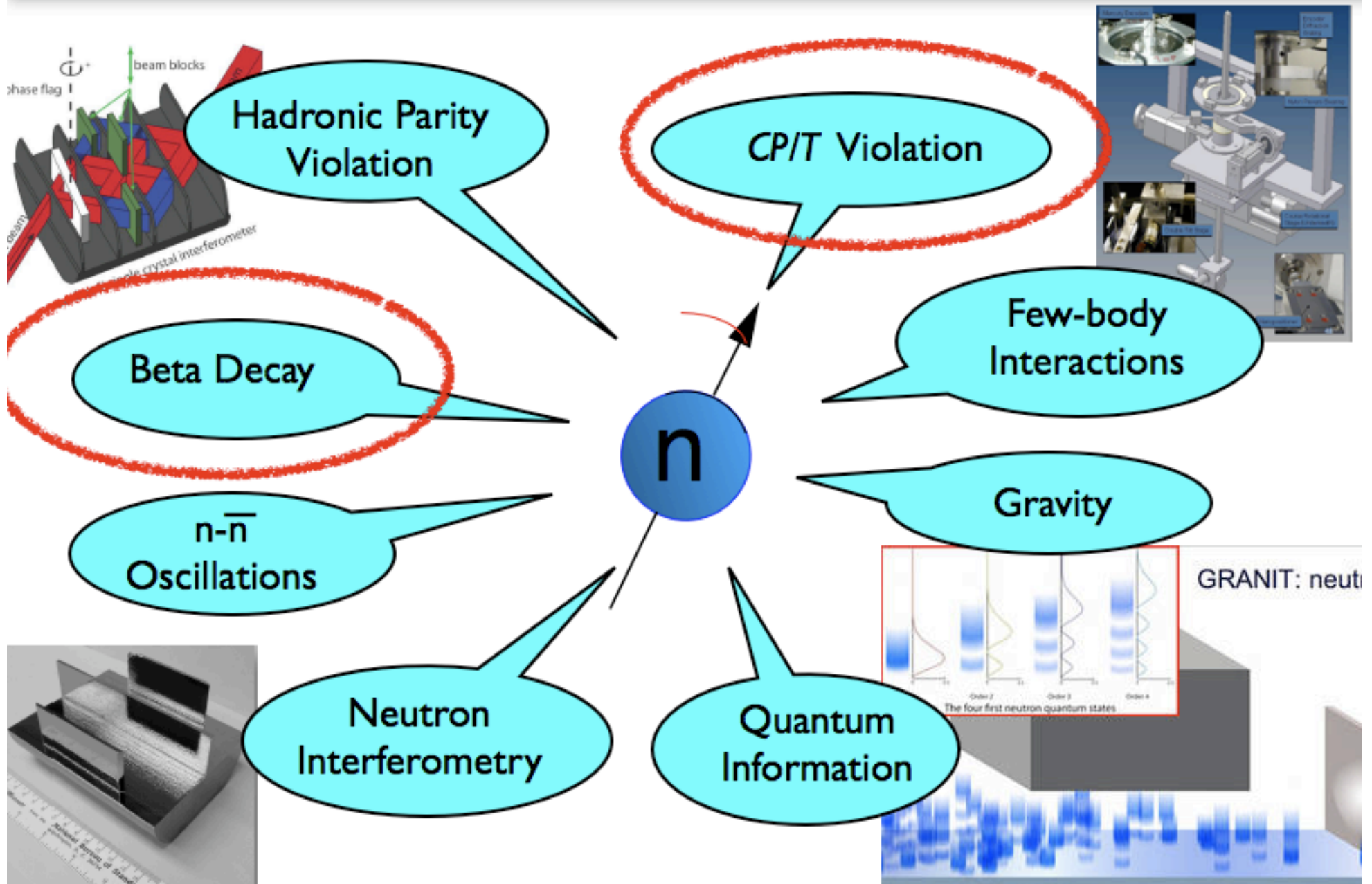


NIST



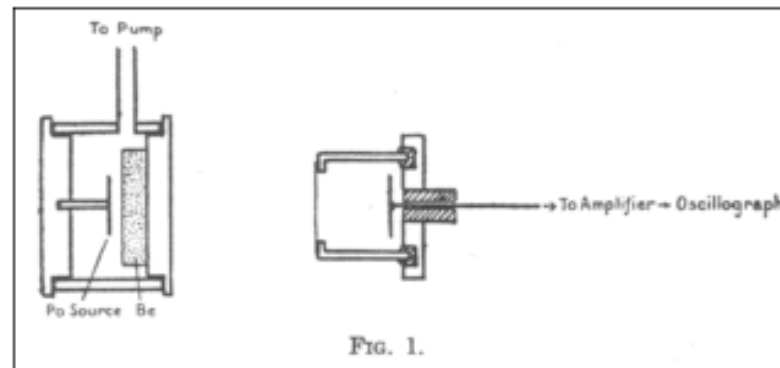
J. Nico, NIST
NNPSS 2011, Chapel Hill, NC
1 July 2011

Physics with (Slow) Neutrons



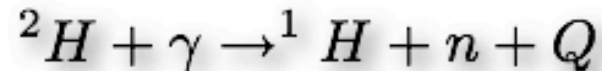
The Neutron

- 1930: Bothe and Becker in Germany bombard beryllium with alpha particles and observe a non-ionizing and penetrating radiation. Assumed to be gamma rays.
- 1932: Irène and Frédéric Joliot-Curie let the radiation hit a block of paraffin and observe that it caused the wax to emit protons. Interpret the protons as ejected by gammas.
- Rutherford and Chadwick do not think that gamma rays are responsible.
- 1932: Neutron discovered in experiment by Chadwick.



Neutron Decay

- 1934: Chadwick and Goldhaber detect the photo-disintegration of the deuteron (“diplon”) in the reaction



From the Q -value, they determine an estimate for the neutron mass, which is *greater* than the proton mass.

- The implication is that the neutron is energetically allowed to decay:



- 1948: Snell and Miller at Oak Ridge definitely observe the neutron decay into a proton (and Robson 1950 at Chalk River).

F12. On the Radioactive Decay of the Neutron. ARTHUR H. SNELL AND L. C. MILLER, *Clinton National Laboratories*.

—A collimated beam of neutrons, three inches in diameter, emerges from the nuclear reactor and passes axially through a thin-walled, aluminum, evacuated cylindrical tank. A transverse magnetic field behind the thin entrance window cleans the beam of secondary electrons. Inside the vacuum, axially arranged, an open-sided cylindrical electrode is held at +4000 volts with respect to ground. Opposite the open side a smoothed graphite plate is held at -4400 volts. The field between these electrodes accelerates and focuses protons which may result from decay of neutrons, so that they pass through a $2\frac{1}{8} \times 1\frac{5}{8}$ inch aperture in the center of the graphite plate, and strike the first dynode of a secondary electron multiplier. The first dynode is specially enlarged so as to cover the entire aperture. Readings are taken (1) with and without a

In "Minor Contributions"

in the neutron beam; (2) with and without a thin foil over the multiplier aperture; (3) with and without the accelerating voltage. In a total counting rate of about 300 per min., about 100 are sensitive to operations (1), (2), and (3). In the absence of the accelerating field or with the foil (2) in, operation (1) does not change the counting rate. Assuming all of the 100 c.p.m. to be due to decay protons, preliminary estimates of the collecting and counting efficiency (10 percent) and of the number of neutrons in the sample (4×10^4) give for the neutron a half-life of about 30 minutes. It is at present much safer however to say that the neutron half-life must exceed 15 minutes. Coincidences are presently being sought between the disintegration betas and the collected protons.

Neutron Decay Parameters

- $(m_n + m_p)c^2 = 1877 \text{ MeV}; \quad (m_n - m_p)c^2 = 1293 \text{ keV}$

- Decay products: $n \rightarrow p + e^- + \bar{\nu}_e; \quad \tau_n \approx 15 \text{ min.}$

$$0 < T_e < 782 \text{ keV}$$

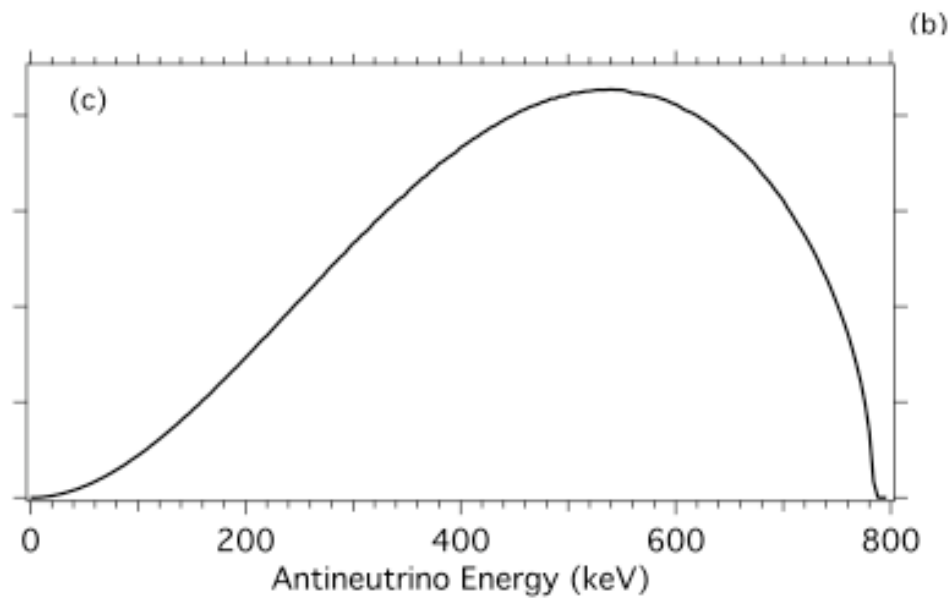
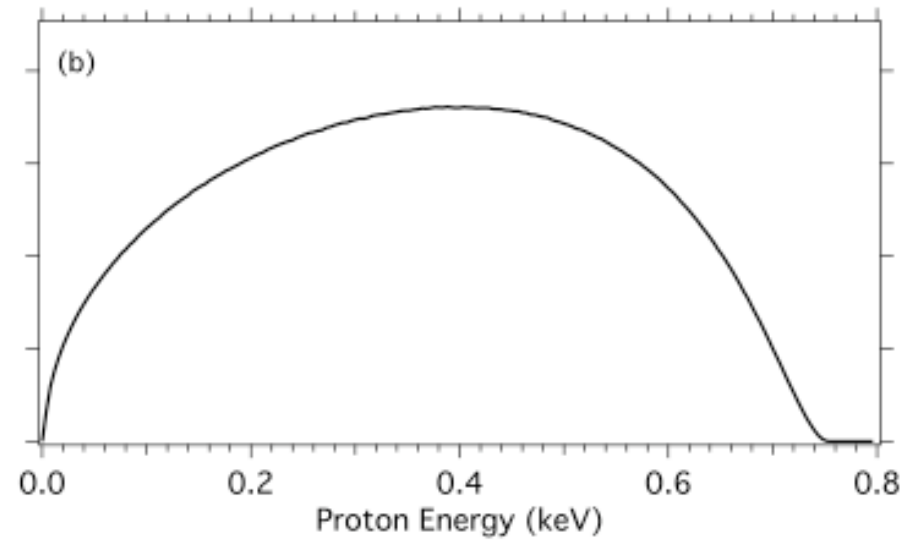
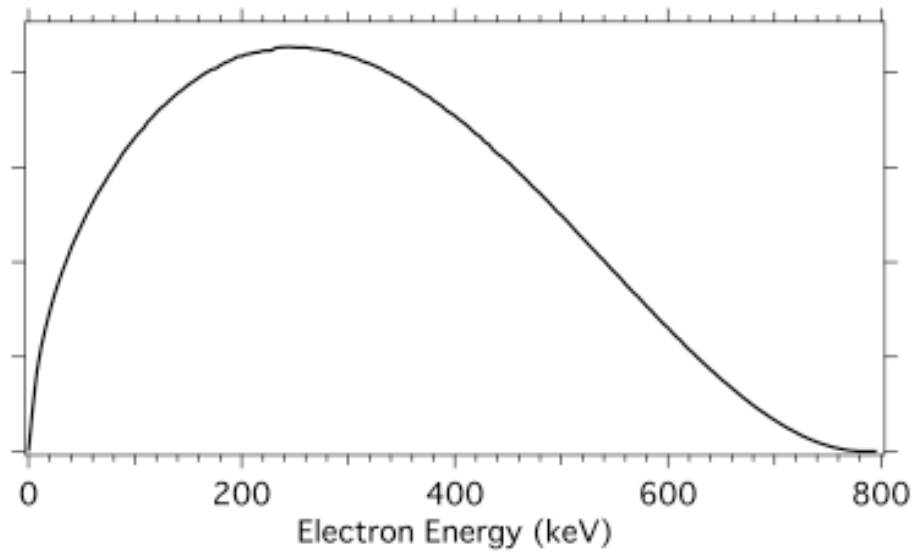
$$0 < T_p < 751 \text{ eV}$$

- Other decay modes:

$$n \rightarrow p + e^- + \bar{\nu}_e + \gamma \quad BR(15 \text{ keV}) \approx 3 \times 10^{-3}$$

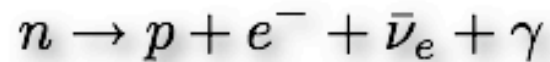
$$n \rightarrow H^0 + \bar{\nu}_e \quad BR \approx 4 \times 10^{-6}$$

Decay Product Energy Spectra

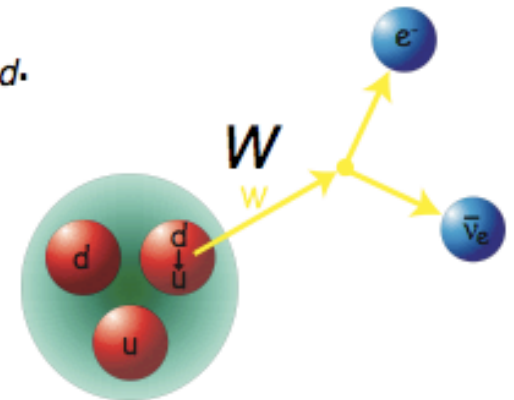


(c)

Physics from Neutron Decay



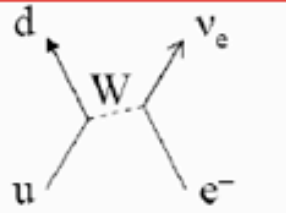
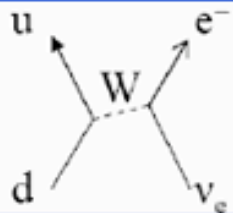
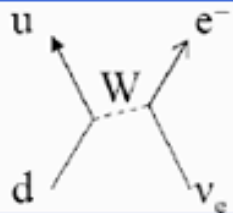
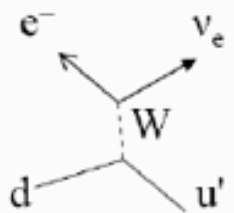
- Big Bang Nucleosynthesis and light element abundance.
- Test of CKM unitarity; determination of V_{ud} .
- Over-constrained measurements give model-independent SM checks.
- Look for scalar, tensor interactions, non-SM physics.
- Measurement of radiative corrections.
- New source of time-reversal (CP) violation?



Fundamental Semileptonic Decay

$$d + \nu_e \leftrightarrow u + e^-$$

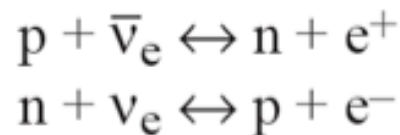
Processes governed by lifetime and g_A/g_V

Cosmology	Primordial element formation (^2H , ^3He , ^4He , ^7Li , ...)	$n + e^+ \rightarrow p + \nu'_e$ $p + e^- \rightarrow n + \nu_e$ $n \rightarrow p + e^- + \nu'_e$	$\sigma_\nu \sim 1/\tau$ $\sigma_\nu \sim 1/\tau$ τ	
	Astronomy	Solar cycle $p + p \rightarrow ^2\text{H} + e^+ + \nu_e$ $p + p + e^- \rightarrow ^2\text{H} + \nu_e$ etc.	$\sim (g_A/g_V)^5$	
Particle Physics	Neutron star formation	$p + e^- \rightarrow n + \nu_e$		
	Pion decay	$\pi^- \rightarrow \pi^0 + e^- + \nu'_e$		
	Neutrino detectors	$\nu'_e + p \rightarrow e^+ + n$		
	Neutrino forward scattering	$\nu_e + n \rightarrow e^- + p$ etc.		
	W and Z production	$u' + d \rightarrow W^- \rightarrow e^- + \nu'_e$ etc.		

from D. Dubbers

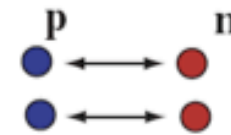
BBN and Light Element Abundance

Thermal Equilibrium



($T > 1 \text{ MeV}$)

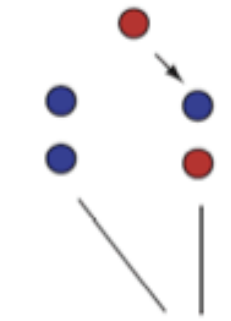
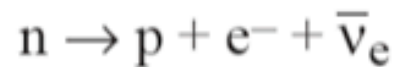
$$n/p \sim e^{-Q/T}$$



$1 \mu\text{s}$

After Freezeout

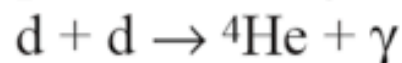
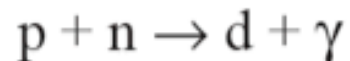
n/p decreases due to neutron decay



1 s

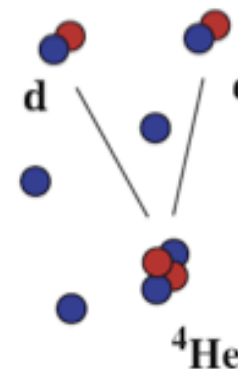
Nucleosynthesis

Light elements are formed.



almost all neutrons present $\rightarrow {}^4\text{He}$

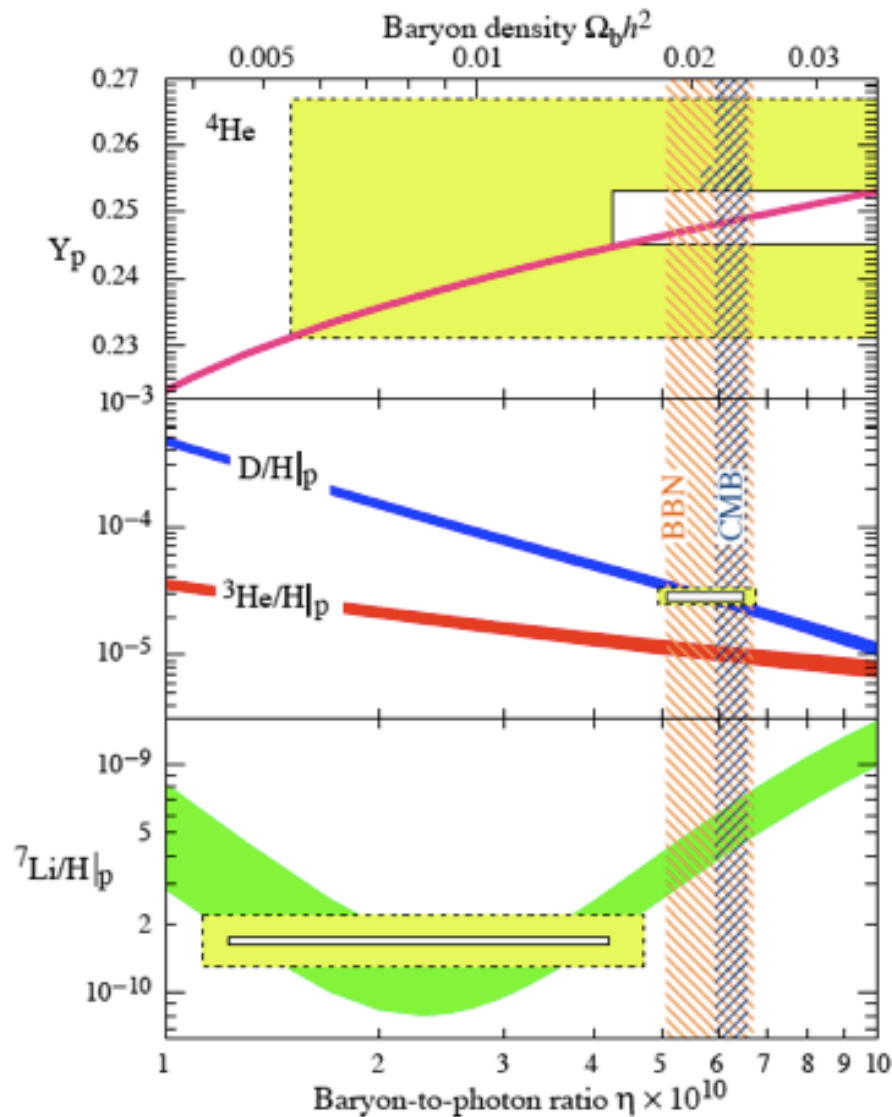
($T \sim 0.1 \text{ MeV}$)



10 min.

Neutron lifetime dominates theoretical uncertainty in ${}^4\text{He}$ abundance.

Light Element Abundance



$$Y_P = \frac{2(n/p)}{1 + (n/p)}$$

$$= 0.249 \pm 0.009$$

WMAP + ACBAR + QUaD
(WMAP arXiv:1001.4538v1 (2010))

$$Y_P = 0.326 \pm 0.075 (68\% \text{ CL})$$

Nuclear Beta-Decay

➤ Nuclear beta-decay can in general be formulated as an interaction involving many possible couplings

C_S - Scalar

C_V - Vector

C_A - Axial-vector

C_T - Tensor

C_P - Pseudoscalar

➤ These couplings can be real or imaginary, parity-violating or conserving. There are 20 possible couplings.

Nuclear Beta-Decay

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C_S - Scalar

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C_T - Tensor

C_P - Pseudoscalar

➤ These couplings can be real or imaginary, parity-violating or conserving. There are 20 possible couplings.

➤ Experimentally, nuclear beta-decay has been very well-described by two, real couplings C_V and C_A in $V-A$ theory.

➤ Experimentalists continue to test the validity of the theory - and search for hints of failure - through increasingly precise measurements of the decay observables.

