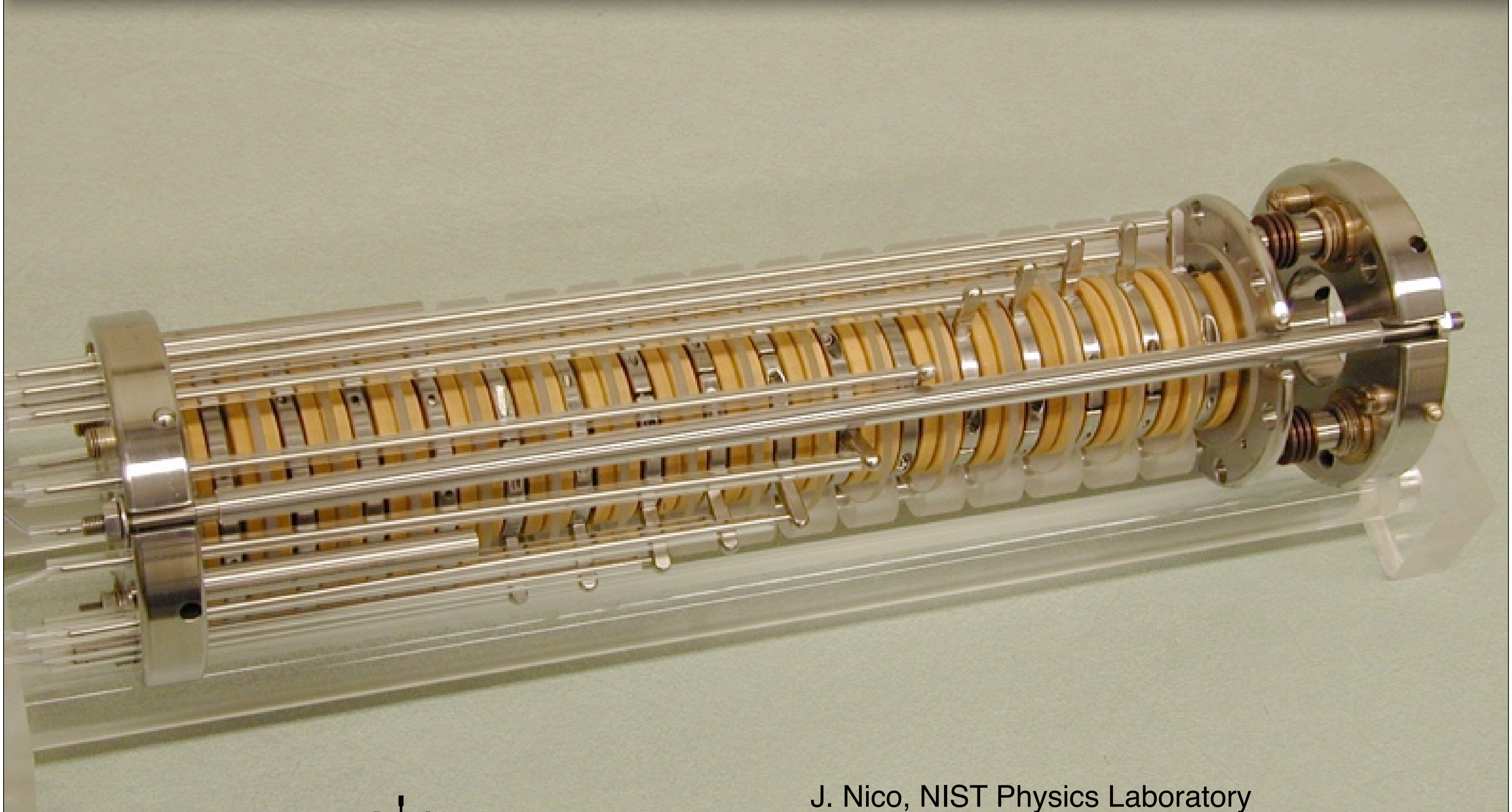
Neutron Lifetime Measurements



J. Nico, NIST Physics Laboratory
Institute for Nuclear Theory - UW
Workshop on Fundamental Neutron Physics
April 6, 2007

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.