Beta Decay Probability of a Free Neutron

One possible interaction $\mathcal{M} = \frac{G_F}{2\sqrt{2}} V_{ud} \bar{\psi}_p \gamma_\mu (f + g\gamma_5) \psi_n \bar{\psi}_e \gamma^\mu (1 + \gamma_5) \psi_\nu$

calculate the transition probability $W = \frac{1}{\tau} = \frac{2\pi}{\hbar} |\langle f | \mathcal{M} | i \rangle|^2 \rho_f$

$$g_V \equiv G_F V_{ud} f(0) \quad g_A \equiv G_F V_{ud} g(0)$$

Express the lifetime tau as $\tau^{-1} \propto f \xi$

where f is a kinematic factor and $\xi = g_V^2 |\langle \mathbf{1} \rangle|^2 + g_A^2 |\langle \sigma \rangle|^2$

yields $\tau = \frac{1}{f(1 + \delta_R)} \frac{K/\ln 2}{(1 + \Delta_R^V)(g_V^2 + 3g_A^2)}$

Neutron Decay w/ Radiative Corrections

$$\tau = \frac{1}{f(1 + \delta_R)} \frac{K}{G_F^2 V_{ud}^2 (1 + \Delta_R^V) (1 + 3\lambda^2)}$$

where $f(1 + \delta_R)$ = statistical rate fct + rad. corrections

$(1 + \Delta_R^V)$ = radiative corrections (nucleus independent)

$$\tau = \frac{4908.7 \pm 1.9}{|V_{ud}|^2 (1 + 3\lambda^2)}$$

Correlation Coefficients

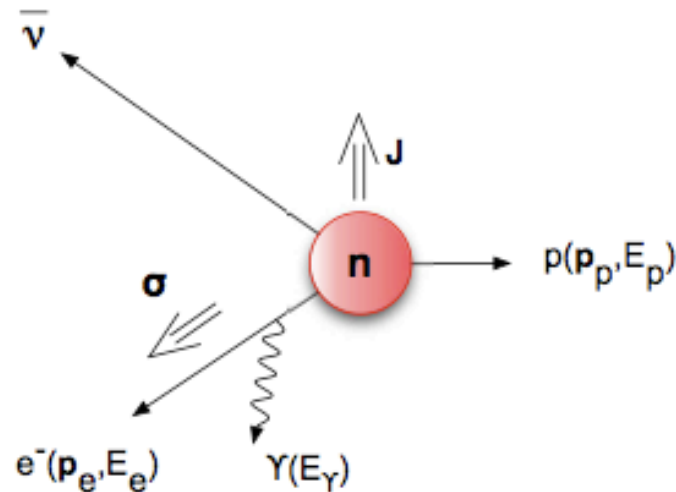
- Angular distribution of decay particles from a polarized nucleus

$$W(\langle \mathbf{J} \rangle, E_e, \Omega_e, \Omega_\nu) dE_e d\Omega_e d\Omega_\nu = \frac{1}{(2\pi)^5} p_e E_e (E^0 - E_e)^2 dE_e d\Omega_e d\Omega_\nu \\ \times \xi \left[1 + a \frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \frac{\langle \mathbf{J} \rangle}{J} \cdot \left(A \frac{\mathbf{p}_e}{E_e} + B \frac{\mathbf{p}_\nu}{E_\nu} + D \frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E_e E_\nu} \right) \right]$$

- Decay of polarized nuclei and its correlations with the electron momentum and polarization σ

$$W(\langle \mathbf{J} \rangle, \sigma, E_e, \Omega_e) dE_e d\Omega_e = \frac{1}{(2\pi)^4} p_e E_e (E^0 - E_e)^2 dE_e d\Omega_e \\ \times \xi \left[1 + \sigma \cdot \left(N \frac{\langle \mathbf{J} \rangle}{J} + R \frac{\langle \mathbf{J} \rangle}{J} \times \frac{\mathbf{p}_e}{E_e} + \dots \right) + \dots \right]$$

Correlation Coefficients



Coefficient	Correlation	Parity (\mathcal{P})	Time (\mathcal{T})
a (Electron–antineutrino correlation)	$\mathbf{p}_e \cdot \mathbf{p}_\nu / E_e E_\nu$	Even	Even
b (Fierz interference)	m_e / E_e	Even	Even
A (Spin-electron asymmetry)	$\langle \mathbf{J} \cdot \mathbf{p}_e / E_e \rangle$	Odd	Even
B (Spin-antineutrino asymmetry)	$\langle \mathbf{J} \cdot \mathbf{p}_\nu / E_\nu \rangle$	Odd	Even
C (Spin-proton asymmetry)	$\langle \mathbf{J} \cdot \mathbf{p}_p / E_p \rangle$	Odd	Even
D (Triple correlation)	$\langle \mathbf{J} \cdot (\mathbf{p}_e \times \mathbf{p}_\nu) / E_e E_\nu \rangle$	Even	Odd
N (Spin-electron spin)	$\sigma \cdot \langle \mathbf{J} \rangle$	Even	Even
R (Electron spin triple correlation)	$\sigma \cdot (\langle \mathbf{J} \rangle \times \mathbf{p}_e) / E_e$	Odd	Odd

Correlation Coefficients

$$dW \propto (g_V^2 + 3g_A^2) F(E_e) \left[1 + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \vec{\sigma}_n \cdot \left(A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right]$$

Electron-antineutrino correlation

$$a = \frac{1 - |\lambda|^2}{1 + 3|\lambda|^2} = (-0.103 \pm 0.004)$$

Lifetime

$$\tau = \frac{1}{f(1 + \delta_R)} \frac{K/\ln 2}{(1 + \Delta_R^V)(g_V^2 + 3g_A^2)} = (881.5 \pm 1.5) \text{ s}$$

Spin-electron asymmetry

$$A = -2 \frac{|\lambda|^2 + |\lambda| \cos \phi}{1 + 3|\lambda|^2} = (-0.1176 \pm 0.0011)$$

Coupling ratio

$$\lambda = \frac{|g_A|}{|g_V|} e^{i\phi} = (-1.2701 \pm 0.0025)$$

Spin-antineutrino asymmetry

$$B = 2 \frac{|\lambda|^2 - |\lambda| \cos \phi}{1 + 3|\lambda|^2} = (0.9807 \pm 0.0030)$$

PDG, 2010 plus
2011 partial update

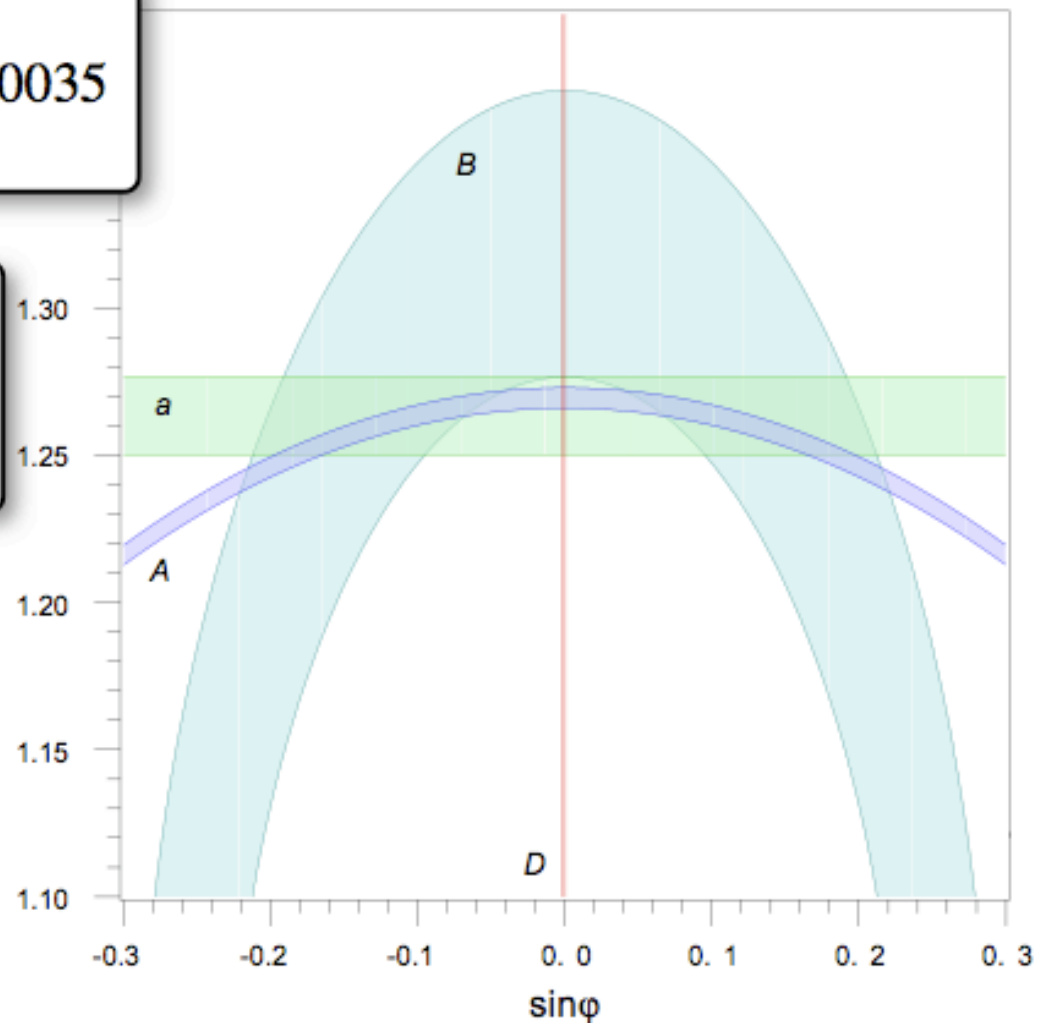
Correlation Coefficients

$$\lambda \equiv \frac{g_A}{g_V} e^{-i\phi} \approx 1.2670 \pm 0.0035$$

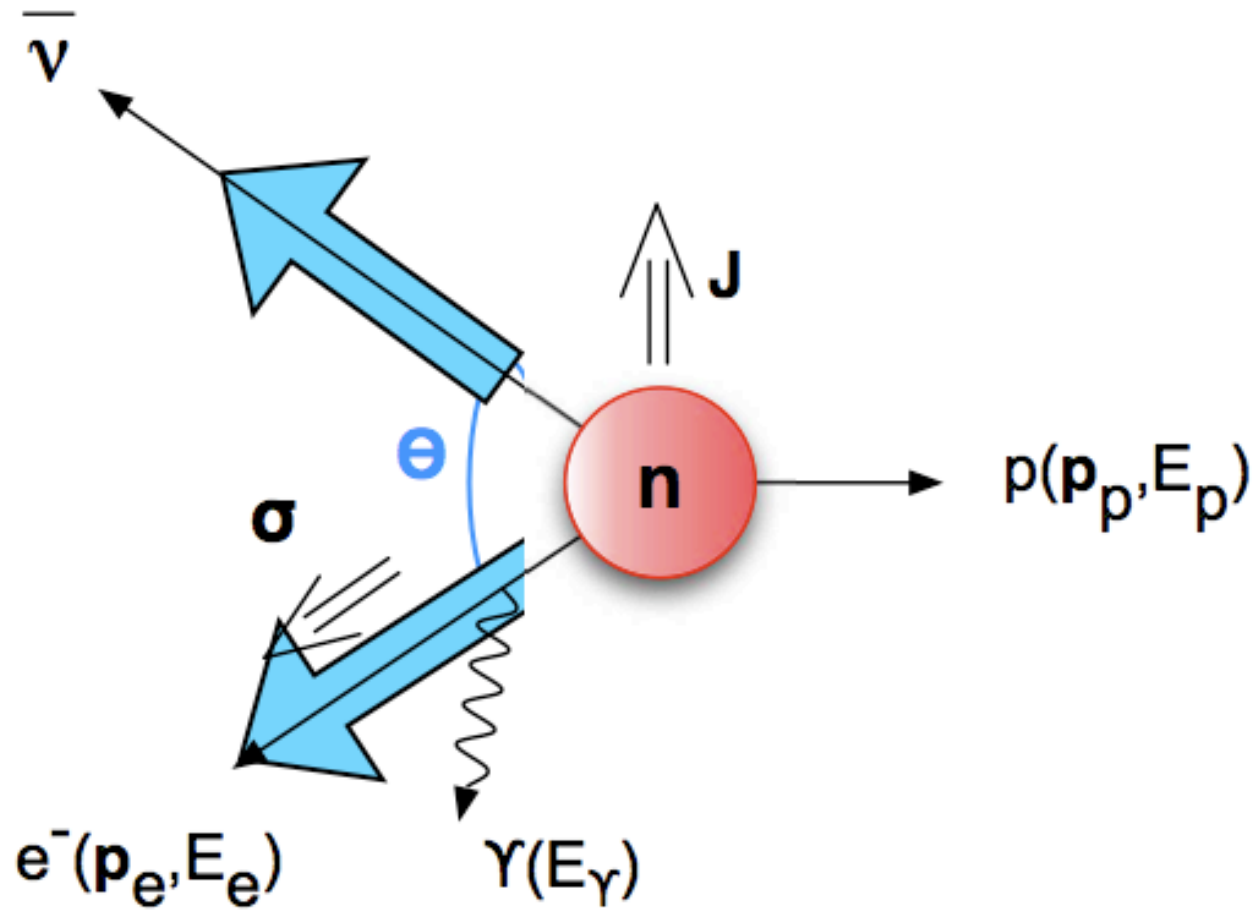
$$A = -2 \frac{|\lambda|^2 + |\lambda| \cos \phi}{1 + 3|\lambda|^2}$$

T-odd (P-even)
triple correlation:

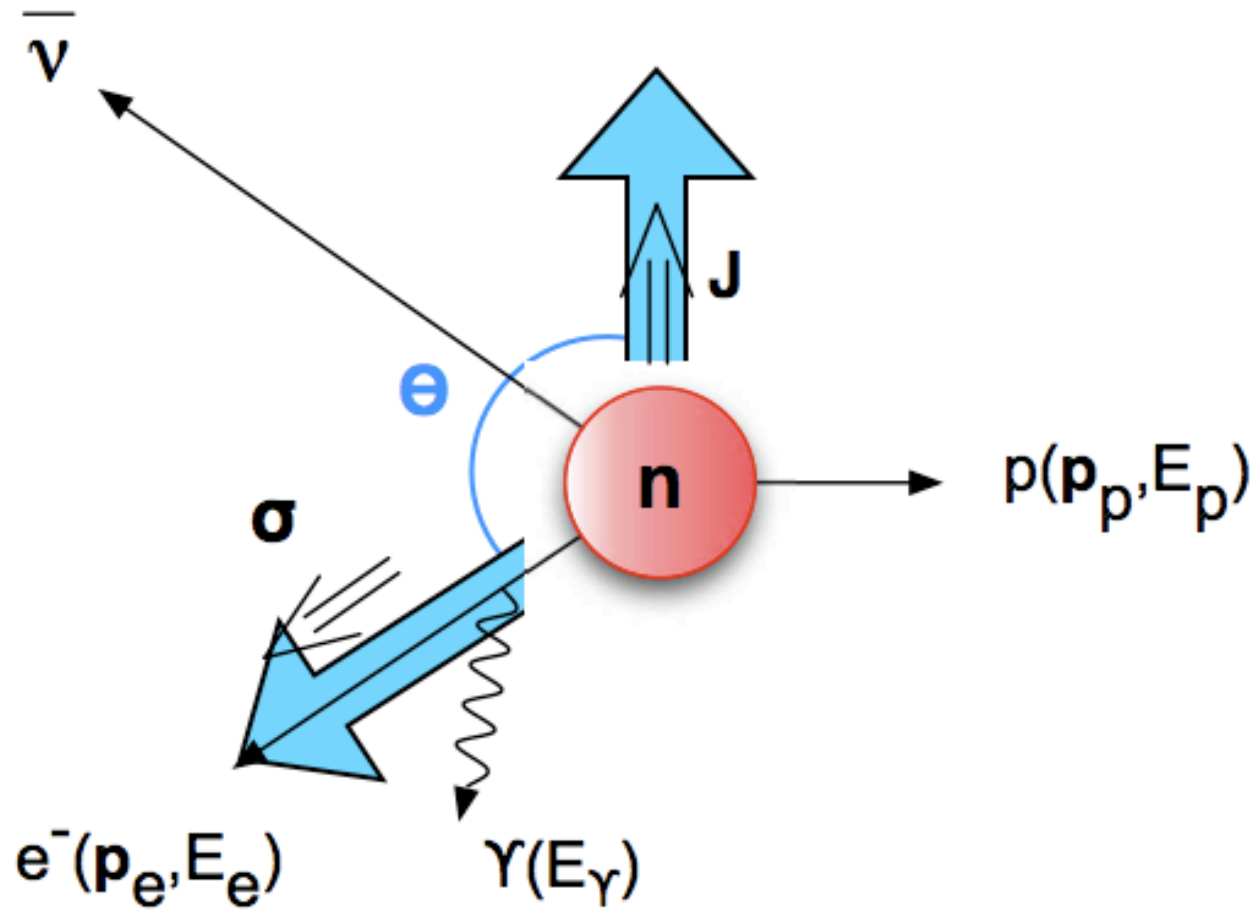
$$D = 2 \frac{|\lambda| \sin \phi}{1 + 3|\lambda|^2}$$



Electron-Antineutrino Correlation - "Little a"



Spin-electron Asymmetry - "Big A"



Big A in Co-60

Experimental Test of Parity Conservation in Beta Decay*

C. S. WU, *Columbia University, New York, New York*

AND

E. AMBLER, R. W. HAYWARD, D. D. HOPPE, AND R. P. HUDSON,
National Bureau of Standards, Washington, D. C.

(Received January 15, 1957)

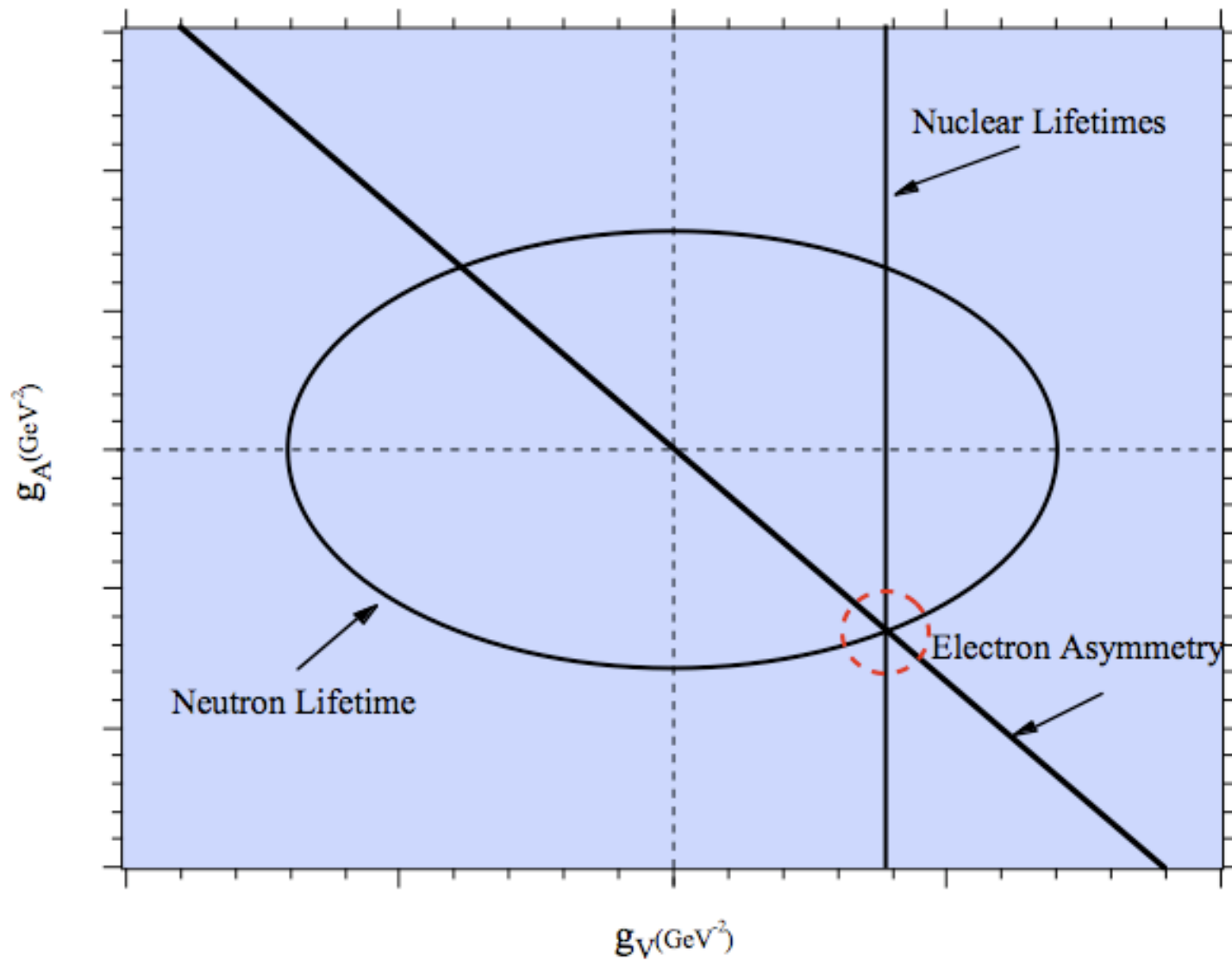
IN a recent paper¹ on the question of parity in weak interactions, Lee and Yang critically surveyed the experimental information concerning this question and reached the conclusion that there is no existing evidence either to support or to refute parity conservation in weak interactions. They proposed a number of experiments on beta decays and hyperon and meson decays which would provide the necessary evidence for parity conservation or nonconservation. In beta decay, one could measure the angular distribution of the electrons coming from beta decays of polarized nuclei. If an asymmetry in the distribution between θ and $180^\circ - \theta$ (where θ is the angle between the orientation of the parent nuclei and the momentum of the electrons) is observed, it provides unequivocal proof that parity is not conserved in beta decay. This asymmetry effect has been observed in the case of oriented Co^{60} .

It has been known for some time that Co^{60} nuclei can be polarized by the Rose-Gorter method in cerium magnesium (cobalt) nitrate, and the degree of polarization detected by measuring the anisotropy of the succeeding gamma rays.² To apply this technique to the present problem, two major difficulties had to be over-

sotropy alone provides a reliable measure of nuclear polarization. Specimens were made by taking good single crystals of cerium magnesium nitrate and growing on the upper surface only an additional crystalline layer containing Co^{60} . One might point out here that since the allowed beta decay of Co^{60} involves a change of spin of



V-A Test



CKM Quark Mixing Matrix

- CKM matrix represents a rotation of the quark mass eigenstates to the weak eigenstates.

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

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

- $|V_{ud}|$ obtained from

1. nuclear decays

2. pion beta decay

3. neutron beta decay

$$|V_{ud}|^2 = \frac{2984.48 \pm 0.05 \text{ s}}{ft(1 + RC)}$$

$$|V_{ud}|^2 = (0.9749 \pm 0.0026)^2 \left[\frac{BR(\pi^+ \rightarrow e^+ \nu_e(\gamma))}{1.2352 \times 10^{-4}} \right]$$

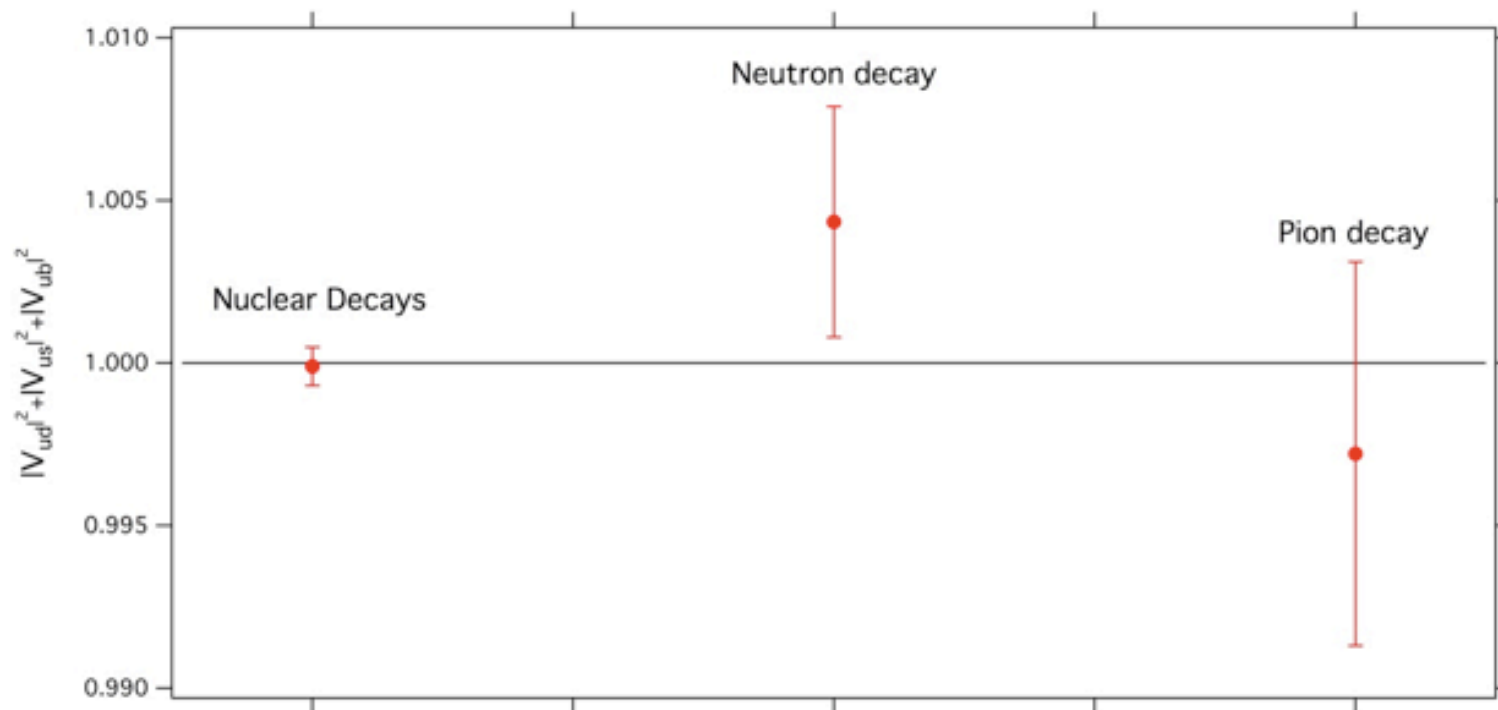
$$|V_{ud}|^2 = \frac{4908.7 \pm 1.9 \text{ s}}{\tau_n(1 + 3\lambda^2)}$$

$|V_{ud}|$ and CKM Comparison - PDG 2011

Nuclear decays: $|V_{ud}|_{0^+} = 0.97425 \pm 0.00022$

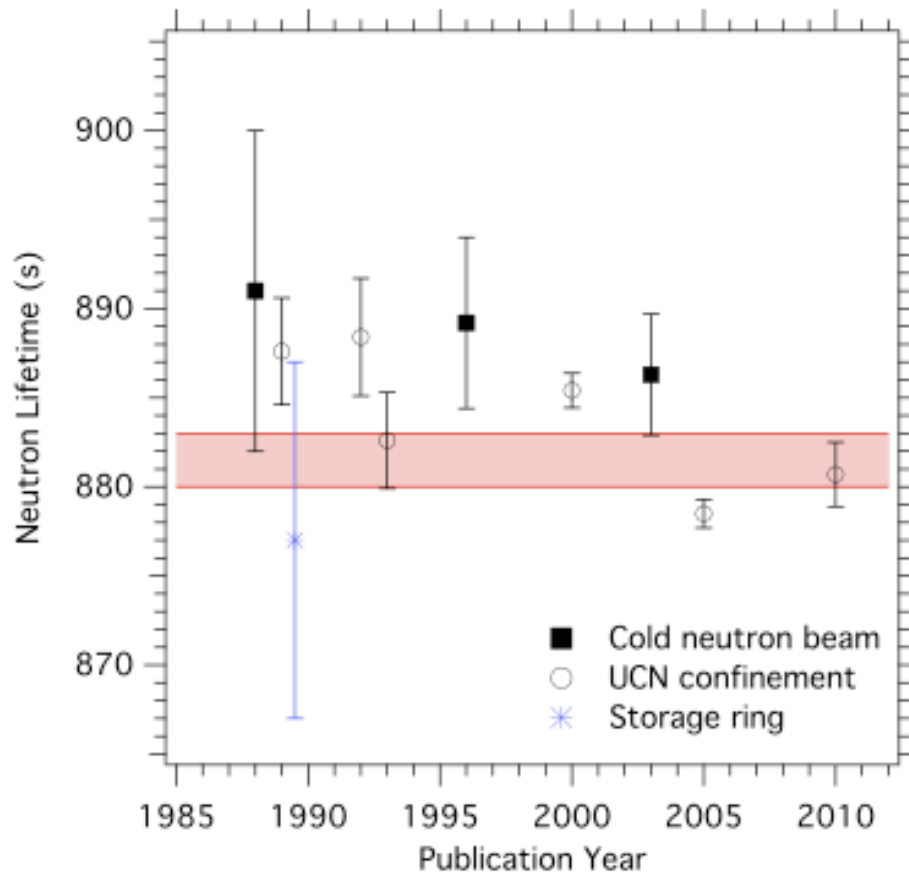
Neutron decay: $|V_{ud}|_n = 0.9765 \pm 0.0018$

Pion decay: $|V_{ud}|_{\pi^+} = 0.9728 \pm 0.0030$

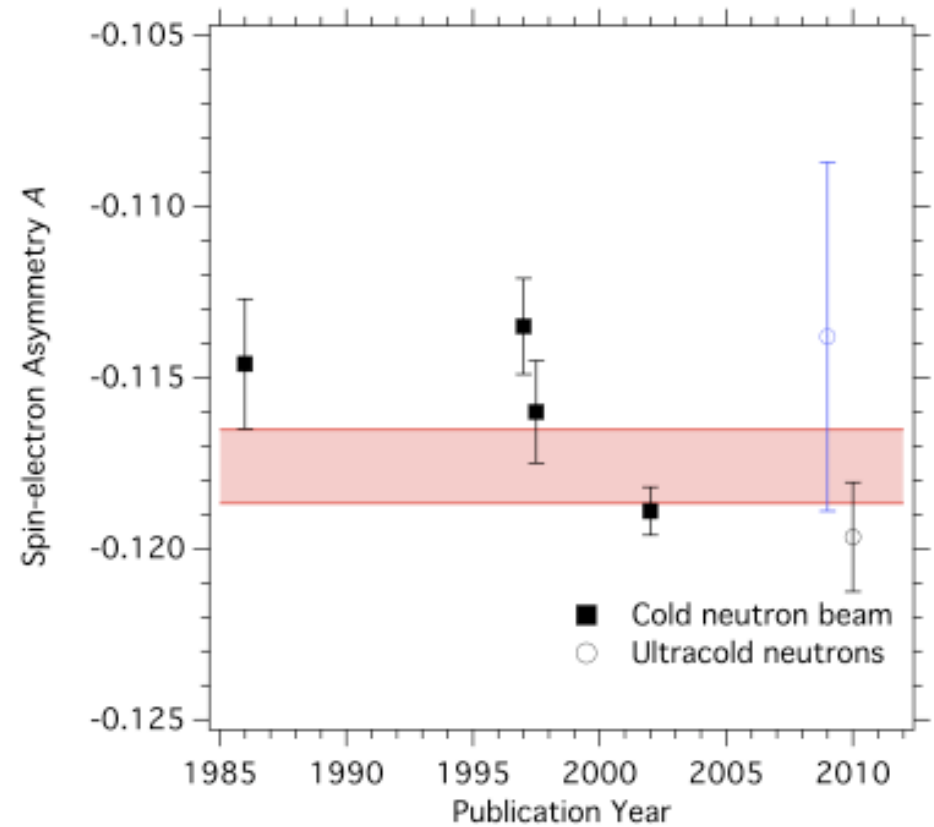


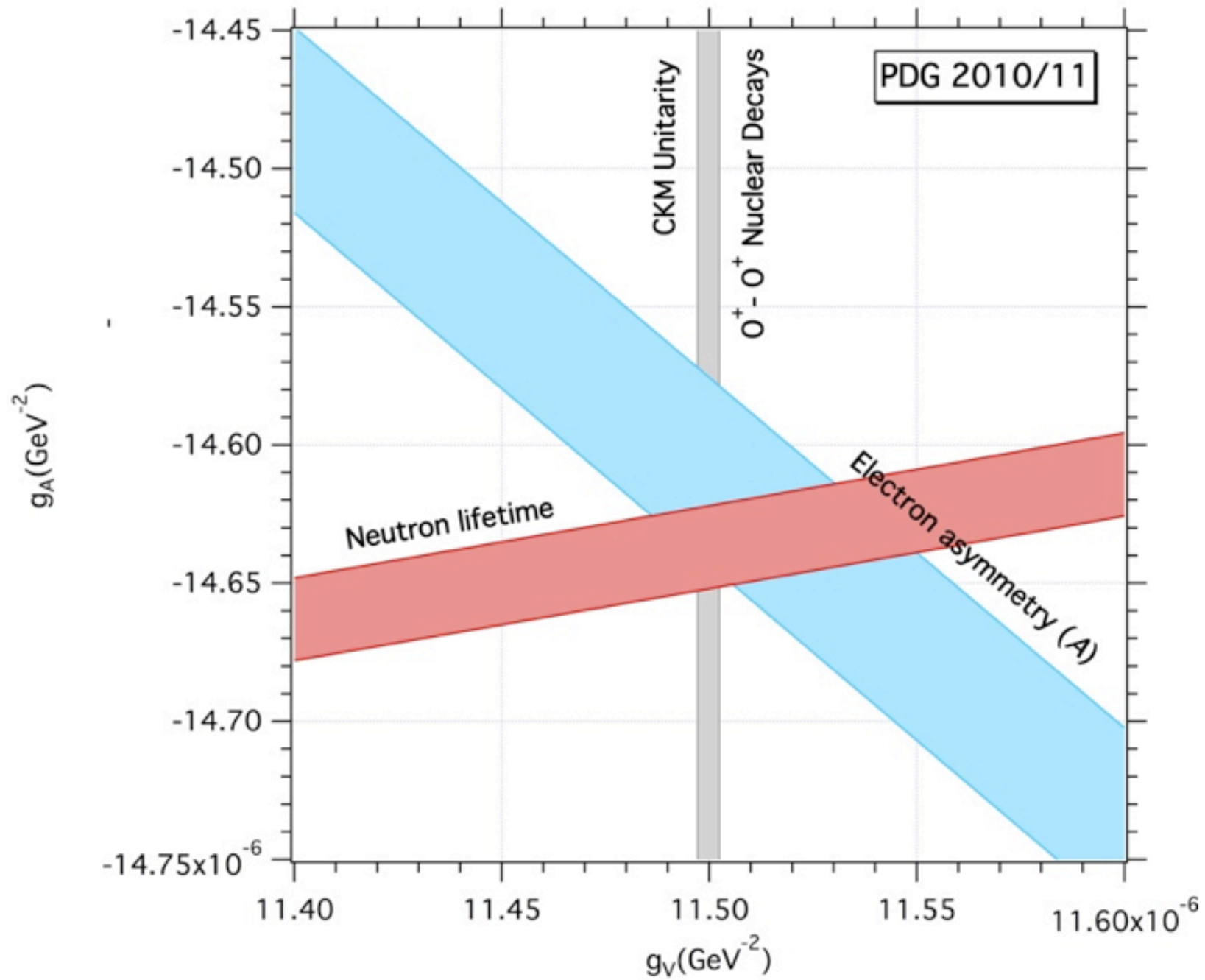
The Caveats ...

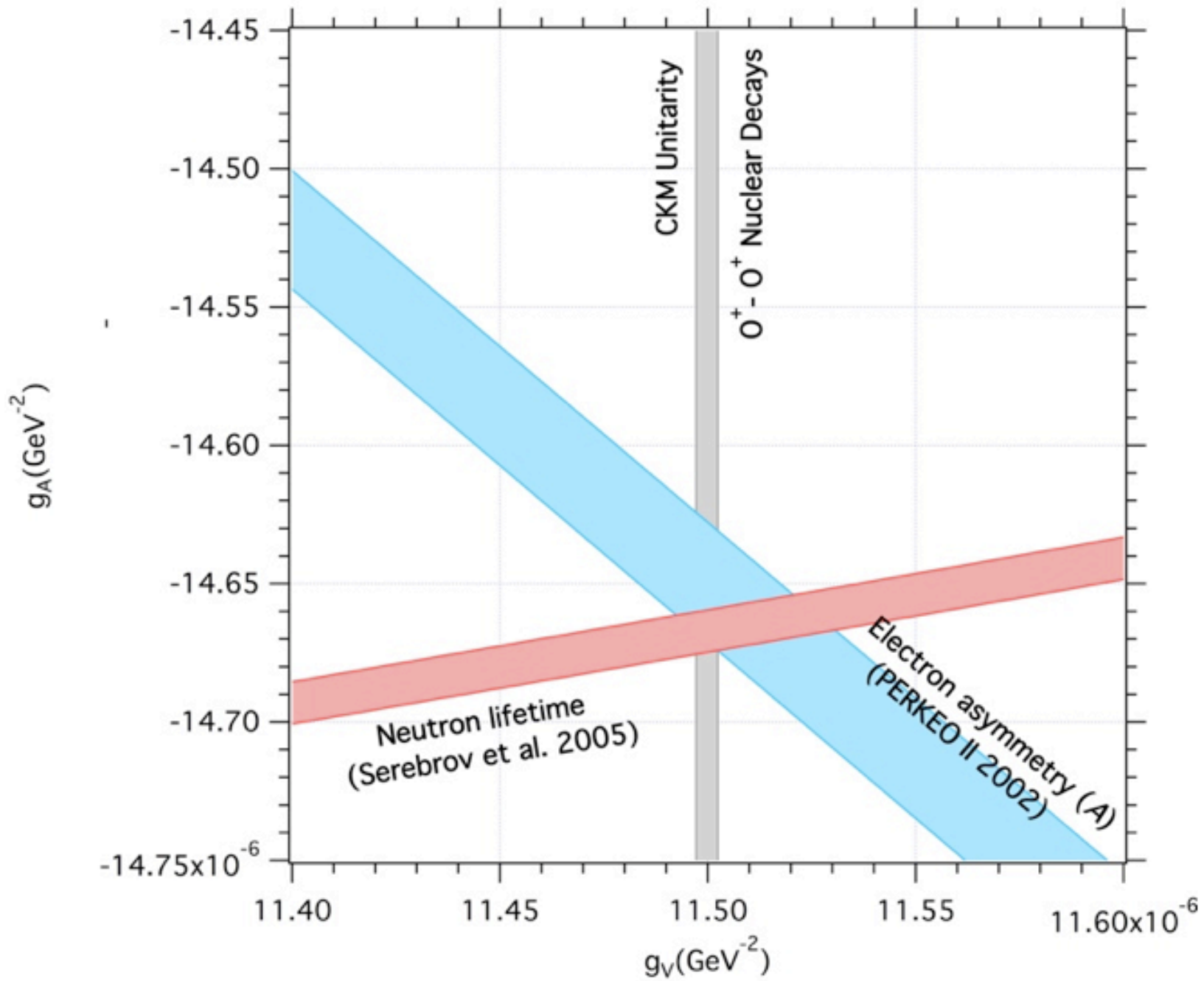
Lifetime



Lambda







Prospects

- Superaligned nuclear decays have done a remarkable job testing V-A theory and limiting additional interactions. The neutron system is not yet competitive, but it is closer than one might think.

$$\frac{\sigma_{\tau}}{\tau} = 0.17\%, \quad \frac{\sigma_{\lambda}}{\lambda} = 0.20\%, \quad \text{and} \quad \frac{\sigma_{th.}}{th.} = 0.04\%$$

- Large uncertainties come from underestimated systematic effects; fundamental limitations are not apparent. Note PDG scaling factors of 1.9 and 2.7.

Experimentation with Slow Neutrons

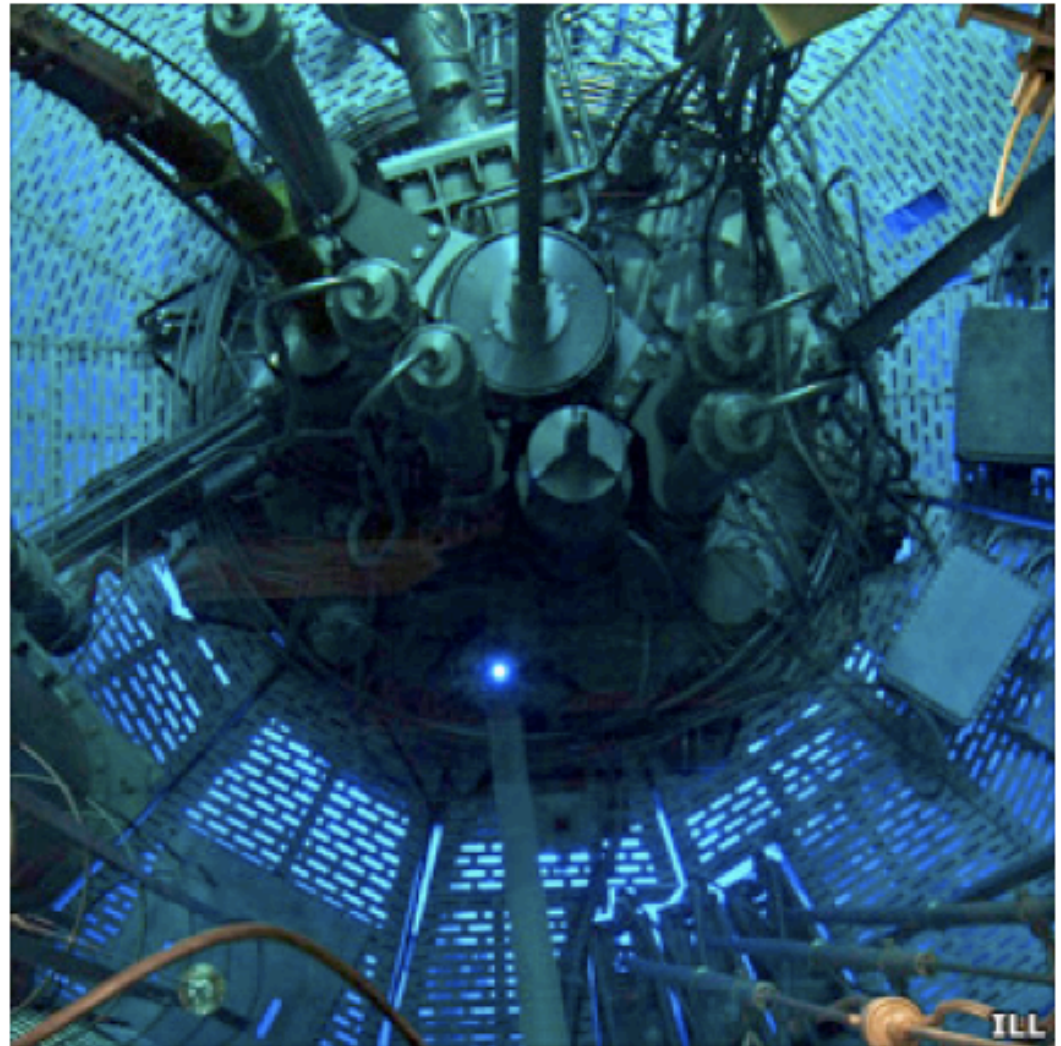
- The lifetime is too long. For a typical cold beam, 10^{-6} decay in detector volume. One must deal with systematics over a 15 minute period.
- Neutrons activate. The destiny of almost all neutrons is to become a potential background event.
- Neutrons are hard to manipulate. One must cool them over many decades of energy before magnetic fields, gravity, and optical potentials become relevant.
- Decay antineutrino is unobservable, and decay proton has an endpoint energy of only 751 eV.

Spectrum of Neutrons

Term	Energy	Velocity (m/s)	Temperature (K)	Wavelength (nm)
<i>fast</i>	> 500 keV	$>1 \times 10^7$		
<i>epithermal</i>	25 meV - 500 keV	2200 - 1×10^7		
<i>thermal</i>	25 meV	2200	300	0.18
<i>cold</i>	0.05 meV - 25 meV	100 - 2200	0.6 - 300	0.18 - 4
<i>very cold</i>	0.2 μ eV - 50 μ eV	6 - 100	0.002 - 0.6	4 - 64
<i>ultracold</i>	< 200 neV	< 6	< 0.002	> 64

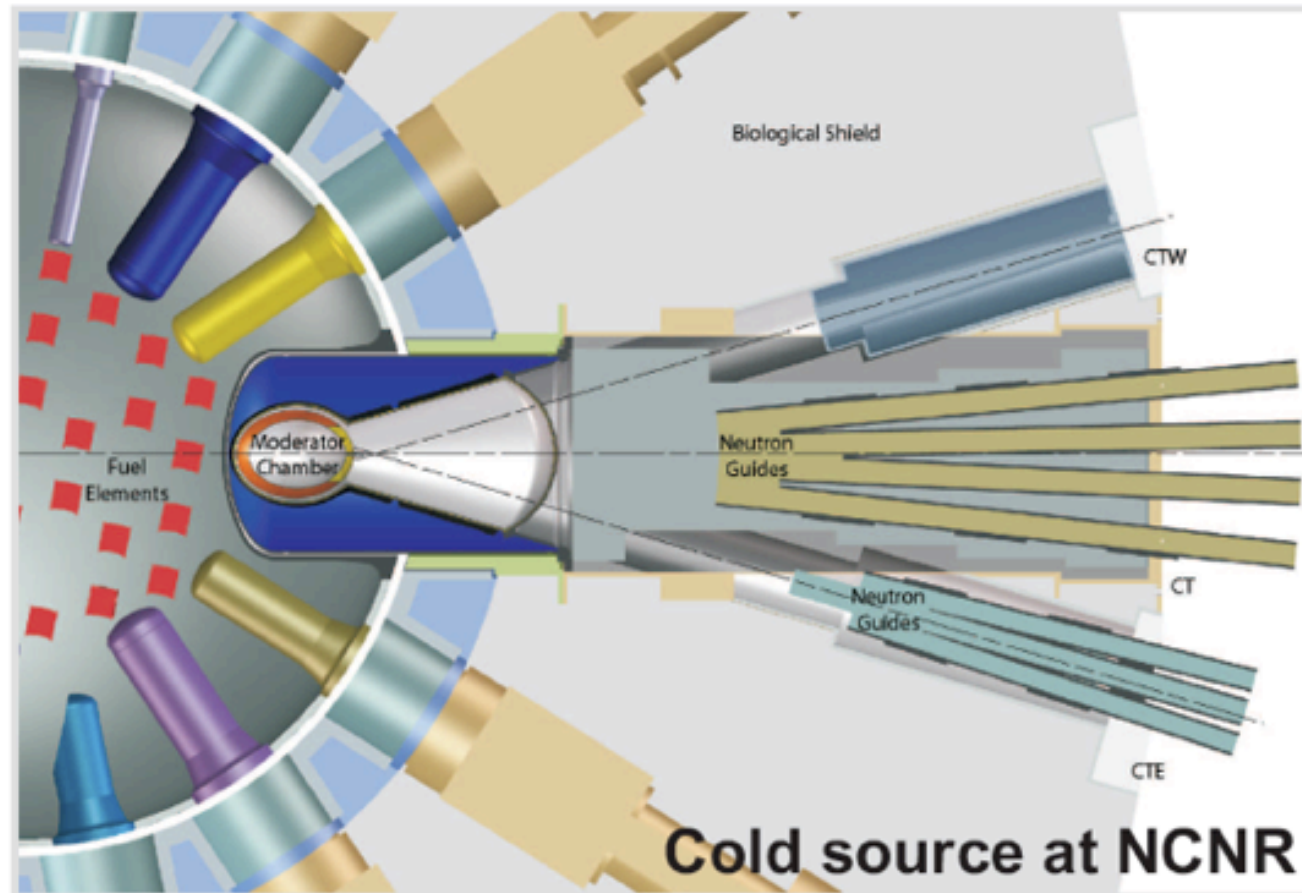
Neutron Production

- Fission source
 - Reactor based
 - Continuous
 - $\sim 2-3$ n/fission
- Spallation source
 - Accelerator based
 - Pulsed
 - 10^8 n/pulse