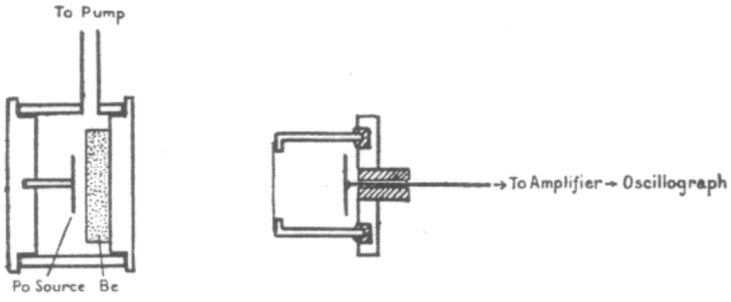


Fig. 1.

Bothe and Becker, *Zeits. f. Physik* **66**, 289 (1930) Chadwick, *Proc. Roy. Soc.,* A, **136,** p. 692-708

Neutron Decay

- 1934: Chadwick and Goldhaber detect the photo-disintegration of the deuteron in the reaction

$$^2H + \gamma \rightarrow ^1H + n + Q$$

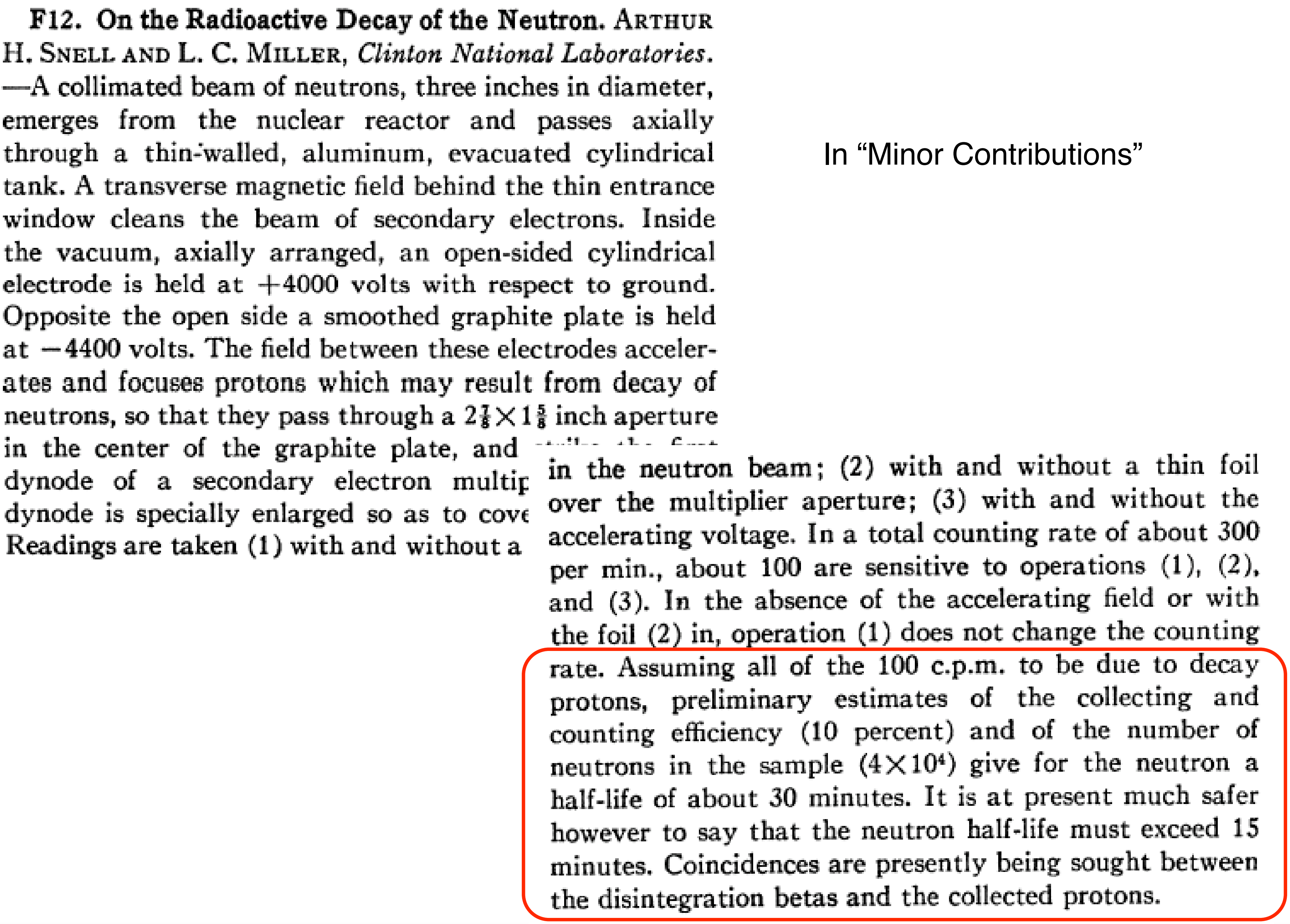
From the *Q*-value, they determine an estimate for the neutron mass, which is *greater* than the proton mass.