ILL reactor core

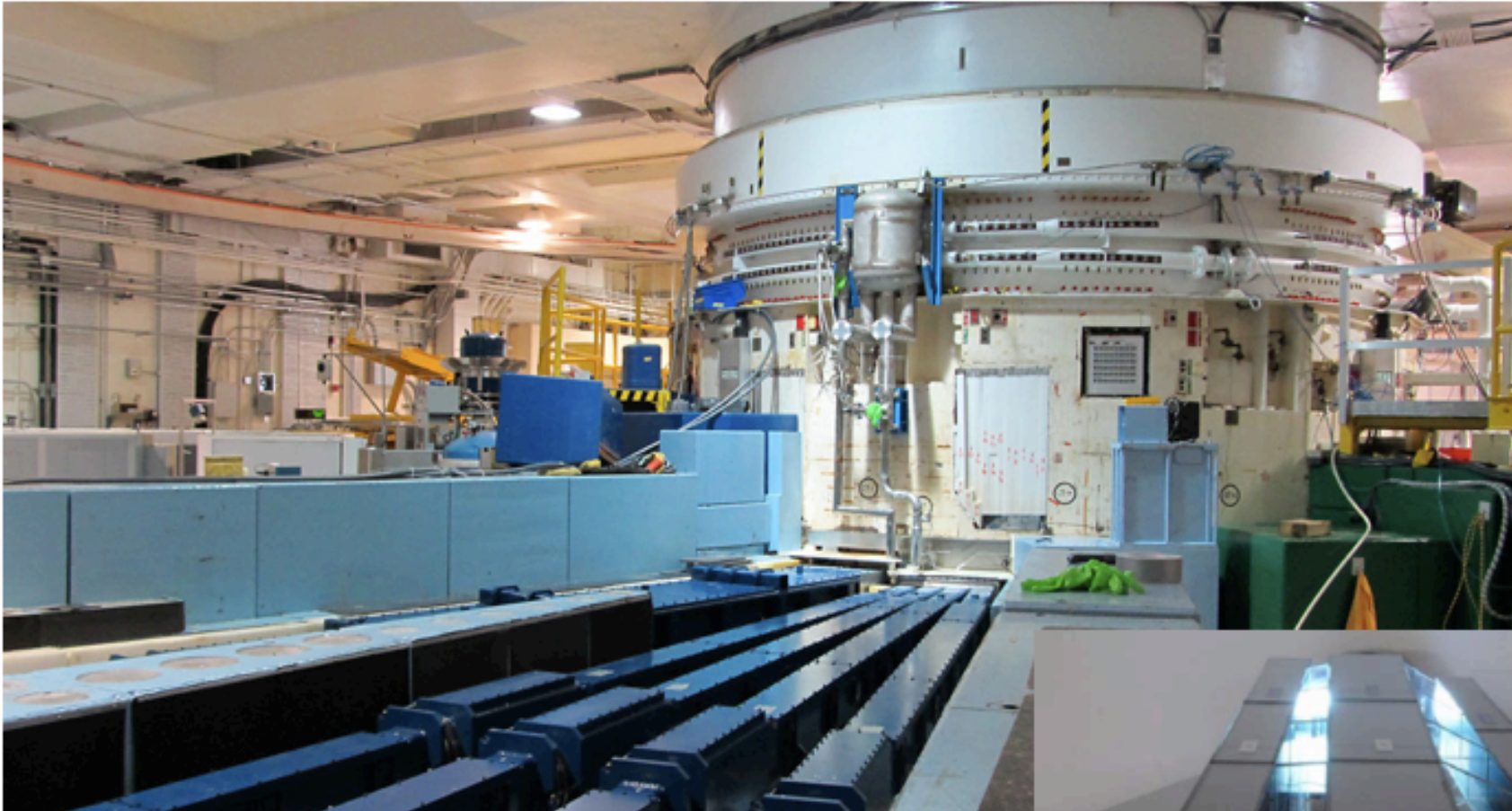
Cold Neutron Production



Neutrons partially thermalize in a cold source

- NCNR, liquid hydrogen (eff. 20K)
- Slow neutrons have larger probability of decaying in the detector
- neutron temp ≈ 40 K
- neutron energy ≈ 3.4 meV
- neutron velocity ≈ 800 m/s
- neutron flux (typ. $\approx 10^9$ cm² s⁻¹)

Cold Neutron Guides

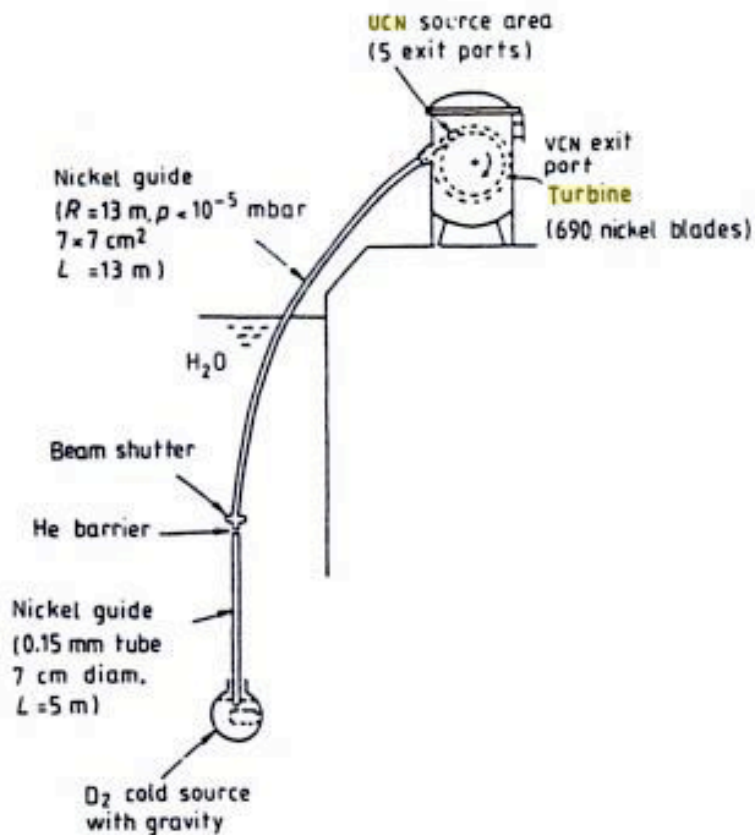


Critical angle for reflection

$$\sin\theta_C \leq \sqrt{(V_F/E_n)}$$

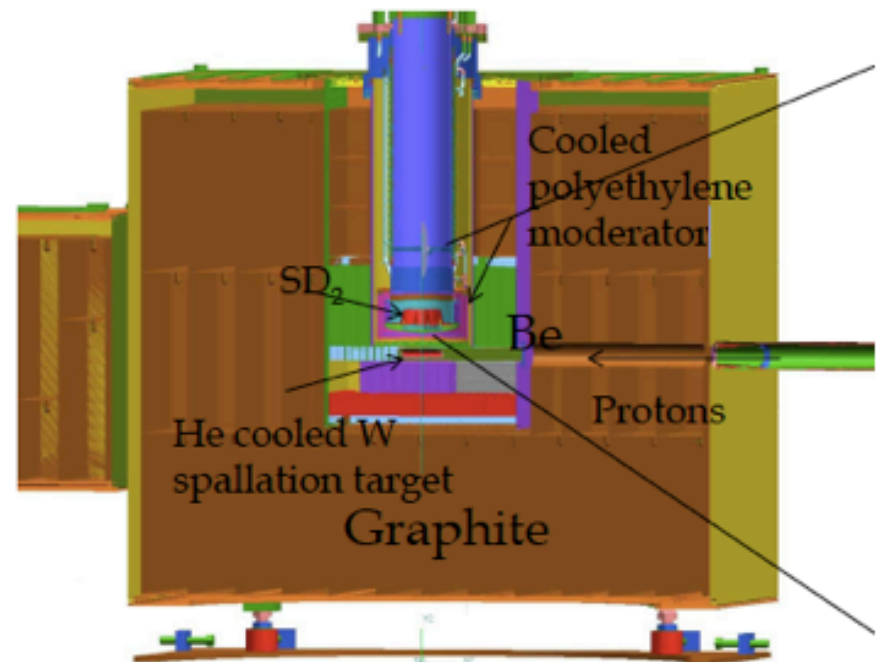
$$\text{where } V_F = \frac{2\pi\hbar^2}{m_n} Nb$$

Ultracold Neutron Production



ILL UCN source
(turbine)

from A. Steyerl

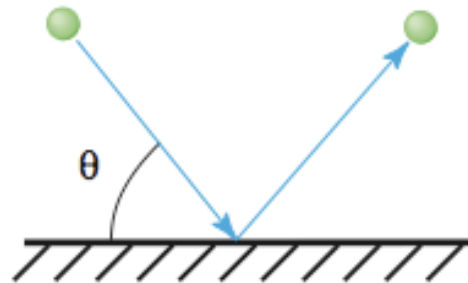


LANL UCN source
(solid deuterium)

from C. Morris

Ultracold Neutrons

- Strong Interaction



$$\sin \theta \leq \sin \theta_c = (V / E)^{1/2}$$

$$V = \frac{2 \pi \hbar^2}{m} Na$$

$$V \sim 10^{-7} \text{eV}$$

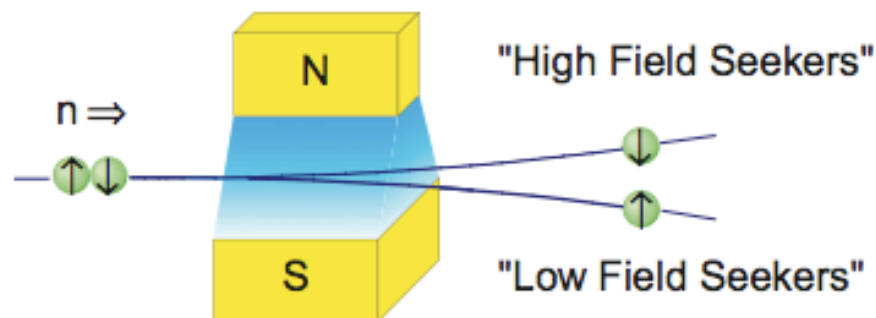
- Gravitational Interaction



$$V_g = mgh$$

$$10^{-7} \text{eV/m}$$

- Magnetic Interaction



$$V_m = -\vec{\mu} \cdot \vec{B}$$

$$10^{-7} \text{eV/T}$$

Facilities



Institut Laue-Langevin
60 MW Research Reactor
Grenoble, France

Facilities



NIST Center for Neutron Research
20 MW Research Reactor
Gaithersburg, MD

Facilities



Spallation Neutron Source at ORNL
1.4 MW
Oak Ridge, TN

Facilities



LANSCE at LANL
Los Alamos, NM

Neutron Lifetime: $N = N_0 e^{-\lambda t}$

1. "In beam" method: $-\frac{dN}{dt} = N\lambda$

Register the decay products from a well-defined volume traversed by a neutron beam of well-determined fluence rate.

2. Neutron "bottles": $N_1/N_2 = e^{-\lambda(t_1-t_2)}$

An ensemble of ultracold neutrons in confined gravitationally or materially. Measure the change in neutron population.

3. Measure the slope of exponential decay: $\ln(N/N_0) = -\lambda t$

Watch the decay product of an ensemble of neutrons as a function of time and measure the slope.

Lifetime Methods

<i>Technique</i>	<i>Detection</i>	<i>Issues</i>	<i>Approach</i>
(1) cold in-beam	proton trap and neutron counter	10^{-3} absolute efficiencies	fastidiousness
(2) UCN material confinement	neutron monitor	UCN energy distribution; wall effects; orbits	“cleaning”; spectrum measurement
(2') UCN magnetic confinement	neutron and/or proton monitor	UCN energy distribution; orbits	“cleaning”; spectrum measurement
(3) UCN in He-4 (or vacuum)	monitor decay electrons/protons	orbits, signal and background	more signal, less background

Proton Trap Experiment

M. S. Dewey, D.M. Gilliam, and J.S. Nico
National Institute of Standards and Technology

F.E. Wietfeldt
Tulane University

X. Fei and W.M. Snow
Indiana University



G.L. Greene
University of Tennessee/ORNL

J. Pauwels, R. Eykens, A. Lamberty, and J. Van Gestel
Institute for Reference Materials and Measurements, Belgium

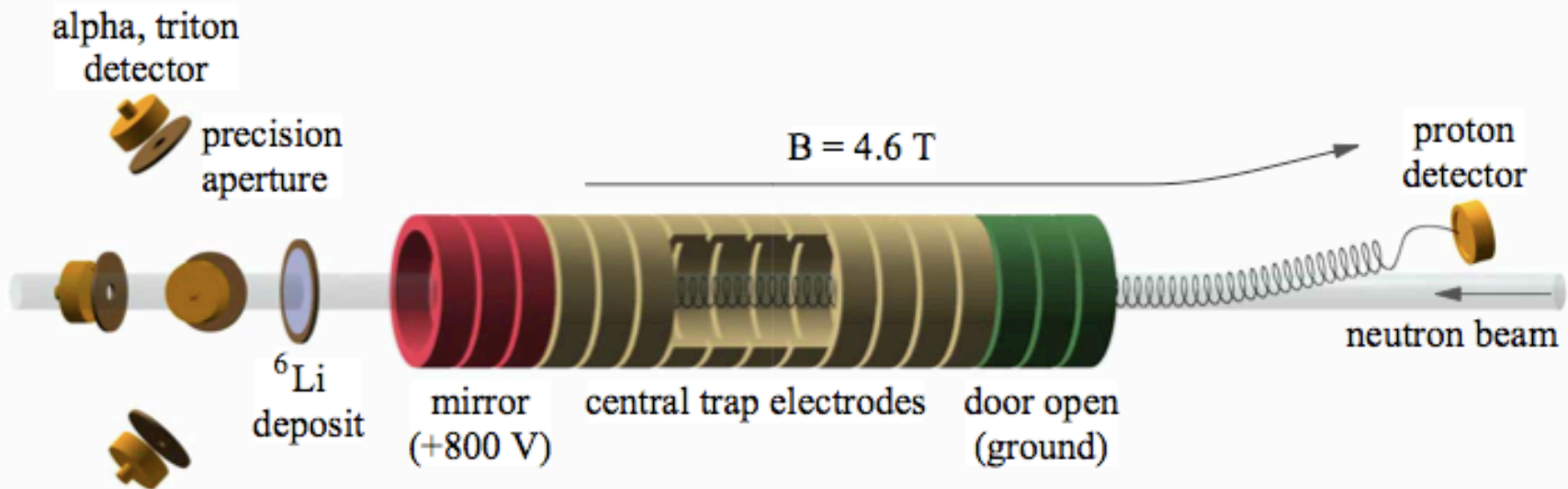
R.D. Scott
Scottish Universities Research and Reactor Centre, U.K.

NIST Center for Neutron Research Cold Neutron Guide Hall



The “in-beam” Method

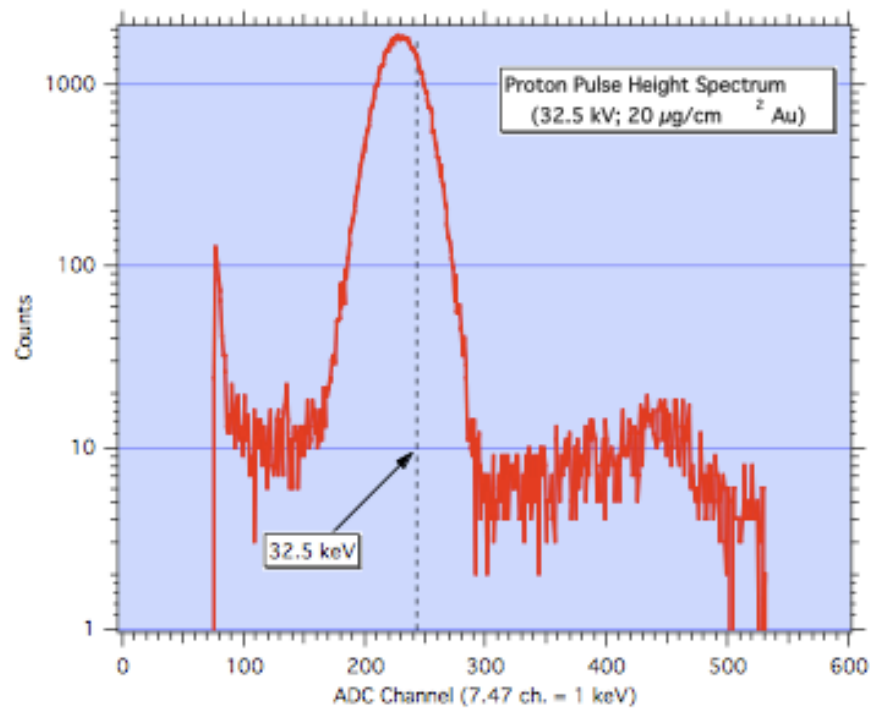
$$\tau = \frac{\dot{N}_{\alpha+t}}{\dot{N}_p} \left(\frac{\epsilon_p}{\epsilon_0 v_0} \right) (nl + L_{end})$$



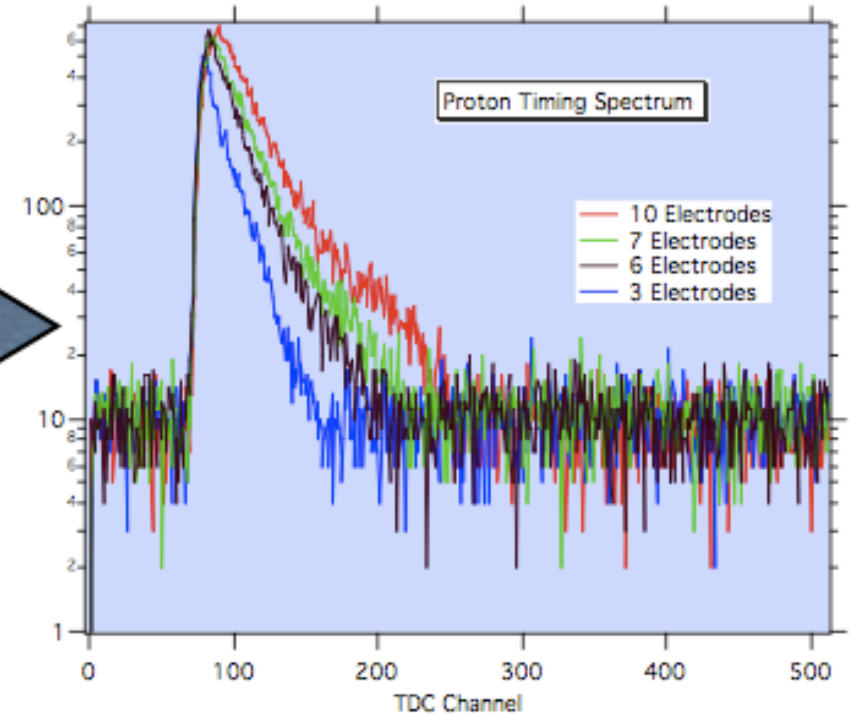
Requires absolute knowledge of neutron and proton counting.
Fit for lifetime and end effects....

Data: Proton Counting

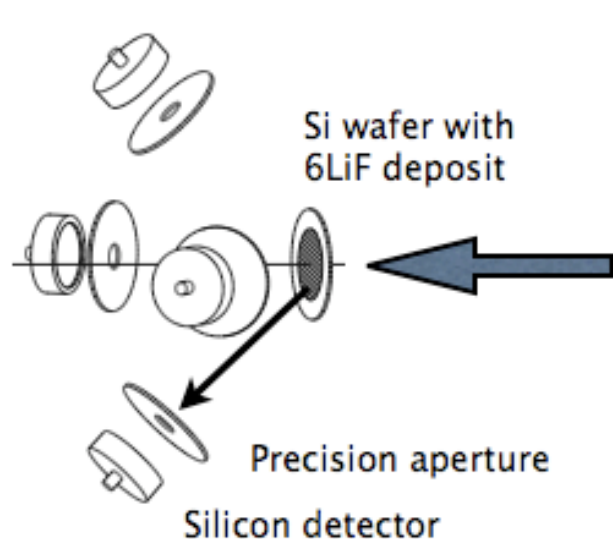
Energy Spectrum



Timing Spectra



Absolute Neutron Counting

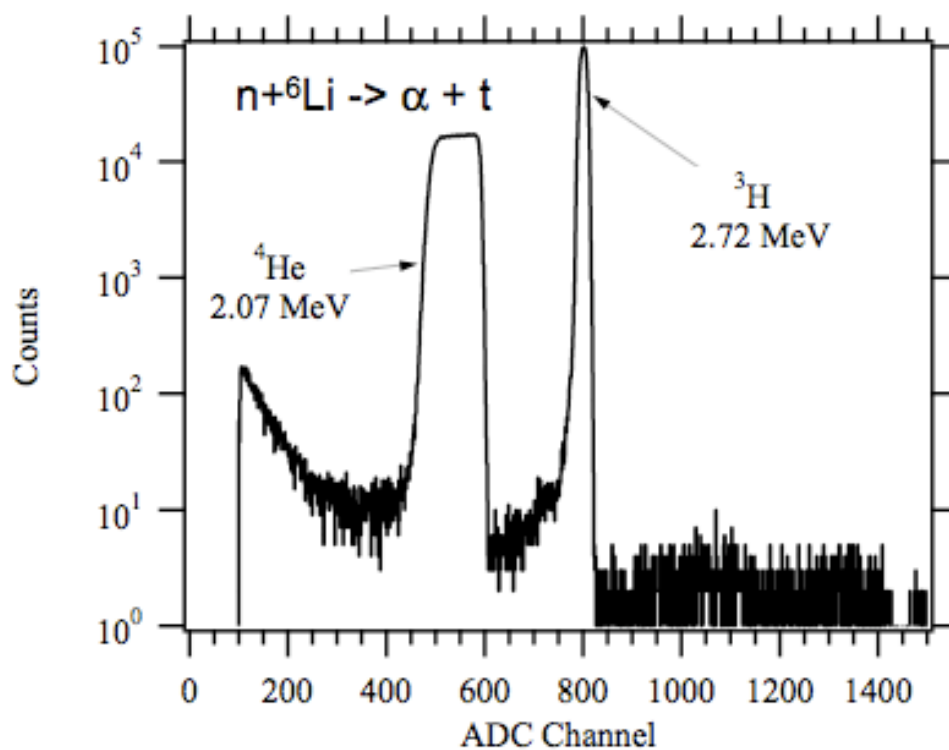
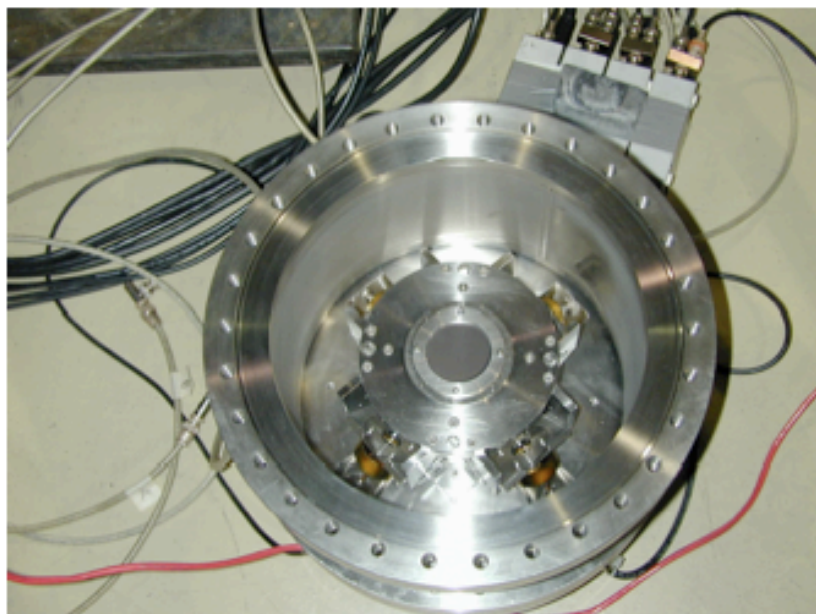


$$\epsilon = \frac{\sigma_{Li}}{4\pi} \int \int \Omega(x, y) \rho(x, y) \Theta(x, y) dx dy$$