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

$$n \rightarrow p + e^- + \bar{\nu}_e + 783\,\mathrm{keV}$$

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

Chadwick and Goldhaber, *Nature* **134**, 237 (1934)



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 $2\frac{7}{8}\times1\frac{5}{8}$ inch aperture in the center of the graphite plate, and
dynode of a secondary electron multip
dynode is specially enlarged so as to cove
Readings are taken (1) with and without a

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.

In “Minor Contributions”

Snell and Miller, *Phys. Rev.* **74**, 1217A (1948)

Snell, Pleasonton, and McCord - Oak Ridge

Beta-Proton Coincidence

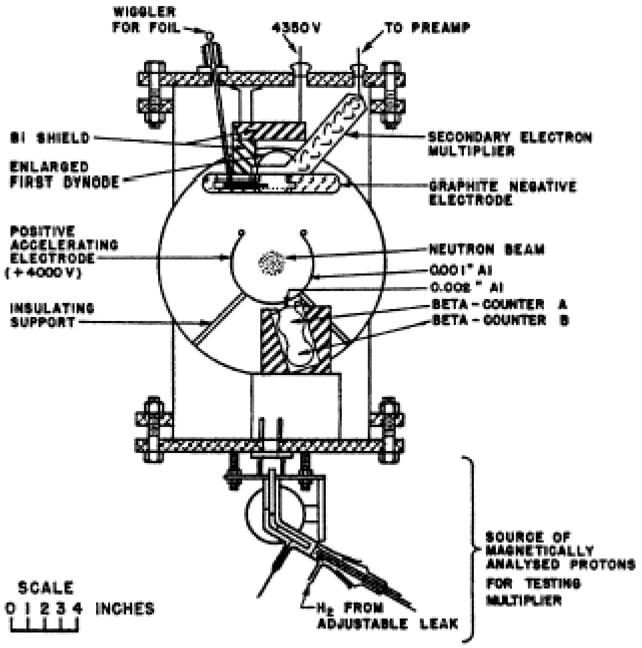


FIG. 1. Apparatus used for seeking beta-proton coincidences arising from neutron decay. The neutron beam is indicated in section at the center. A vertical electric field accelerates the protons upward and focuses them upon the secondary electron multiplier; the beta-particles register in the double beta-proportional counter below.

"...half-life in the range 10-30 minutes...consistent with all our observations."

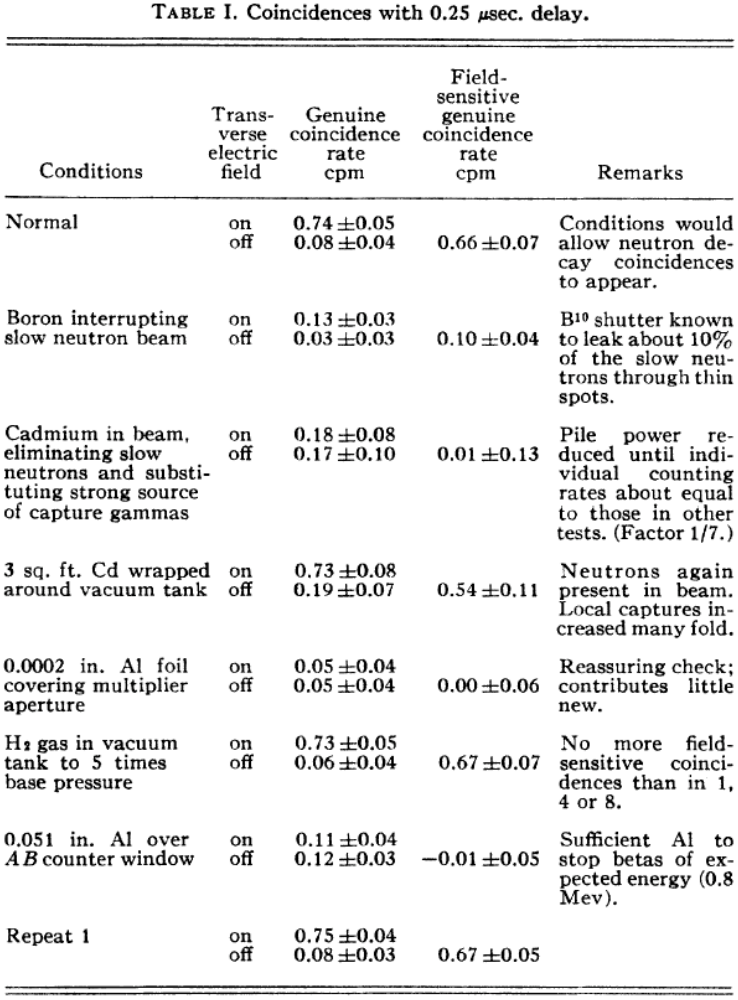


TABLE I. Coincidences with 0.25 μsec. delay.

Conditions	Transverse electric field	Genuine coincidence rate cpm	Field-sensitive genuine coincidence rate cpm	Remarks
Normal	on off	0.74 ±0.05 0.08 ±0.04	0.66 ±0.07	Conditions would allow neutron decay coincidences to appear.
Boron interrupting slow neutron beam	on off	0.13 ±0.03 0.03 ±0.03	0.10 ±0.04	B^{10} shutter known to leak about 10% of the slow neutrons through thin spots.
Cadmium in beam, eliminating slow neutrons and substituting strong source of capture gammas	on off	0.18 ±0.08 0.17 ±0.10	0.01 ±0.13	Pile power reduced until individual counting rates about equal to those in other tests. (Factor 1/7.)
3 sq. ft. Cd wrapped around vacuum tank	on off	0.73 ±0.08 0.19 ±0.07	0.54 ±0.11	Neutrons again present in beam. Local captures increased many fold.
0.0002 in. Al foil covering multiplier aperture	on off	0.05 ±0.04 0.05 ±0.04	0.00 ±0.06	Reassuring check; contributes little new.
H_2 gas in vacuum tank to 5 times base pressure	on off	0.73 ±0.05 0.06 ±0.04	0.67 ±0.07	No more field-sensitive coincidences than in 1, 4 or 8.
0.051 in. Al over *AB* counter window	on off	0.11 ±0.04 0.12 ±0.03	−0.01 ±0.05	Sufficient Al to stop betas of expected energy (0.8 Mev).
Repeat 1	on off	0.75 ±0.04 0.08 ±0.03	0.67 ±0.05	

Phys. Rev. **78**, 310 (1950)