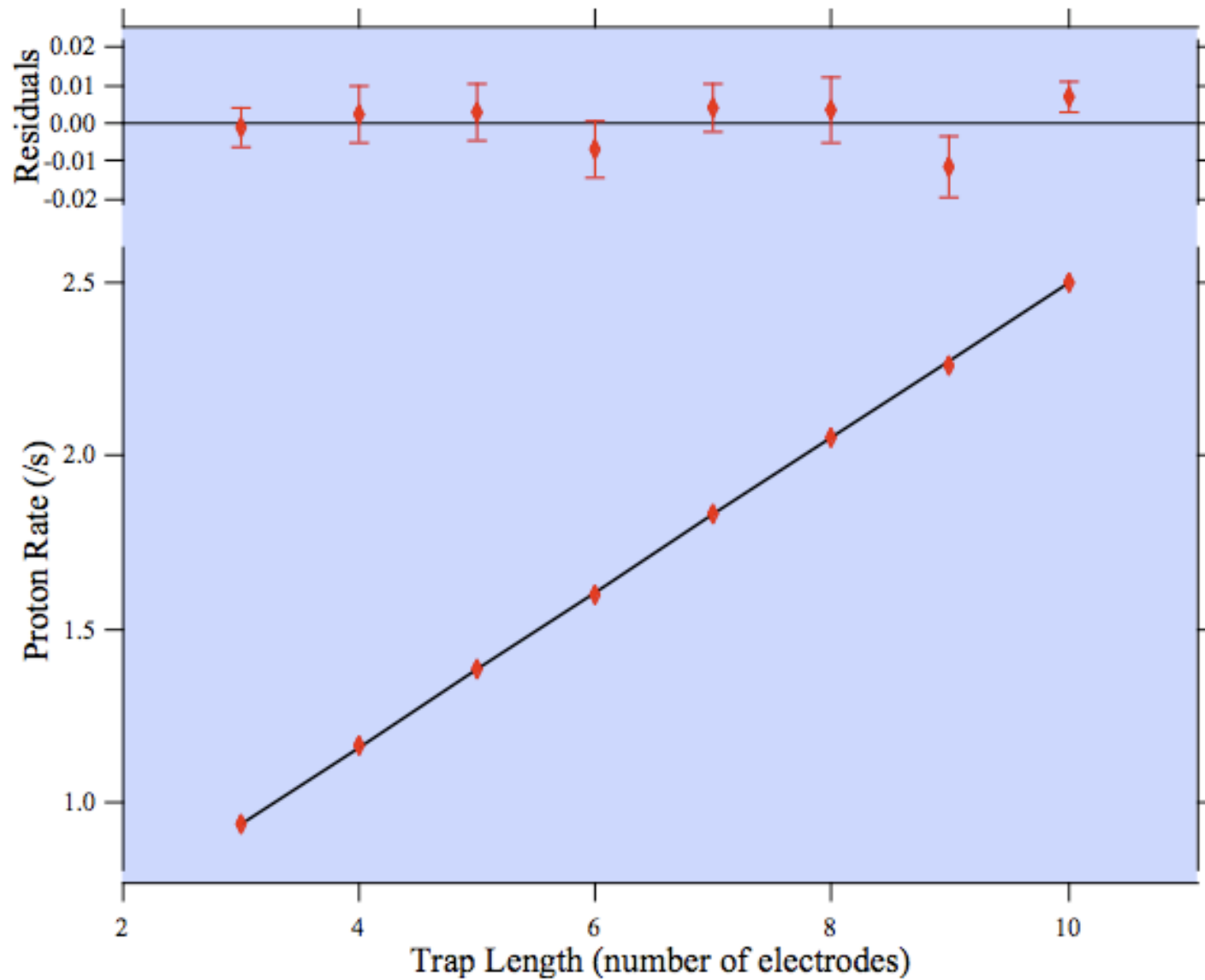
areal density of deposit

solid angle

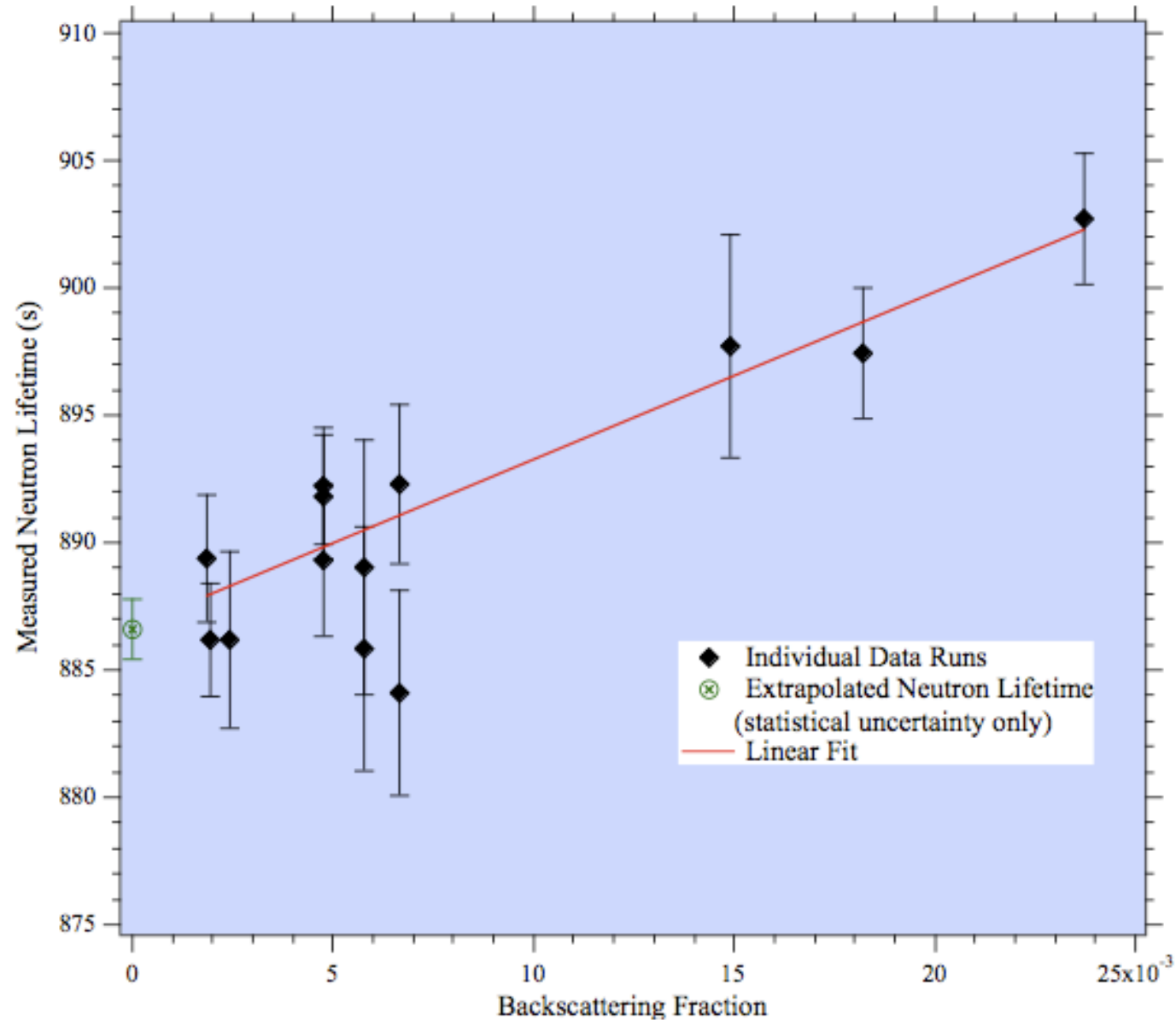
beam profile



Data: Extrapolation in Electrode Length



Result: Extrapolation in Backscattering



Systematics

Source of correction	Correction (s)	Uncertainty (s)	Section
⁶ LiF deposit areal density		2.2	IV A
⁶ Li cross section		1.2	IID
Neutron detector solid angle		1.0	IID 1
Absorption of neutrons by ⁶ Li	+5.2	0.8	IV A 2
Neutron beam profile and detector solid angle	+1.3	0.1	IV A 2
Neutron beam profile and ⁶ Li deposit shape	-1.7	0.1	IV A 2
Neutron beam halo	-1.0	1.0	IV B 2
Absorption of neutrons by Si substrate	+1.2	0.1	IV A 2
Scattering of neutrons by Si substrate	-0.2	0.5	IV A 3
Trap nonlinearity	-5.3	0.8	IV C
Proton backscatter calculation		0.4	IV D 3
Neutron counting dead time	+0.1	0.1	IID
Proton counting statistics		1.2	IV D 2
Neutron counting statistics		0.1	IID
Total	-0.4	3.4	

$\tau = (886.3 \pm 1.2[\text{stat}] \pm 3.2[\text{sys}]) \text{ s}$
 Result dominated by systematics related to neutron counting efficiency.

UCN Gravitational Trap Experiment at ILL

**A. Serebrov^{1,3}, V. Varlamov¹, A. Kharitinov¹, A. Fomin¹,
Yu. Pokotilovski², P. Geltenbort⁴, J. Butterworth⁴,
I. Krasnoschekova¹, M. Lasakov¹, K. Schechenbach⁵,
R. Taldaev¹, A. Vassiljev¹, and O. Zherebtov¹**

1 - Petersburg Nuclear Physics Institute

2 - Joint Institute for Nuclear Research, Dubna

3 - Paul Scherrer Institut

4 - Institute Laue-Langevin

5 - Technische Universität München



Method of “Gravitrap” Experiment

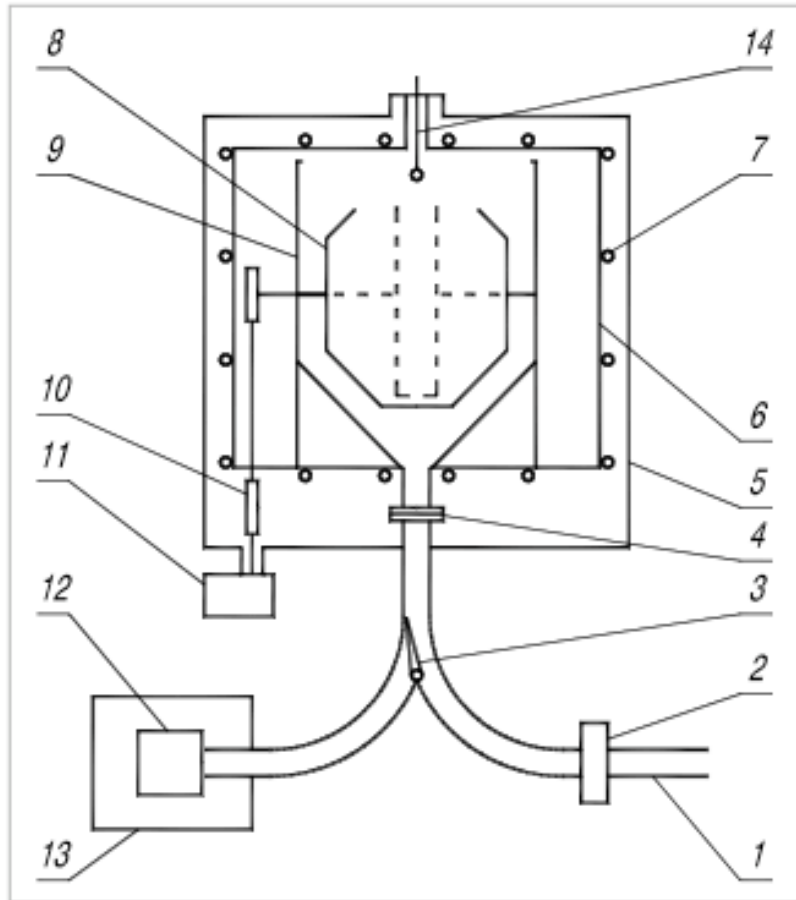
- Confine UCNs gravitationally in material “bottle” (low temperature fomblin oil).
- Storage lifetime as a function of UCN energy and temperature.
- For an ideal wall (step function potential):

$$\lambda_{st} = \lambda_n + \eta\gamma$$

where $\eta = -Im(V_F)/Re(V_F) =$ wall loss coefficient
 $\gamma =$ loss-weighted collision frequency

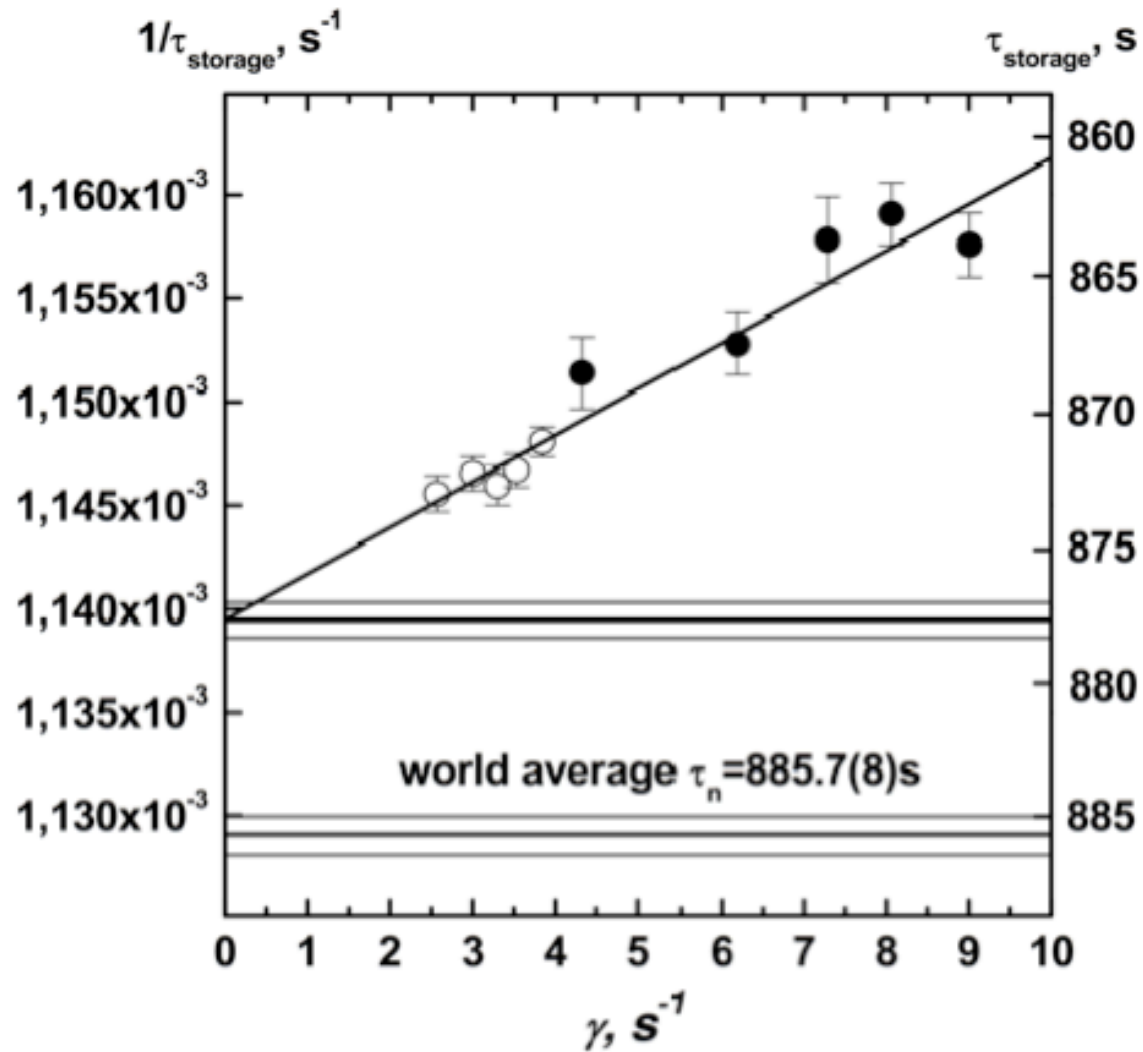
- Use two traps to reduce systematics: measure $\lambda_{st}^1, \lambda_{st}^2$
 calculate γ^1, γ^2
- Extrapolate neutron lifetime as function of gamma.

Gravitrap UCN storage



- 1 – neutron guide from UCN Turbine;
- 2 – UCN inlet valve;
- 3 – beam distribution flap valve;
- 4 – aluminium foil (now removed);
- 5 – “dirty” vacuum volume;
- 6 – “clean” (UHV) vacuum volume;
- 7 – cooling coils;
- 8 – UCN storage trap;
- 9 – cryostat;
- 10 – mechanics for trap rotation;
- 11 – stepping motor;
- 12 – UCN detector;
- 13 – detector shielding;
- 14 – evaporator

Extrapolation



Result and Systematics

Size extrapolation	Value,s	Uncertainty, s
n-lifetime	878.07	0.73
Systematic effect	Value,s	Uncertainty, s
Method of γ values calculation	0	0.236
Influence of mu-function shape	0	0.144
Spectrum uncertainties	0	0.104
Uncertainties of traps sizes(1mm)	0	0.058
Influence of the residual gas	0.40	0.024
Uncertainty of LTF critical energy (20 neV)	0	0.004
Total systematic effect	0.40	0.30

$$\tau_n [\text{s}] = 878.5 \pm 0.7_{\text{stat}} \pm 0.3_{\text{syst}}$$

“Gravitrapp II”



1. Statistical accuracy $0.7 \text{ s} \rightarrow 0.2 \text{ s}$;
2. Vacuum correction $0.4 \text{ s} \rightarrow 0.04 \text{ s}$;
3. Measurement in two positions without disassembling;
4. Improvement of loss factor ? $2 \times 10^{-6} \rightarrow 10^{-6}$?
5. Expected accuracy: statistical $\sim 0.2 \text{ s}$
 systematical $< 0.1 \text{ s}$

Magnetically Trapped UCN using Superfluid He-4

**K.J. Coakley, M. S. Dewey, M. Huber, P. Hughes,
H.P. Mumm, A.K. Thompson**

National Institute of Standards and Technology

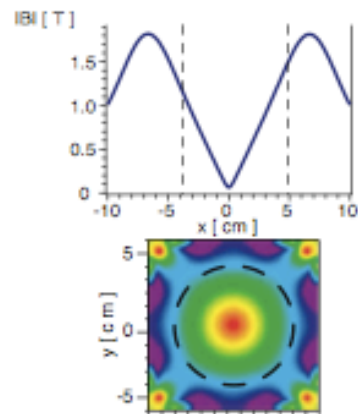
**R. Golub, C. Huffer, P.R. Huffman, E. Korobkina,
C. O'Shaughnessy, K. Schelhammer, B. Schmookler**

North Carolina State University

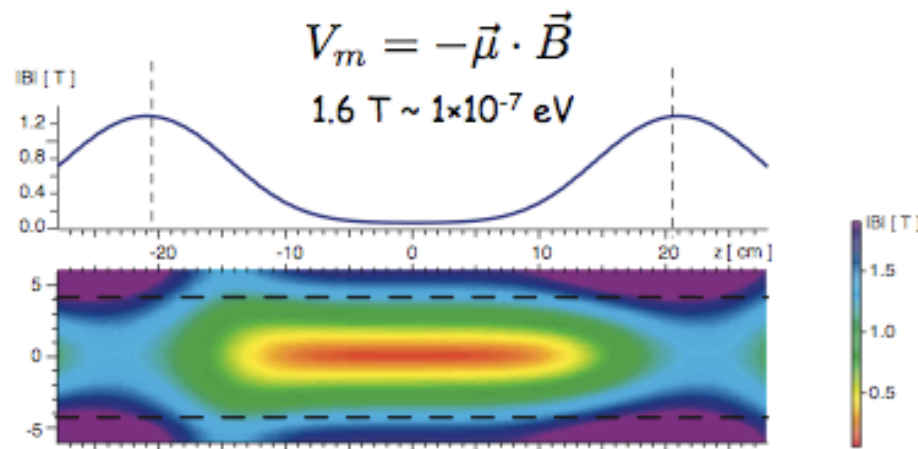
L. Yang
SLAC



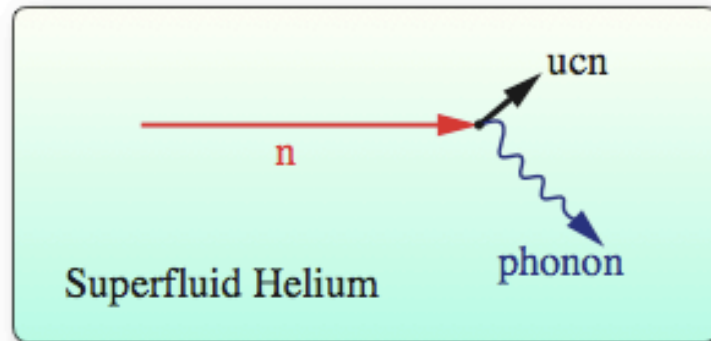
Radial Confinement



Axial Confinement



Superthermal process



$$\vec{p}_{UCN} = \vec{p}_n - \vec{q}_{phonon}$$

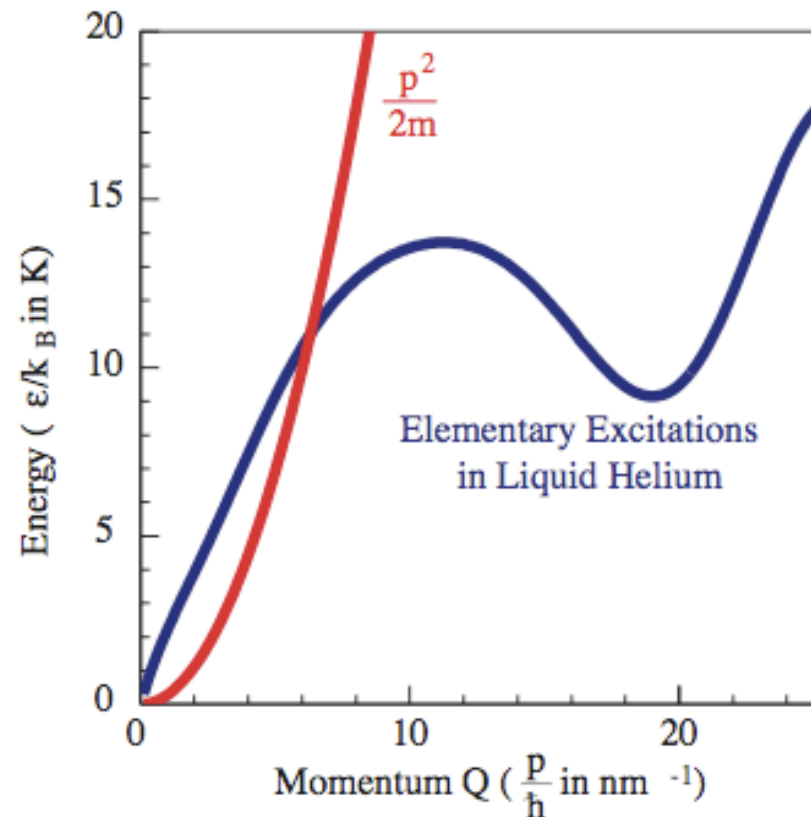
$$E_{UCN} = E_n - E_{phonon}$$

- ~0.95 meV (12 K or 0.89 nm) neutrons can scatter in liquid helium to near rest by emission of a single phonon.

- Upscattering

(by absorption of an 12 K phonon)

• Population of 12 K phonons $\sim e^{\frac{-12K}{T_{bath}}}$



Magnetic Trapping

Prototype trap

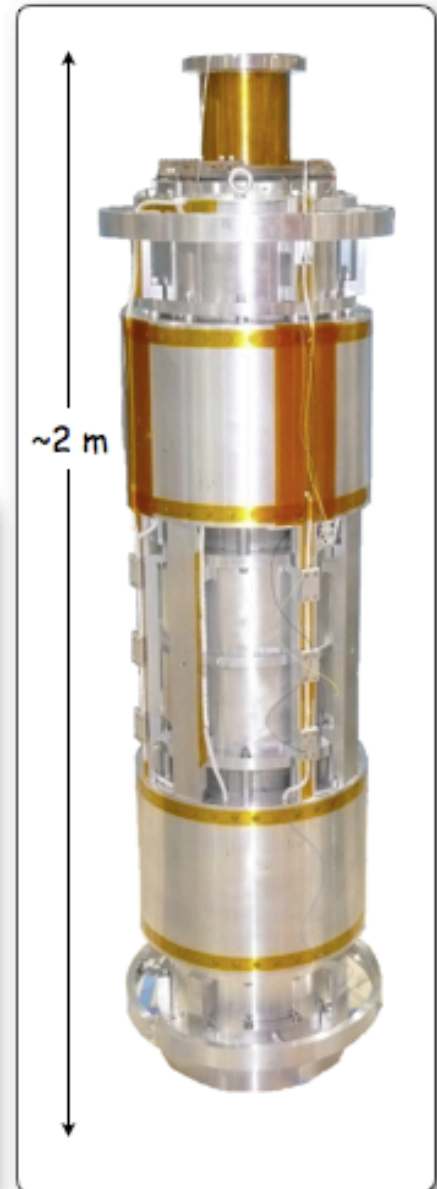
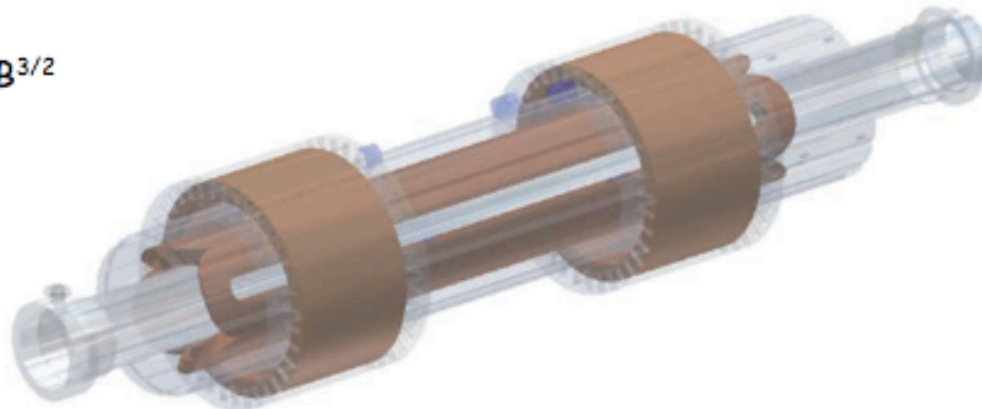
1.1 T deep trap: $n_T \propto B^{3/2}$

1.5 L volume: $n_T \propto V$

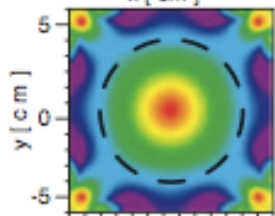
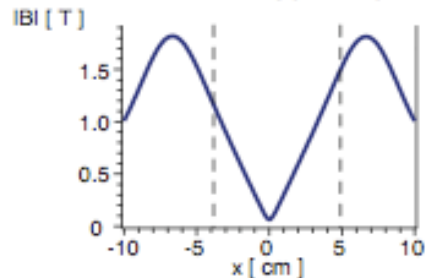
KEK Trap

3.1 T trap depth

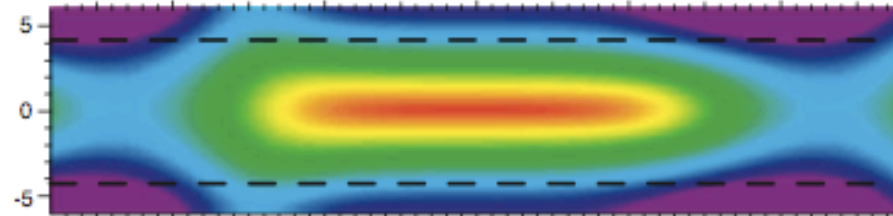
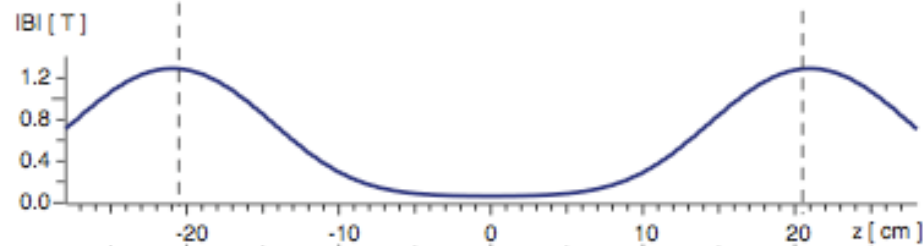
~9 L



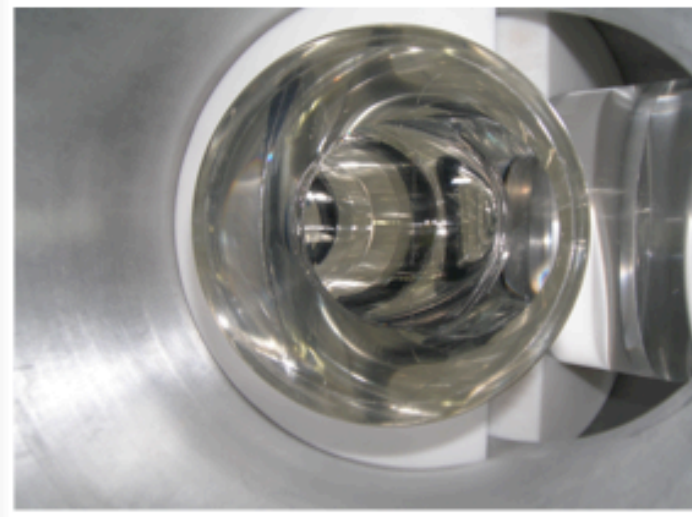
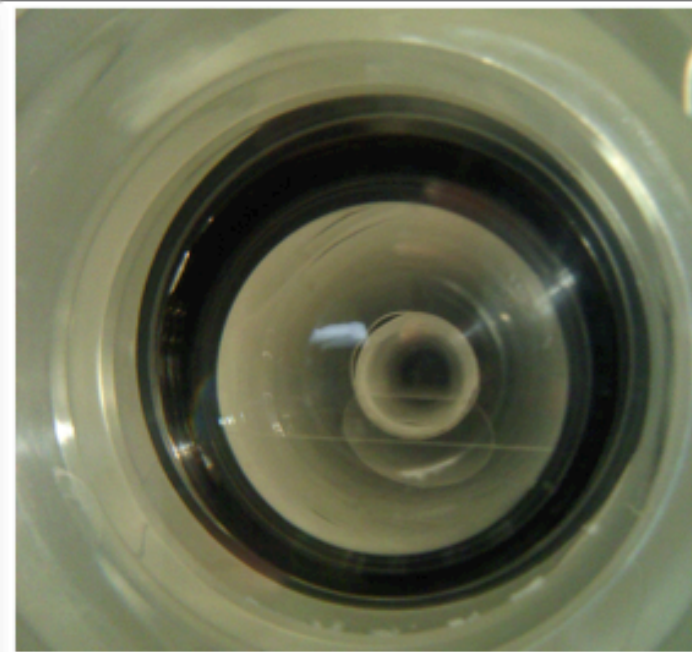
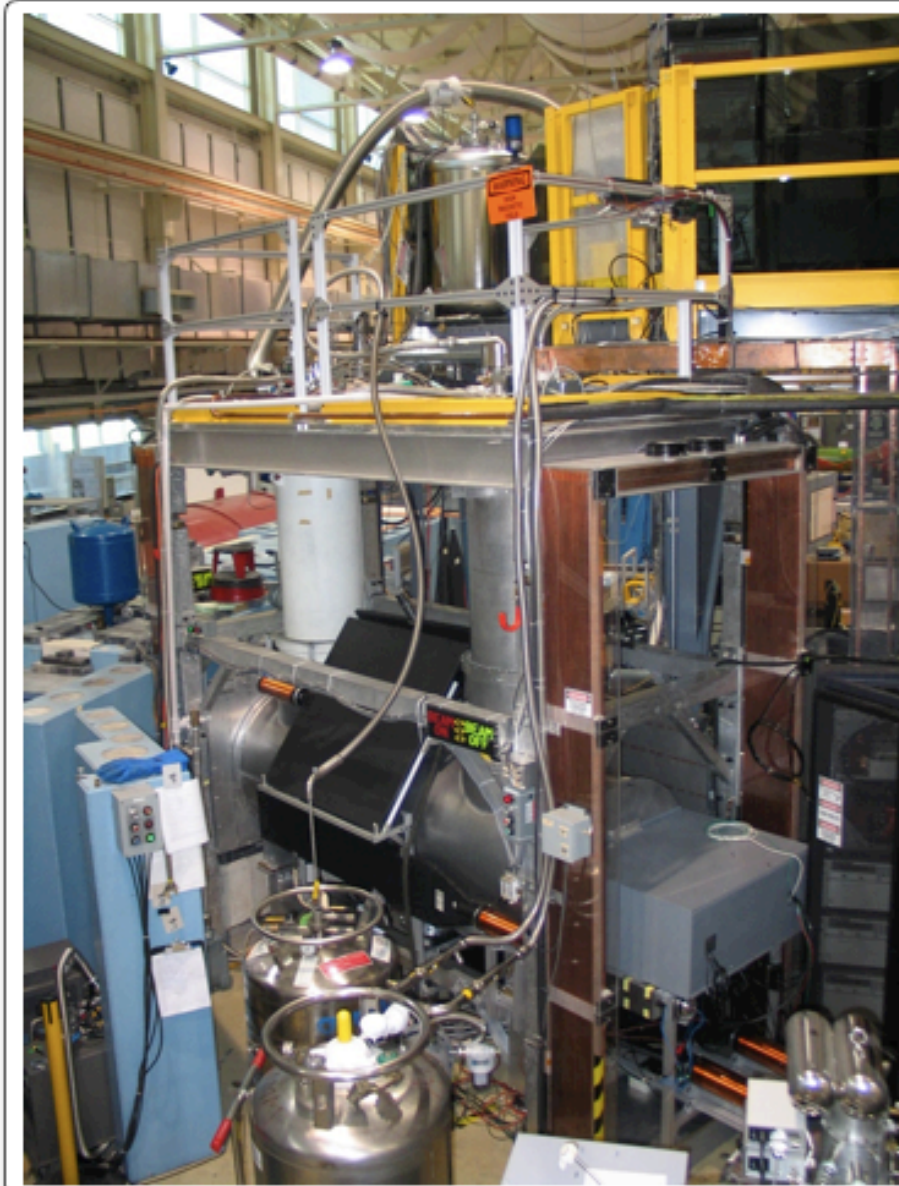
Radial Confinement
(Prototype trap)



Axial Confinement
(Prototype trap)

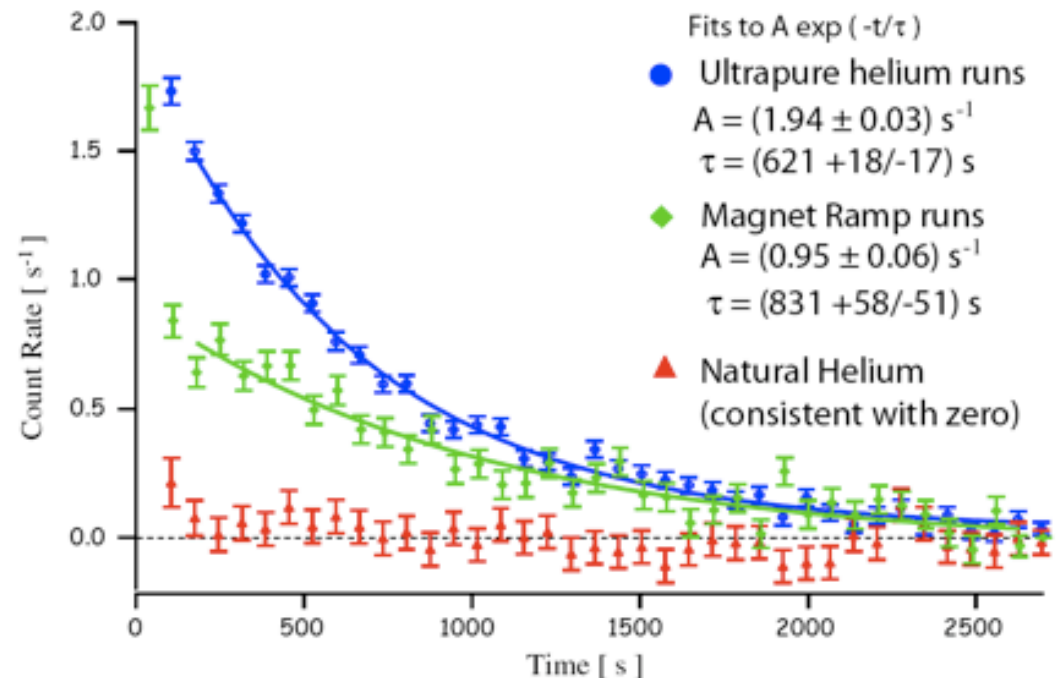


Apparatus



Prospects

- Current value $\tau = (831^{+58}_{-51})$ s
- Studies of systematics from previous measurement show they are tractable at approximately the 1 s level.
- Key components of the next generation experiment have been tested and are operational.
- Two test cooldowns below 4 K. Cooldown in progress for first data run.



Goal of a 1-2 s measurement

More experiments and ideas...

➤ I. Altarev, F.J. Hartmann, A. Müller, S. Paul, R. Picker, O. Zimmer
(*Technische Universität München*)

- Superconducting magnetic and gravitational trap
 - Detect decay protons
 - Monitor depolarization

➤ LANL, SNS, Caltech, NCSU

- UCN in vacuum quadrupole trap
 - Monitor decay electrons

➤ Ezhov et al. (*Petersburg, ILL, T. U. Munich*)

- Confinement using permanent magnets
 - Count UCN

➤ Shimizu et al. (*J-PARC*)

- Cold neutron beam and He-3 TPC
 - Absolute counting

Precision < 1 s

Experimental Efforts on λ

Spin-electron asymmetry, A

- PERKEO at ILL (cold beam) - data run completed
- UCNA at LANL (ultracold neutrons) - in progress

Antineutrino-electron correlation, a

- aSPECT at ILL (cold beam) - in progress
- aCORN at NIST (cold beam) - in progress
- nab/abBA at SNS (cold, pulsed beam) - design stage

...

UCNA Collaboration

California Institute of Technology

R. Carr, B. Filippone, A. Perez Galvan, [K. Hickerson](#), J. Liu, [M. Mendenhall](#), [R. Russell](#),
[R. Schmid](#)

Idaho State University

[R. Rios](#), E. Tatar

Indiana University

C.-Y. Liu

Institut Laue-Langevin

P. Geltenbort

Los Alamos National Laboratory

T. J. Bowles, S. Currie, S. Clayton, G. Hogan, T. Ito, M. Makela, C. L. Morris, J.
Ramsey, A. Saunders (co-spokesperson), S. Seestrom, W. Sondheim

North Carolina State University/TUNL/Princeton

H. O. Back, [L. Broussard](#), [J. Hoagland](#), [A. T. Holley](#), [R. W. Pattie](#), [B. M. VornDick](#), A. R.
Young (co-spokesperson), [B. A. Zeck](#)

Texas A&M University

D. Melconian

University of Kentucky

[B. Hona](#), B. Plaster, [H. Yan](#)

University of Washington

A. Garcia, [S. Hoedl](#), [A. Sallaska](#), [S. Sjue](#), C. Wrede

University of Winnipeg

J. Martin

Virginia Polytechnic Institute and State University

[R. R. Mammei](#), M. Pitt, R. B. Vogelaar

The Standard Model and Beyond: V_{ud}

- Together with τ_n and the muon lifetime, measurements of g_A permit a nuclear structure independent extraction of CKM matrix element V_{ud}
- **Assuming τ available at 0.1s level, require $\delta A/A \sim 0.1\%$** to produce an uncertainty of ± 0.00022 in V_{ud} , the current value from $0^+ \rightarrow 0^+$ decays
 - Cross-check with neutrons would provide valuable confirmation
 - Recent theoretical activity probing accuracy of nuclear structure corrections (no serious challenges at present)
- V_{ud} critical input to unitarity test, one of the most stringent constraints on “chirality conserving” interactions such as V-A:
 - 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

J. Hardy and I. Towner, Phys. Rev. C 79, 055502 (2009)

I.Towner and J. Hardy, Phys. Rev. C 82, 065501 (2010)

Antonelli *et al*, Phys. Rep. **494**, 197 (2010)

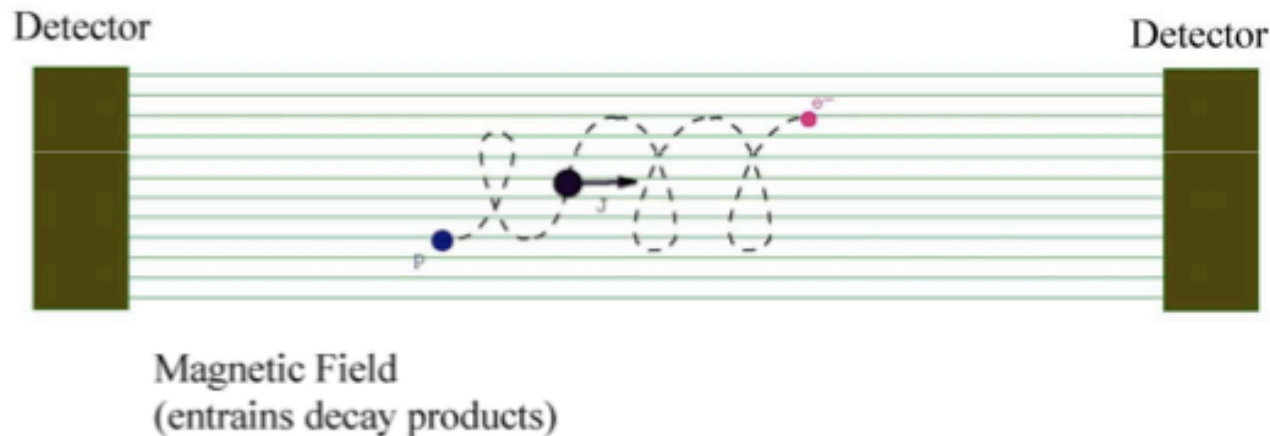
Ramsey-Musolf, Phys. Rev. D **62**, 056009 (2000)

Cirigliano *et al*, Nucl. Phys. B**830**, 95 (2010)

from A. Young

A General Measurement Strategy

β directional distribution: $1 + P \frac{v}{c} A(E) \cos\theta$
(polarized neutrons)



$$A(E) \propto \frac{N_+ - N_-}{N_+ + N_-}$$

We must determine P (the average neutron polarization), v and E
(the β velocity and energy) and $\cos\theta$

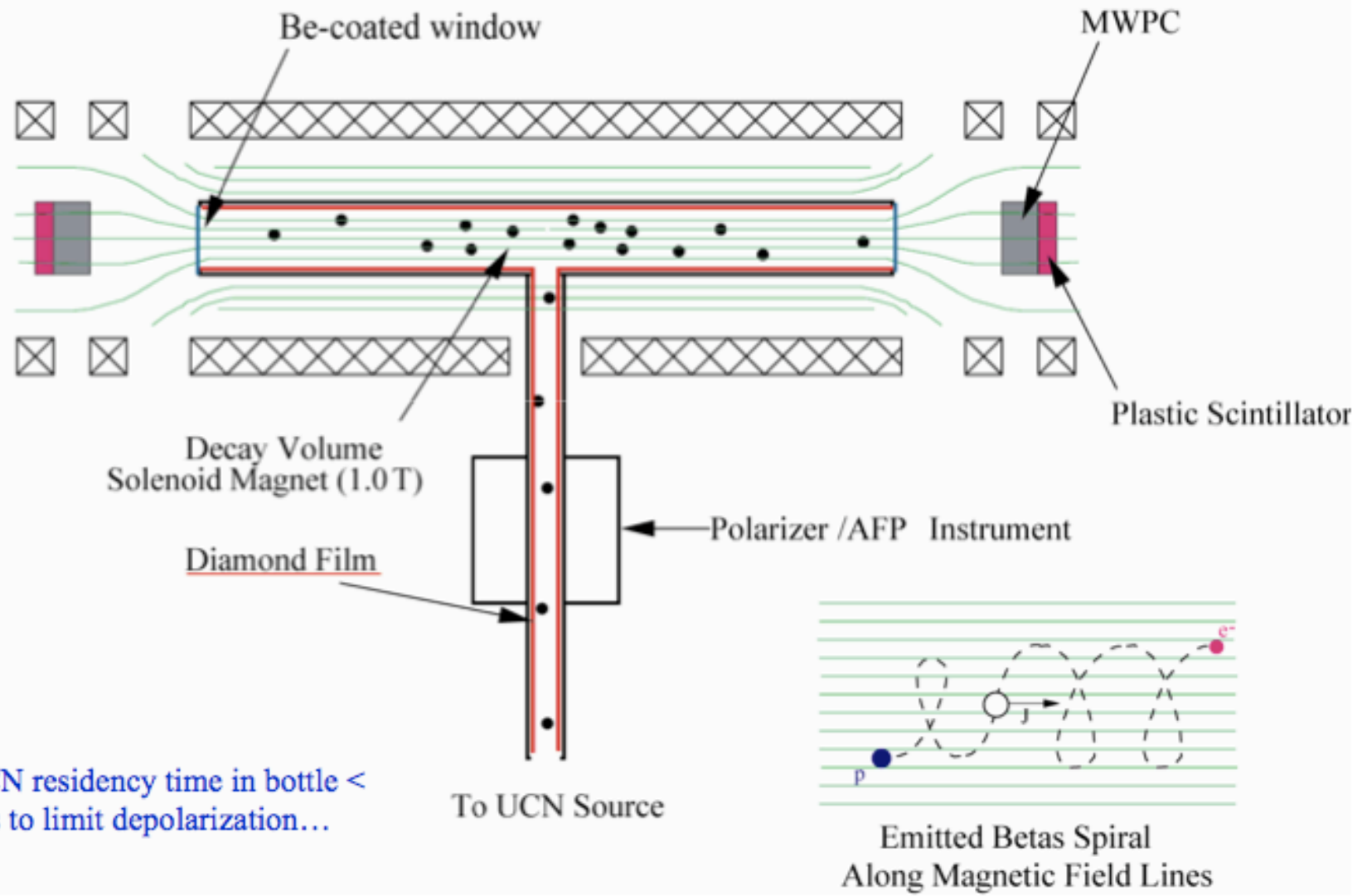
N_+, N_-, v and E : Signals from the detector arrays \rightarrow singles backgrounds subtraction critical

$\cos\theta$: use magnetic fields to capture all decay products $\rightarrow \langle \cos\theta \rangle = \pm 1/2$ (with small corrections)

P : polarize UCN, limit depolarization and measure depolarized UCN fraction

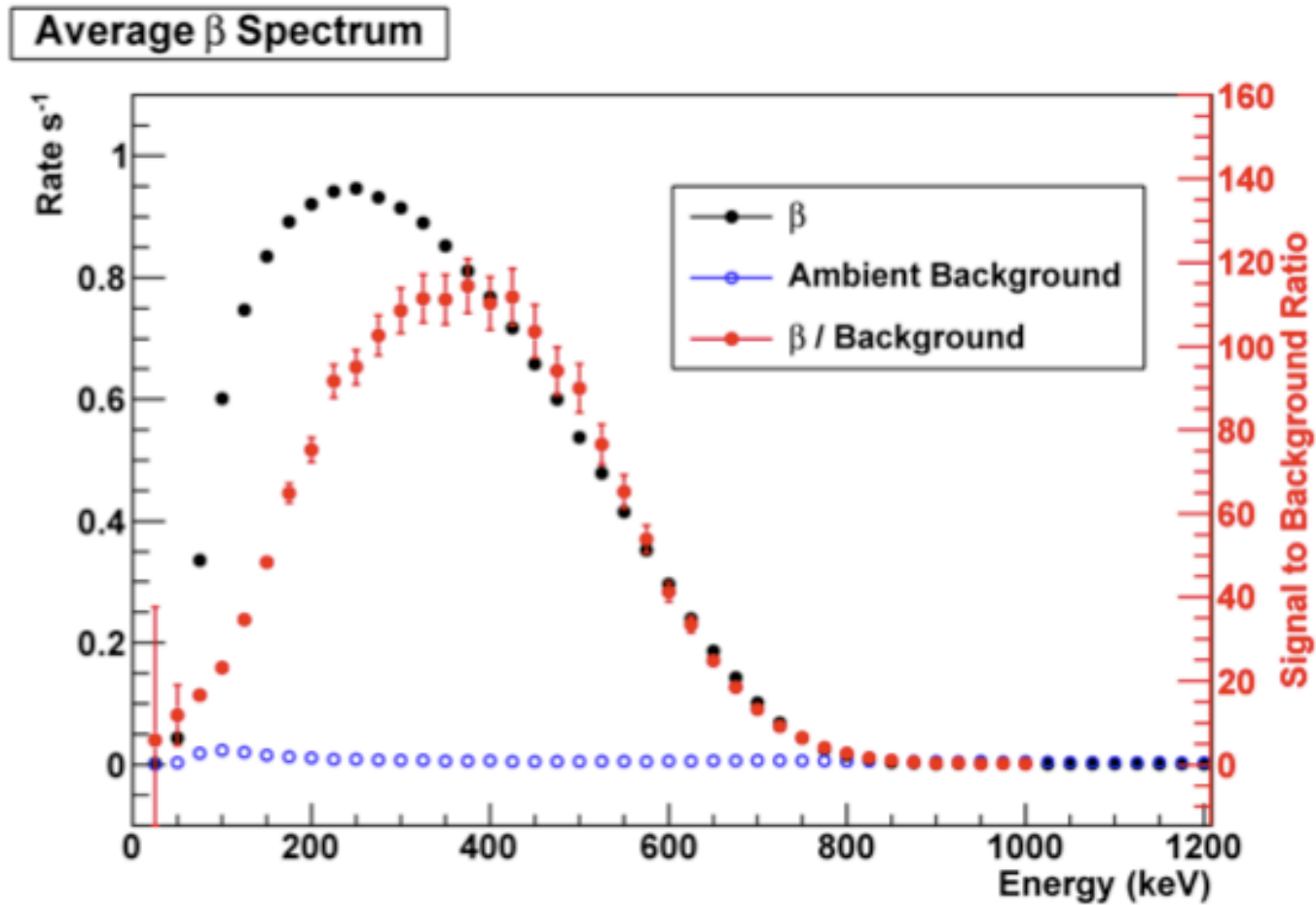
from A. Young

$$A \propto \frac{\sqrt{R}-1}{\sqrt{R}+1}, \text{ where } R = \frac{N_1^+ N_2^-}{N_2^+ N_1^-} \text{ is a "super-ratio"}$$