Robson Experiment - Chalk River

Magnetic Spectrometer

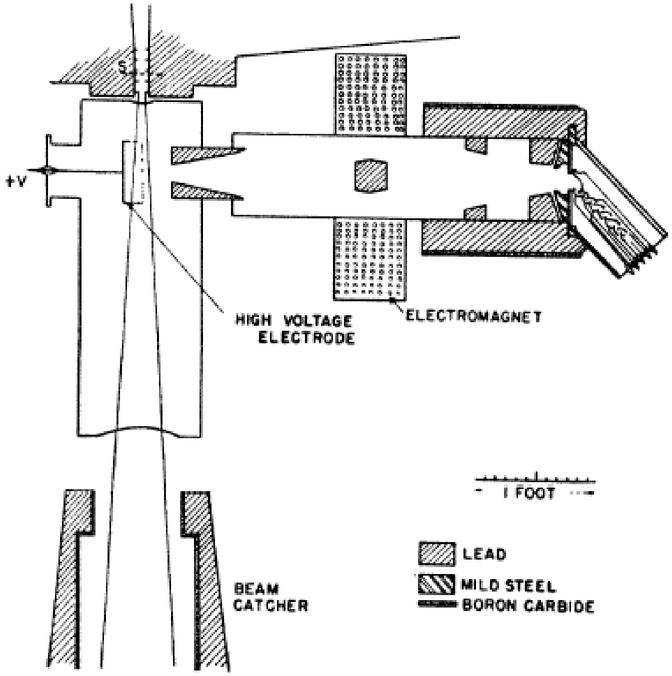


FIG. 1. Plan view of the apparatus.

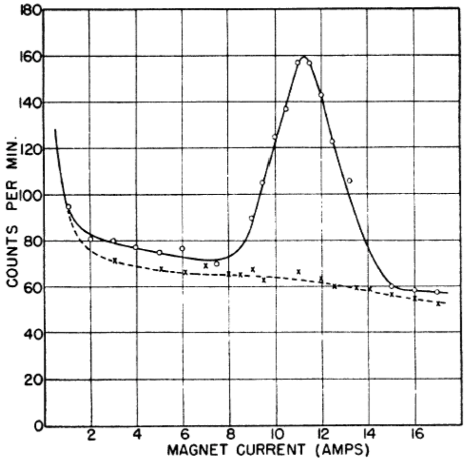


FIG. 2. Electron multiplier counting rate as a function of magnetic field for a potential of 15 kv on the high voltage electrode. The solid curve corresponds to the boron shutter "out" and the dotted curve to the boron shutter "in."

“...half-life...minimum of 9 minutes and a maximum of about 25 minutes.”