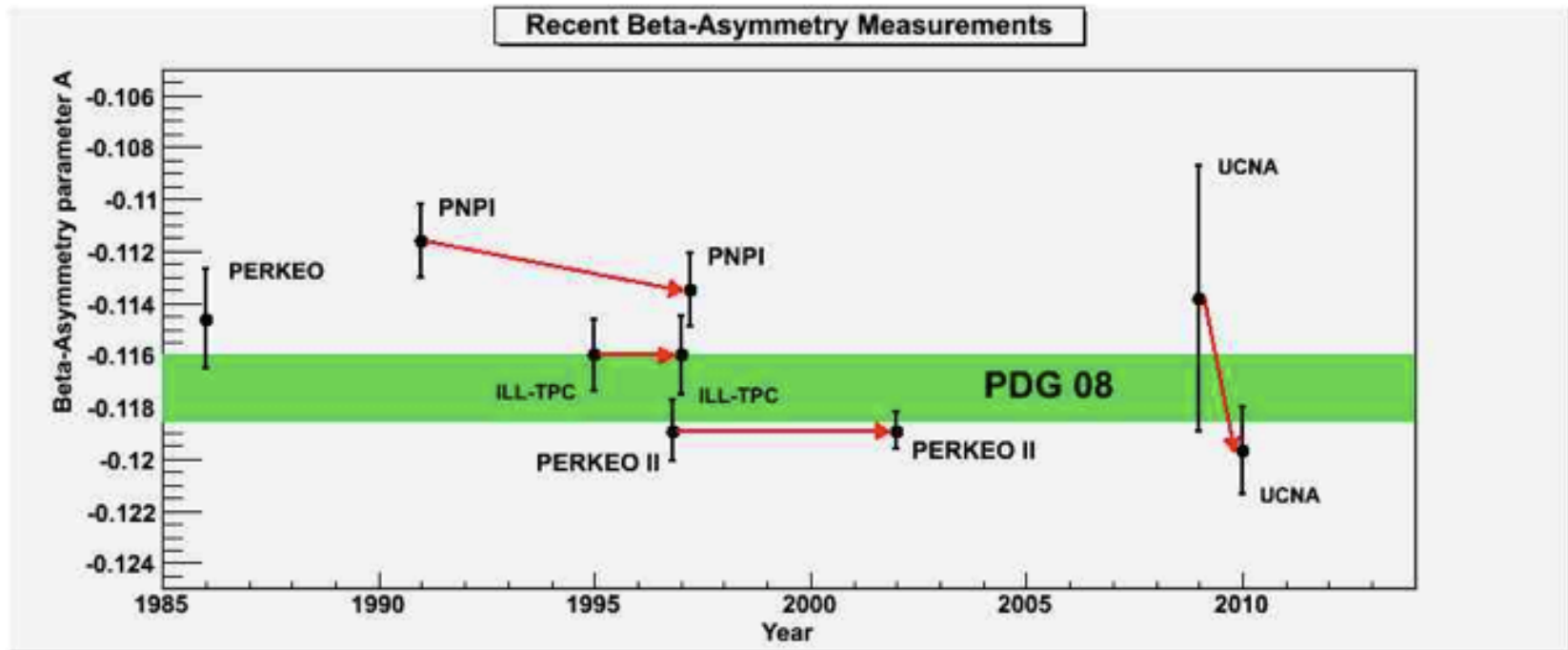
from A. Young

2010 Beta-decay spectrum and ambient backgrounds



$$S/B [200 < E \text{ keV} < 625] = 105$$

from A. Young



Accidental cancellation makes A_0 small

$$A_0 = -0.1173 \pm 0.0013 \text{ (PDG 2010, expands error by 2.3)}$$

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

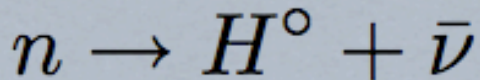
2011 UCNA Goal: sub-0.4% measurement with complementary systematic errors to existing and planned cold neutron experiments

from A. Young

Bound Beta-Decay of the Neutron

W. Schott, G. Dollinger, T. Faestermann, J. Friedrich, F.J. Hartmann, R. Hertenberger, N. Kaiser, A.R. Müller, S. Paul, and A. Ulrich

Technische Universität München



$$E_{\bar{\nu}} = 783 \text{ keV}$$

$$E_H = 352 \text{ keV}$$

$$BR \approx 4 \times 10^{-6}$$

Measure hyperfine state population of H

- sensitive to small scalar and tensor contributions.
- yields constraint on neutrino left-handedness.

Hyperfine State Population

Typically, one measures the polarization of the final state products to determine correlations, where the products are the outgoing electron or proton.

However, one can measure precisely the relative spin alignments of the decay products into H.

<i>i</i>	<i>v</i>	<i>n</i>	<i>p</i>	<i>e</i>	<i>Trans.</i>	<i>W_i</i> (%)
1	←	←	←	→	F/G-T	44.174(017)
2	←	←	→	←	G-T	55.211(013)
3	←	→	→	→	F/G-T	.622(003)
4	→	←	←	←	F/G-T	0

Sensitivity to SM Extensions

Scalar and tensor couplings
and R-L symmetric models

$$W_{1,2,3} = W(g_A, g_V, g_S, g_T)$$

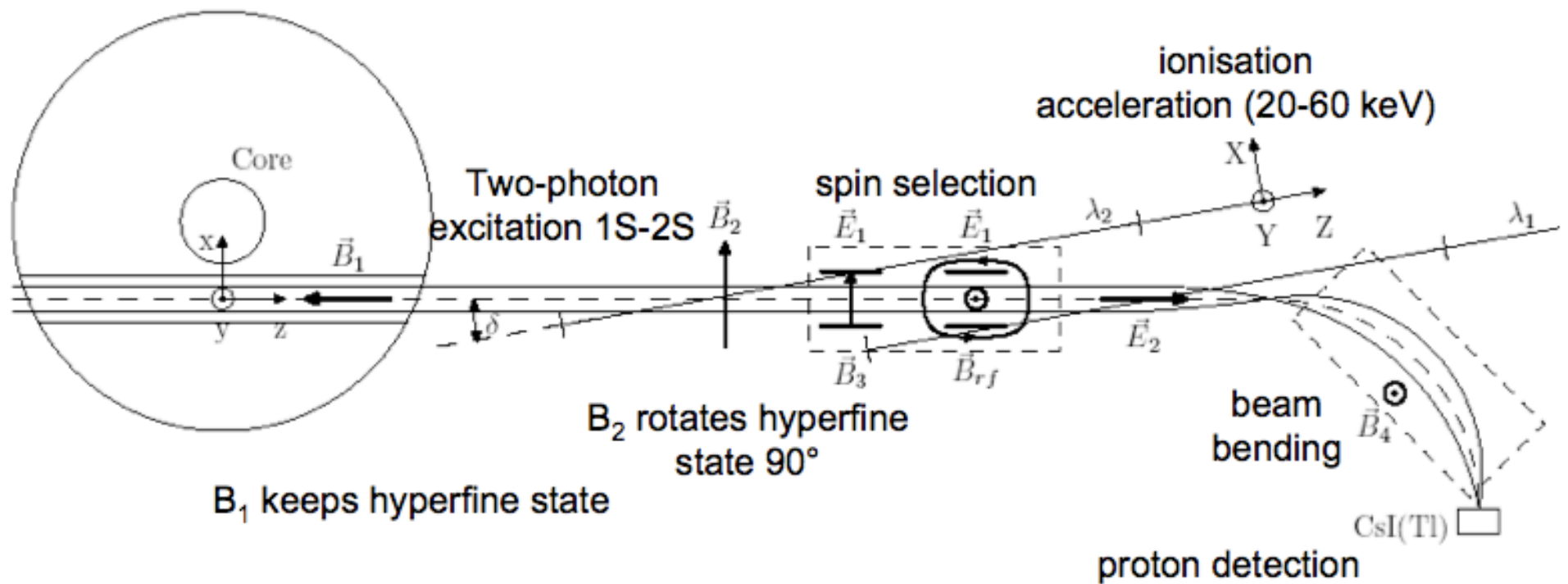
$$W_4 = W(g_A, g_V, \eta, \zeta)$$

$$H_{\bar{\nu}} = H_{\bar{\nu}}(g_A, g_V, \eta, \zeta)$$

i	$g_S=0$ $g_T=0$	$g_S=0.1$ $g_T=0$	$g_S=0$ $g_T=0.02$
1	44.174	46.479	43.440
2	55.211	53.288	55.789
3	0.622	0.233	0.771
4	0	0	0

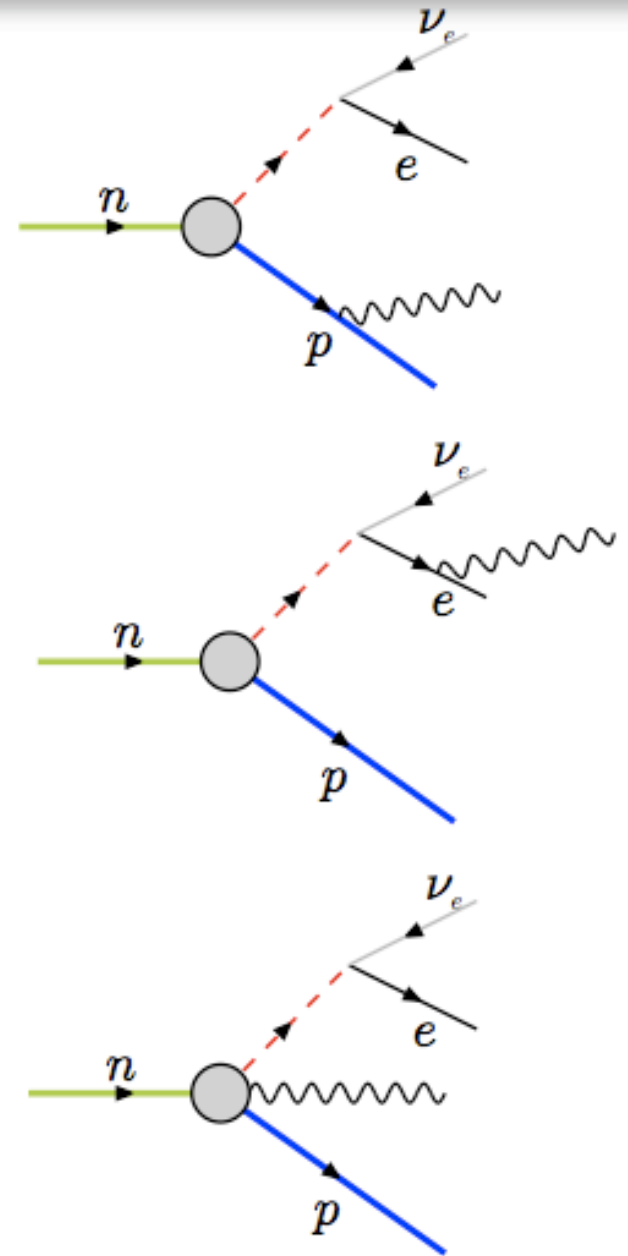
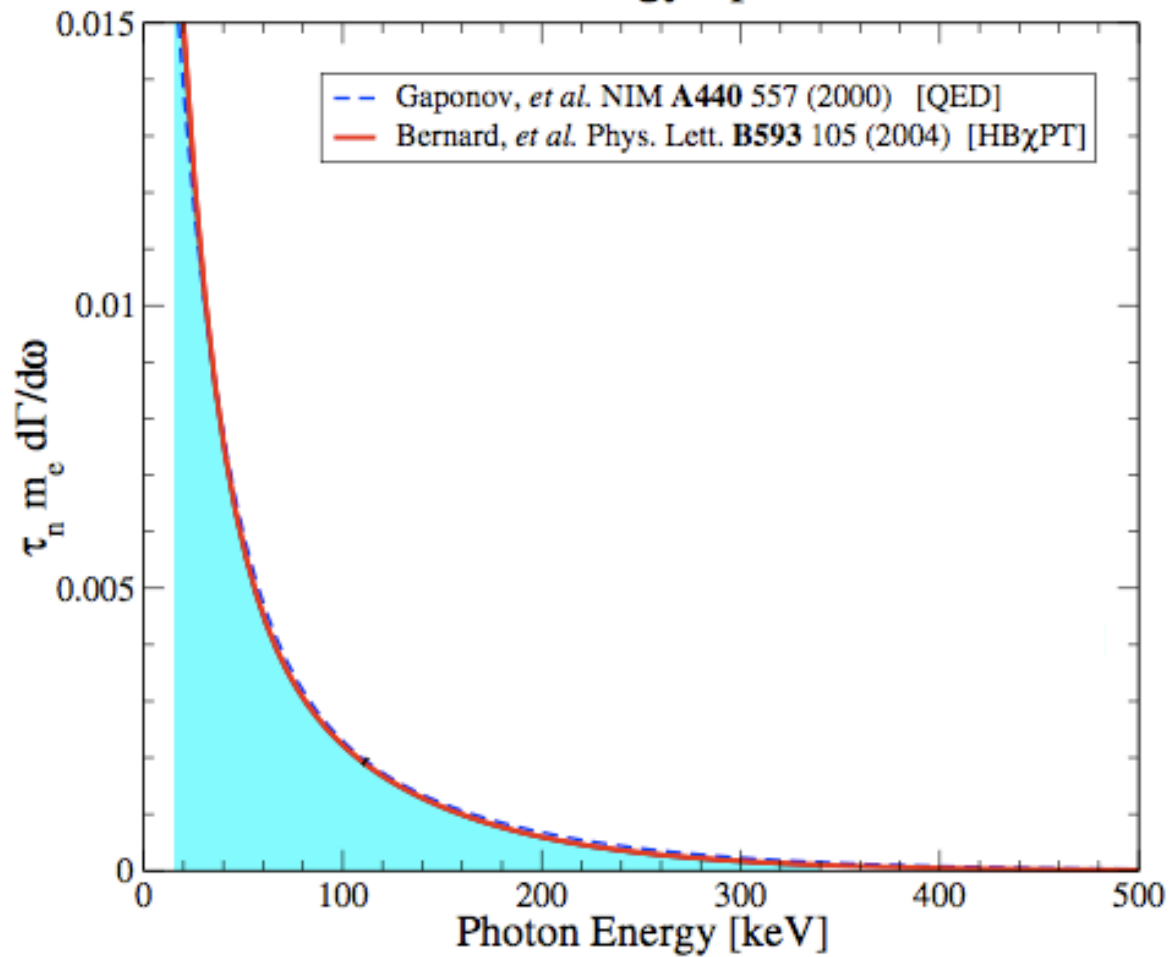
where η is mass ratio squared of two intermediate vector bosons (m_{W1}/m_{W2})
and ζ is mass eigenstate mixing angle

The Experiment



Radiative Neutron Decay

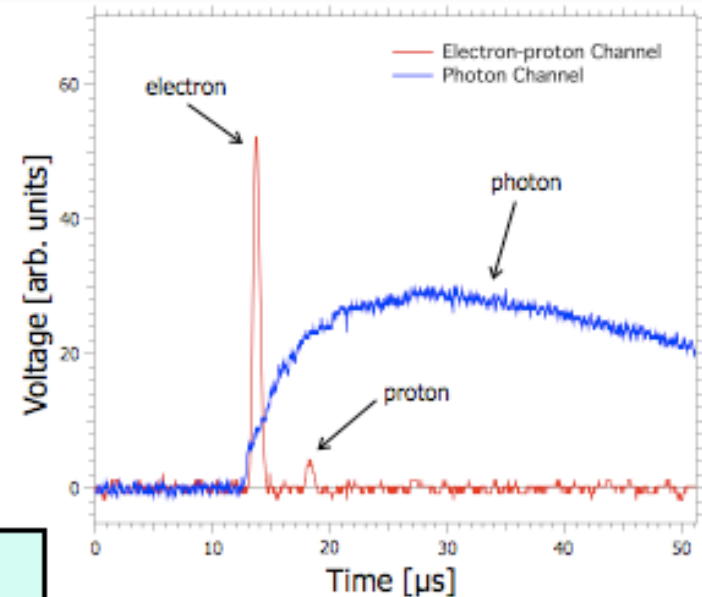
Photon Energy Spectrum



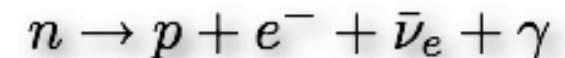
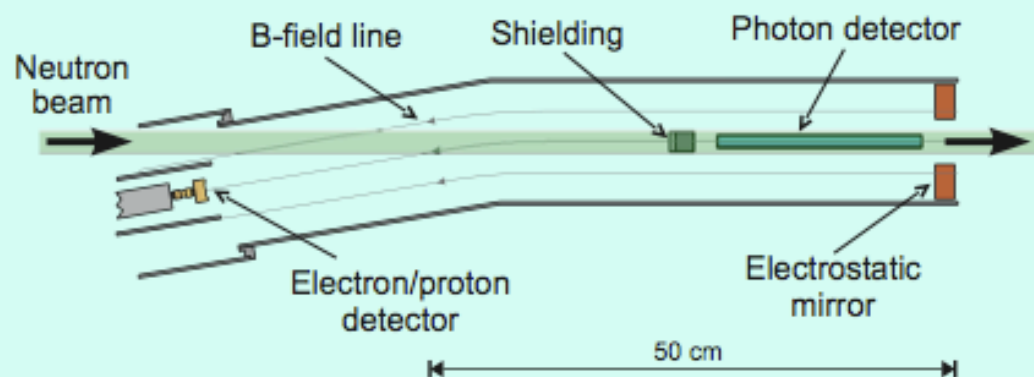
Radiative Neutron Decay - RDK I

- Previously unmeasured process in a fundamental semileptonic decay. Testing QED in a weak process.

Collaboration: NIST, Tulane, Maryland, Michigan, Sussex, Arizona State



RDK I operated at NIST NCNR cold neutron source. Measured e- γ coincidences followed by delayed proton.

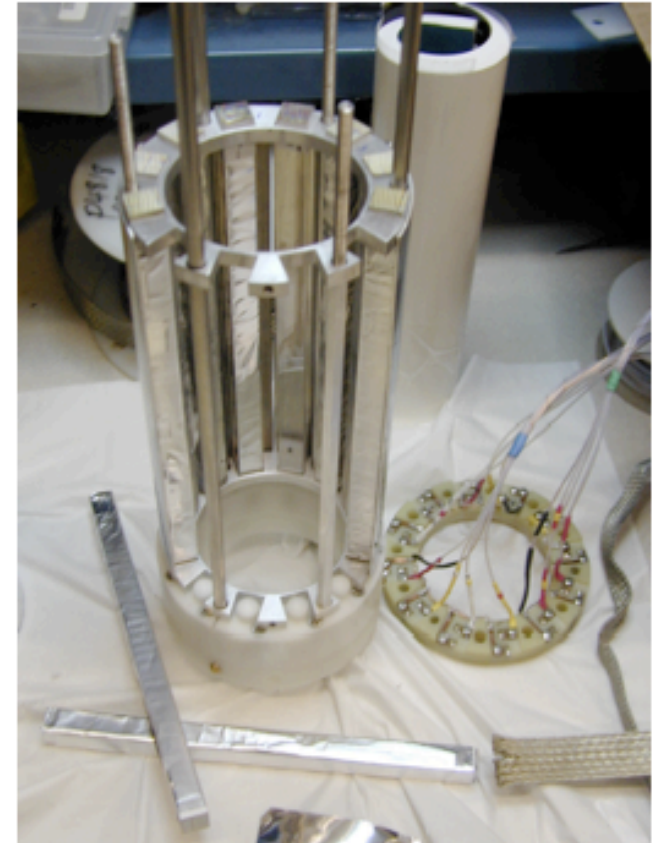


Measured branching ratio:

$$BR_{\text{RDK I}} = (3.13 \pm 0.34) \times 10^{-3}$$
$$BR_{\text{QED}} = 2.81 \times 10^{-3}$$

Physics below 0.5%

- Physics with tagged photons
- Probe non-leading order terms: recoil terms, proton bremsstrahlung
- Photon polarization
- New classes of angular correlations, e.g. $A(\mathbf{J}_n \cdot \mathbf{k})$, $D(\mathbf{J}_n \cdot (\mathbf{k} \times \mathbf{p}_v))$, $(\mathbf{p}_e \times \mathbf{p}_v) \cdot \mathbf{k}$.



Why Time-Reversal Violation?

- CP violation exists:

It was seen in neutral kaon decays in 1964 and neutral B mesons more recently.

- Preponderance of matter over antimatter:

There isn't sufficient CP violation in the Standard Model to account for baryogenesis.

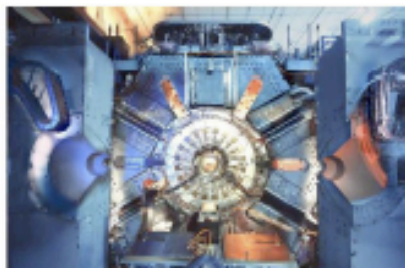
- The Strong CP problem:

Why is Θ_{QCD} so small?

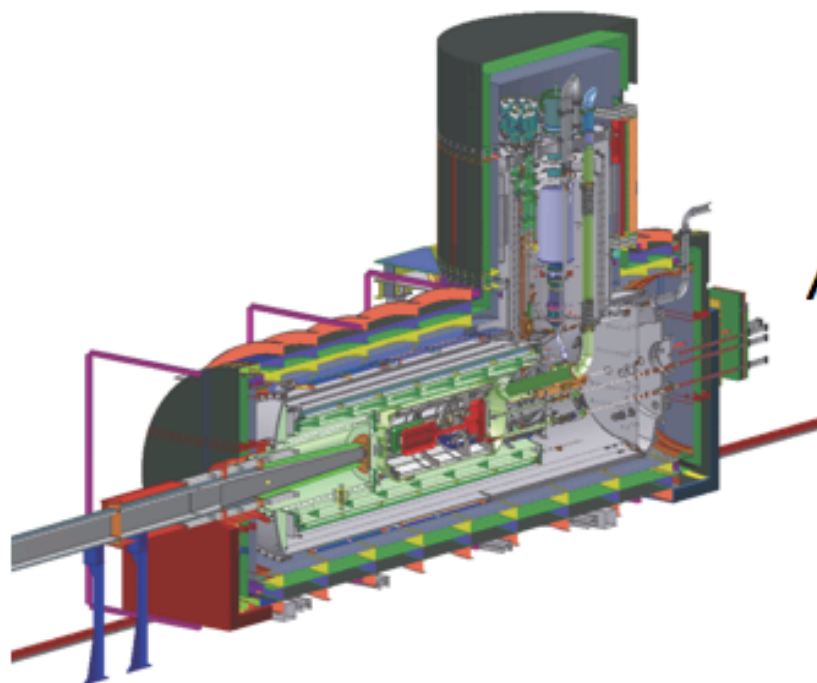
- We know that the Standard Model is incomplete:

Other theories generate phases significantly larger than the SM that would generate EDMs at levels within experimental reach.