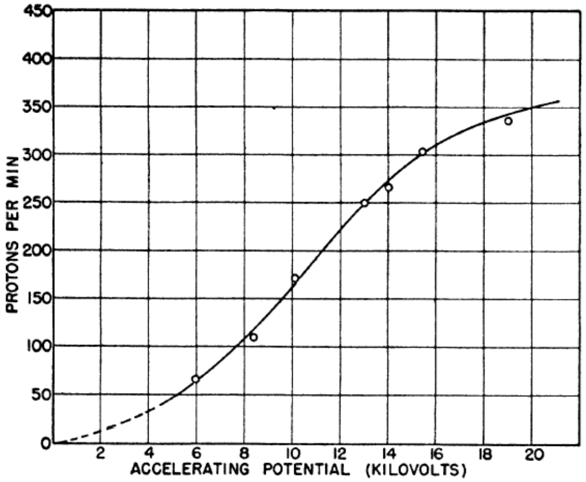
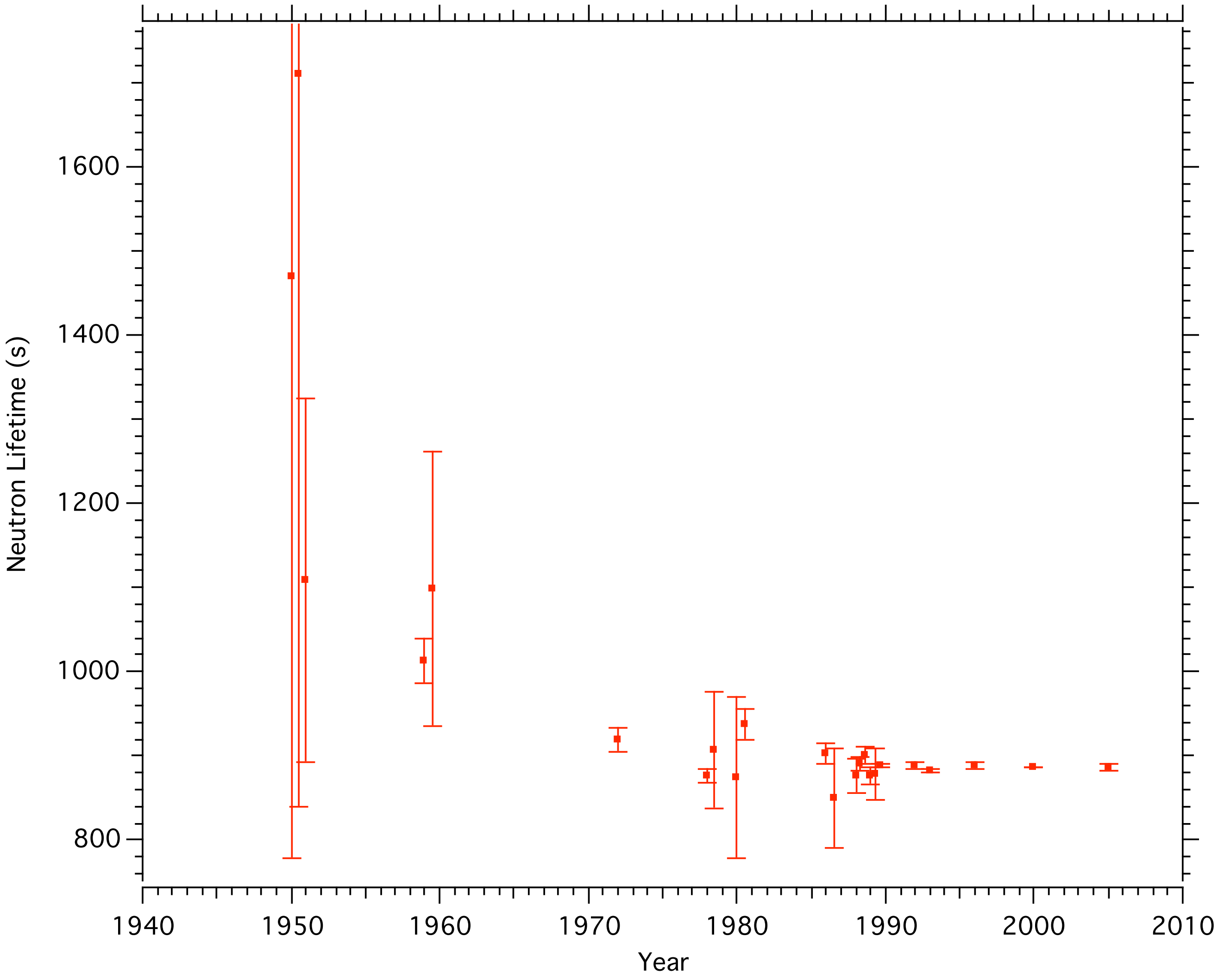


FIG. 3. Variation of number of focused protons with the potential on the high voltage electrode.

Phys. Rev. **78**, 311 (1950)

History of Neutron Lifetime 1950-2005



Schreckenbach and Mampe, *J. Phys. G* **18**, 1 (1992)

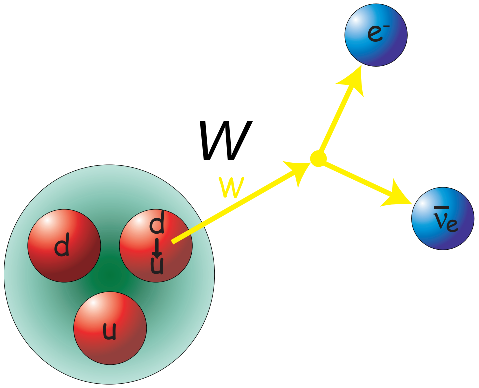
Physics from Neutron Decay

➢ Solar physics: $p + p \rightarrow {}^2H + e^+ + \nu_e$

➢ 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 forces, non-SM physics.

➢ Measurement of radiative corrections.

➢ New source of time-reversal (*CP*) violation?