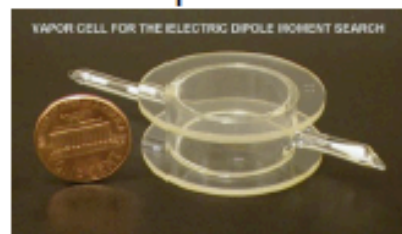
Searching for Sources of Time-Reversal Violation



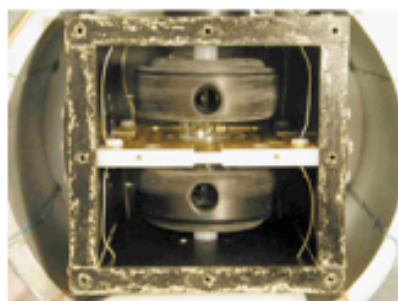
K and B mesons



neutron EDM



Atomic and electron EDMs



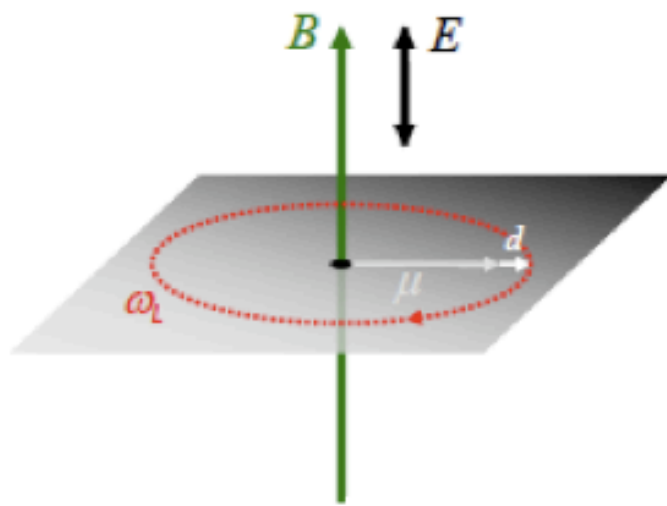
nuclear EDMs
(Rn, Ra, Hg, Xe)



Angular
Correlations

Probing T-violation: an EDM

$$H = -(\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E})$$

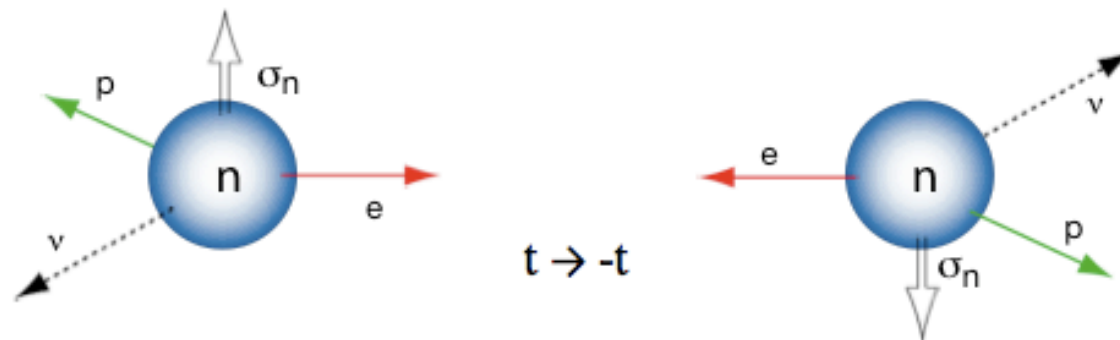


$$\omega_1 = \frac{2\vec{\mu} \cdot \vec{B} + 2\vec{d} \cdot \vec{E}}{\hbar}$$

$$\omega_2 = \frac{2\vec{\mu} \cdot \vec{B} - 2\vec{d} \cdot \vec{E}}{\hbar}$$

$$\Rightarrow \omega_1 - \omega_2 = \frac{4dE}{\hbar}$$

Probing T-violation: a correlation



$$\frac{dw}{dE_e d\Omega_e d\Omega_\nu} = G(E_e) \left(1 + a \frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + b \frac{m_e}{E_e} + \mathbf{P} \cdot \left(A \frac{\mathbf{p}_e}{E_e} + B \frac{\mathbf{p}_\nu}{E_\nu} + D \frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E_e E_\nu} \right) \right)$$

T-odd, P-even

Not quite T reversal; Initial and final states are *not* reversed:
final state interactions:

$$|D_{f.s.}| \sim 2 \times 10^{-5}$$

Time reversal violation in nuclear β -decay

- In the Standard Model the size of measured CP and T violating effects imply extremely tiny (non-observable) T violating effects in nuclear beta decay.
- Yet the observed matter - antimatter asymmetry indicates the existence of CP violation (and corresponding T-violation) perhaps arising from non-SM interactions.
 - Left-Right Symmetric
 - Exotic Fermion
 - Leptoquark
- T violating contributions to beta decay can arise from
 - Parity violating, Time reversal violating N-N interactions
 - Parity conserving, Time reversal violating N-N interactions
 - Time reversal violating charged current quark-lepton interactions

Searches for T violation in nuclear beta decay have the potential to be sensitive to interactions beyond the SM.

β -decay tests of T invariance

- Combine T-odd combinations of three kinematic variables

$$D\sigma_n \cdot (p_e \times p_\nu) \quad R\sigma_n \cdot (\sigma_e \times p_e)$$

- Require competing amplitudes with a relative phase
- Must account for final state effects

^8Li

$$R = (0.9 \pm 2.2) \times 10^{-3}$$

J. Sromicki *et al.* *Phys. Rev. Lett.* **82** 57 (1999)

^{19}Ne

$$D = (1 \pm 6) \times 10^{-4}$$

F. Calaprice, in *Hyperfine Interactions* (Springer, Netherlands, 1985), Vol. 22

neutron

$$R = (8 \pm 15(\text{stat.}) \pm 5(\text{syst.})) \times 10^{-3}$$

$$D = (-2.8 \pm 7.1) \times 10^{-4}$$

$$D = (-6 \pm 12(\text{stat.}) \pm 5(\text{syst.})) \times 10^{-4}$$

Kozela *et al.* *Phys. Rev. Lett.* **102** 172301 (2009)

T. Soldner *et al.* *Phys. Lett. B* **581** (2004)

emiT I *Phys. Rev. C* **62** 055501 (2000)

The emiT Experiment: A Search for Time-reversal Invariance Violation in Polarized Neutron Beta Decay



H.P. Mumm, J.S. Nico, and A.K. Thompson
National Institute of Standards and Technology

S.J. Freedman and B.K. Fujikawa
*University of California - Berkeley/
Lawrence Berkeley National Laboratory*

G.L. Jones
Hamilton College

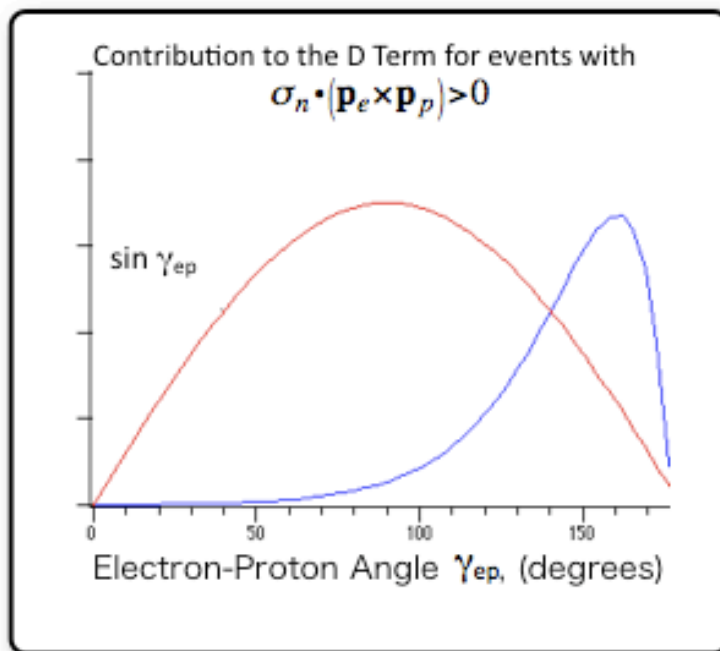
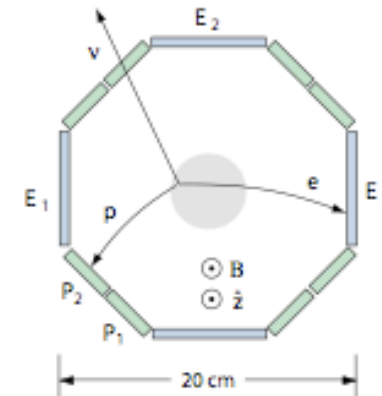
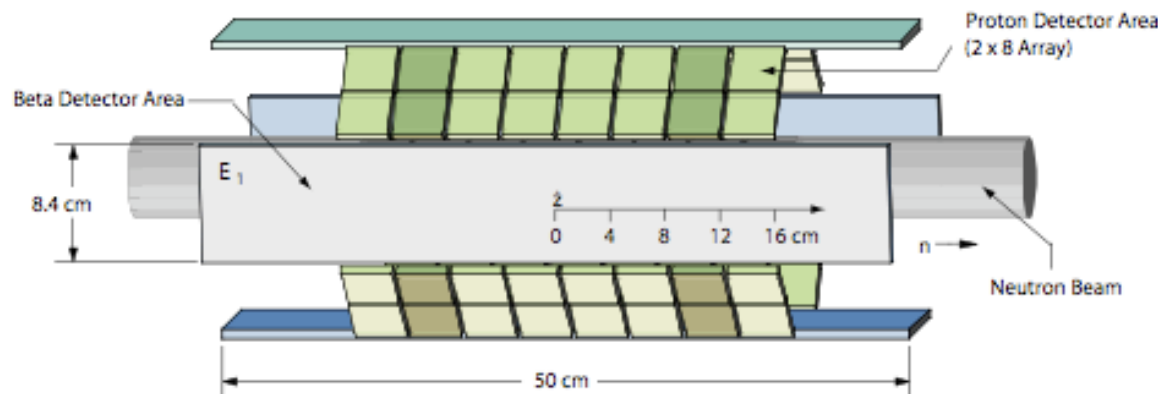
C. Trull and F.E. Wietfeldt
Tulane University

T.E. Chupp and R.L. Cooper, K.P. Coulter
University of Michigan

J.F. Wilkerson
*University of North Carolina & Oak Ridge National
Laboratory*

A. Garcia
University of Washington

emiT measurement technique

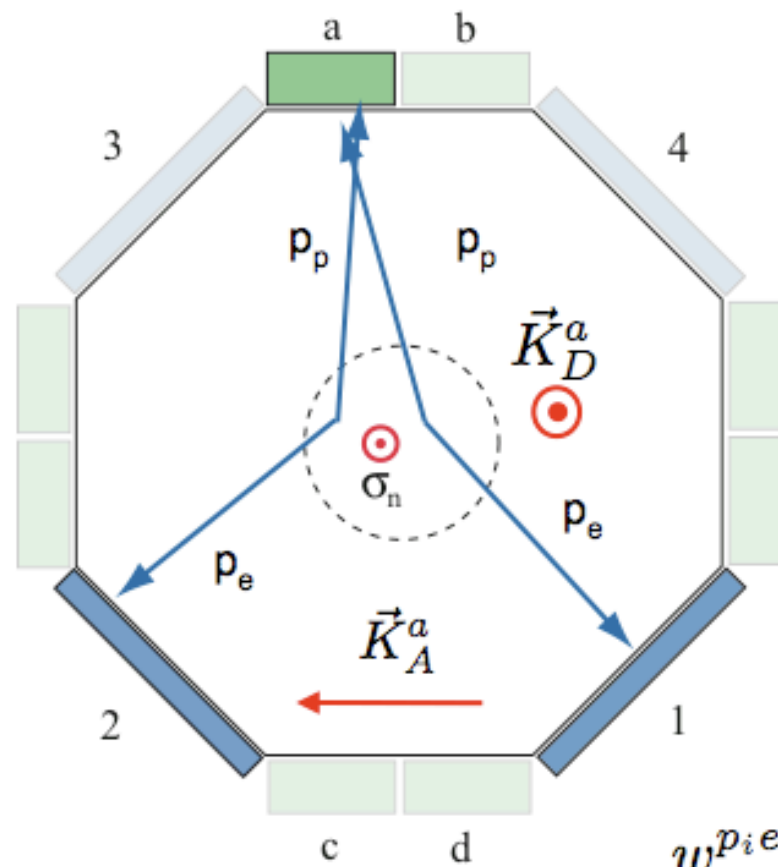


- Symmetrical, segmented detector to minimize or cancel instrumental asymmetries that could yield false coincidences
- Detector geometry to maximize sensitivity to $D\sigma_n \cdot (\mathbf{p}_e \times \mathbf{p}_p)$ (minimize sensitivity to other terms in decay distribution)
- emiT gained a factor of three increase in “effective” beam flux over previous “right angle” geometry beam experiments

Challenges

- proton endpoint 750 eV (requires acceleration)
- Neutron lifetime (requires intense source)
- Uniform magnetic guide fields
- Well defined and understood beam

emiT “blind” analysis



- Proton Detector
- Electron Detector

Efficiency independent ratio,

$$w^{p_i e_j} = \frac{N_+^{p_i e_j} - N_-^{p_i e_j}}{N_+^{p_i e_j} + N_-^{p_i e_j}} + \mathcal{B} \hat{z} \cdot \tilde{\mathbf{K}}_D^{p_i e_j}$$

↑
hidden blind offset

w is sensitive to D , but also to A, B
Define a parameter,

$$v^{p_i} = \frac{1}{2} (w^{p_i R} - w^{p_i L})$$

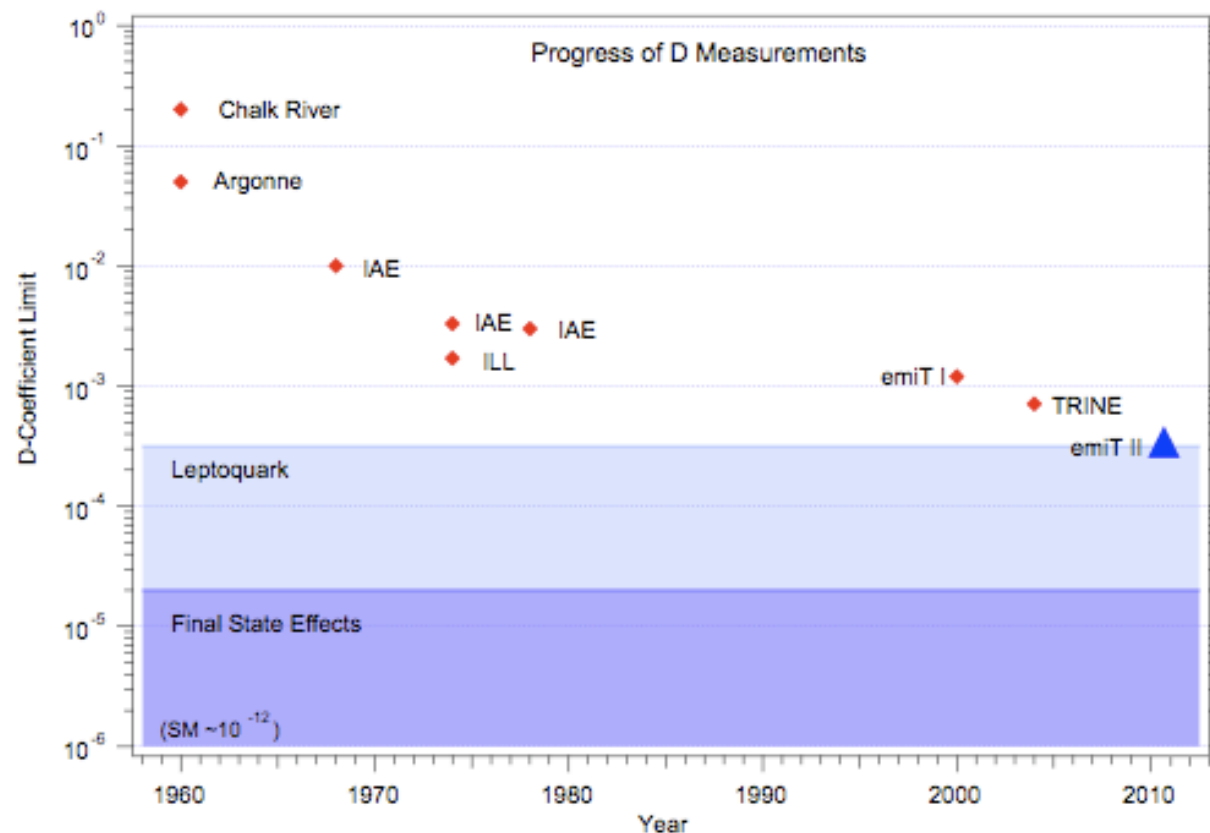
For a real detector,

$$w^{p_i e_j} \approx \mathbf{P} \cdot \left(A \tilde{\mathbf{K}}_A^{p_i e_j} + B \tilde{\mathbf{K}}_B^{p_i e_j} + D \tilde{\mathbf{K}}_D^{p_i e_j} \right)$$

emiT Summary

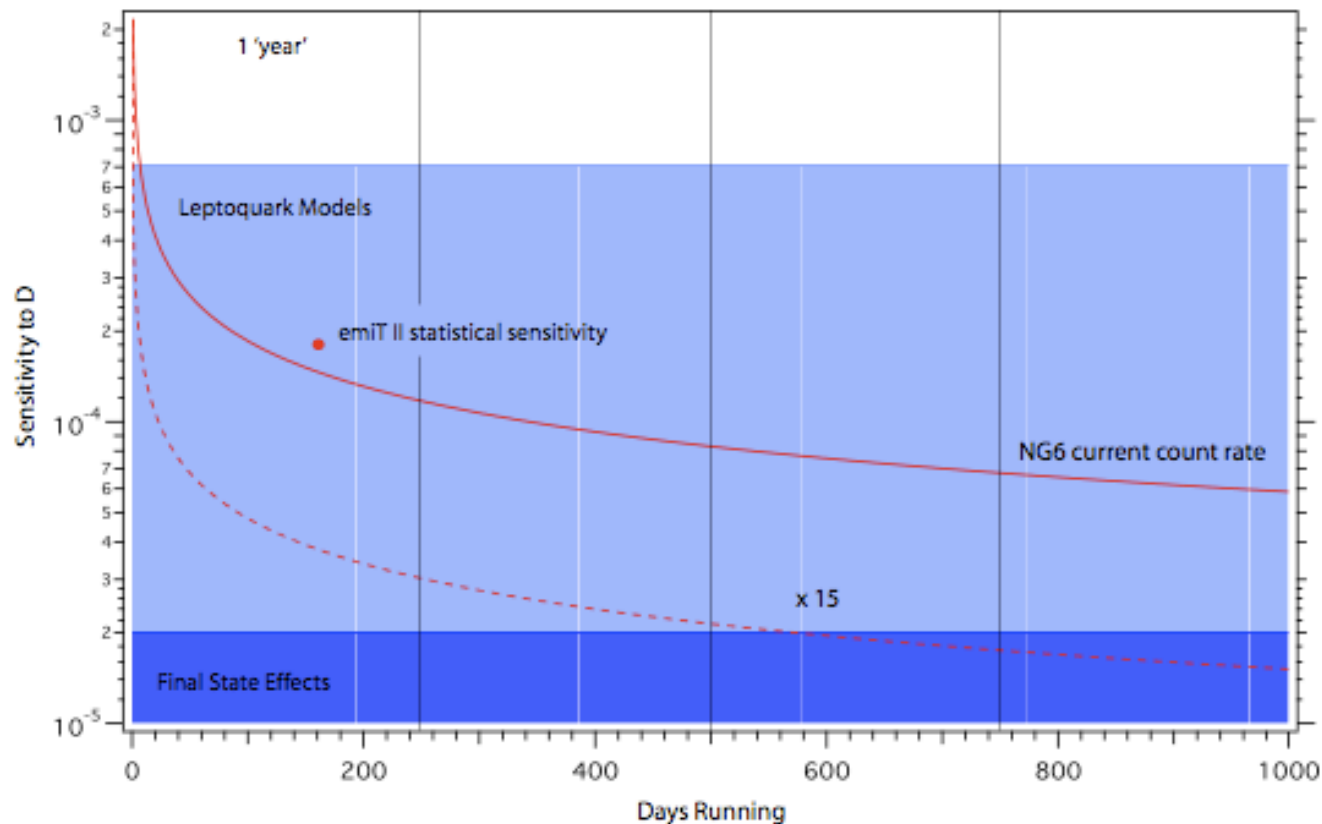
Have completed the most sensitive measurement of the D coefficient in nuclear beta decay. (arXiv:1104.2778)

$$D = (-0.96 \pm 1.89(\text{stat}) \pm 1.01(\text{sys})) \times 10^{-4}$$



Future D measurement, emiT III?

- The new NGC beam line could provide over a factor of 10 increase in neutron flux
- Current emiT apparatus might be capable of reaching $2-3 \times 10^{-5}$ with modest upgrades and improvements.
- At this level one should see the effect of final state effects.
- No definite plan at this time.



Observations

- Precision measurements in beta decay play an important role in searching for new physics and provide complementary information to high energy experiments
- Many new experimental efforts are in progress to resolve differences. New UCN experiments should illuminate existing disagreement; results should be imminent (1-2 years).
- New high-flux facilities coming online world-wide for fundamental neutron physics: PSI, FRM-II, SNS, LANL, JSNS, NIST upgrade...

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A. Serebrov - PNPI
H.M. Shimizu - J-PARK
J. F. Wilkerson - UNC
A. Young - NCSU

For more

List of facilities worldwide: <http://www.ncnr.nist.gov/nsources.html>

Neutron resources: <http://pdg.lbl.gov/>
<http://www.ill.eu/>
<http://www.ncnr.nist.gov/resources/n-lengths/>
<http://www.nndc.bnl.gov/>
<http://www.ncnr.nist.gov/resources/>
<http://www.neutron.anl.gov/software.html>

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- Abele, Prog. Part. Nucl. Phys. (2008).
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- Nico and Snow, Annu. Rev. Nucl. Part. Sci. (2005)

Texts:

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- Alexandrov, [Fundamental Properties of the Neutron](#) (1992)
- Grotz and Klapdor, [The Weak Interaction in Nuclear, Particle and Astrophysics](#) (1990)
- Holstein, [Weak Interactions in Nuclei](#) (1989)
- Commins and Bucksbaum, [Weak Interactions of Leptons and Quarks](#) (1983)
- Krupchitsky, [Fundamental Research with Polarized Slow Neutron](#) (1965)
- Turchin, [Slow Neutrons](#) (1965)

Homework

1) There are a large number of angular correlations, but A (neutron spin - electron momentum) is the most frequently measured to determine λ . Why is that?

[The reason can be shown with straightforward calculations.]

2) The angular correlation a (electron momentum - antineutrino momentum) has nearly the sensitivity as A , but it has been measured with less precision. Speculate on the (experimental) reason why that is.

3) In the beam lifetime experiment, nowhere was the beam energy (i.e., velocity) discussed. It is a factor in the number of protons that are produced, so one might think that it must be known quite well. In fact, it is irrelevant. Speculate on the reason why.