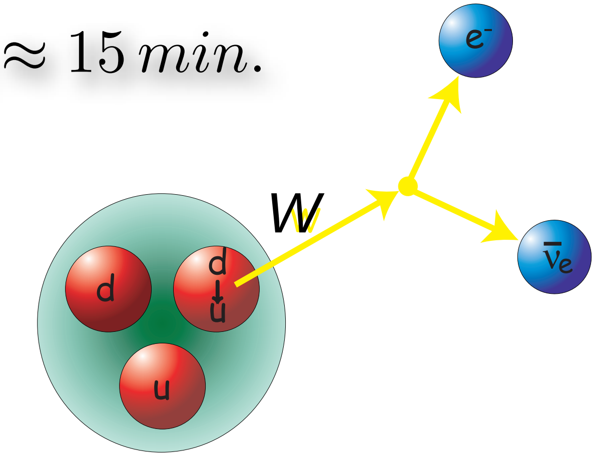
Neutron Decay Parameters

- $(m_n + m_p)c^2 = 1877\,\mathrm{MeV}; \qquad (m_n - m_p)c^2 = 1293\,\mathrm{keV}$

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

$$0 < T_e < 783\,\mathrm{keV}$$

$$0 < T_p < 751\,\mathrm{eV}$$



- Other decay modes:

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

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

Nature **444,** 1059 (2006) Schott *et al., Eur. Phys J. A* **30** (2006)

Beta Decay Probability of a Free Neutron

With one possible matrix element (*V-A*)

$$\mathcal{M} = \frac{G_F}{2\sqrt{2}} V_{ud} \overline{\psi_p} \gamma_\mu (f + g\gamma_5) \psi_n \overline{\psi_e} \gamma^\mu (1 + \gamma_5) \psi_\nu$$

we can calculate the transition probability

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

Define new coupling constants

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

and express the lifetime tau as $\tau^{-1} \propto f\xi$,

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

Beta Decay Probability of a Free Neutron

Here

$\langle \mathbf{1} \rangle$ - Fermi matrix element; vector

$\langle \sigma \rangle$ - Gamov-Teller matrix element; axial

Evaluate the matrix elements for the case of neutron decay gives

$$|\langle \mathbf{1} \rangle|^2 = 1 \qquad |\langle \sigma \rangle|^2 = 3$$

Substitution yields

$$\boxed{f\tau = \frac{K/ln2}{(g_V^2 + 3g_A^2)}}$$

Commins and Bucksbaum, *Weak interactions of leptons and quarks, Cambridge Univ. Press (1983)*

Neutron Decay w/ Radiative Corrections

$$\tau = \frac{1}{f(1+\delta_R)} \frac{K/ln2}{G_F^2 V_{ud}^2 (1+\Delta_R^V)(1+3\lambda^2)}$$

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

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

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

Towner and Hardy, *J. Phys. G.* **29** (2003). Marciano and Sirlin, *PRL* **96** (2006)

Lifetime and Correlation Coefficients

$$dW \propto (g_V^2 + 3g_A^2)F(E_e)[1 + a\frac{\vec{p_e}\cdot\vec{p_\nu}}{E_eE_\nu} + \vec{\sigma_n}\cdot(A\frac{\vec{p_e}}{E_e} + B\frac{\vec{p_\nu}}{E_\nu} + D\frac{\vec{p_e}\times\vec{p_\nu}}{E_eE_\nu})]$$

Lifetime

$$\tau = \frac{1}{f(1+\delta_R)}\frac{K/ln2}{(1+\Delta_R^V)(g_V^2+3g_A^2)} = (885.7 \pm 0.8)\,\mathrm{s}$$

Coupling ratio

$$\lambda = \frac{|g_A|}{|g_V|}e^{i\phi} = (-1.2695 \pm 0.0029)$$

Electron-antineutrino asymmetry

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

Spin-antineutrino asymmetry

$$B = 2\frac{|\lambda|^2 - |\lambda|cos\phi}{1+3|\lambda|^2} = (0.981 \pm 0.004)$$

Spin-electron asymmetry

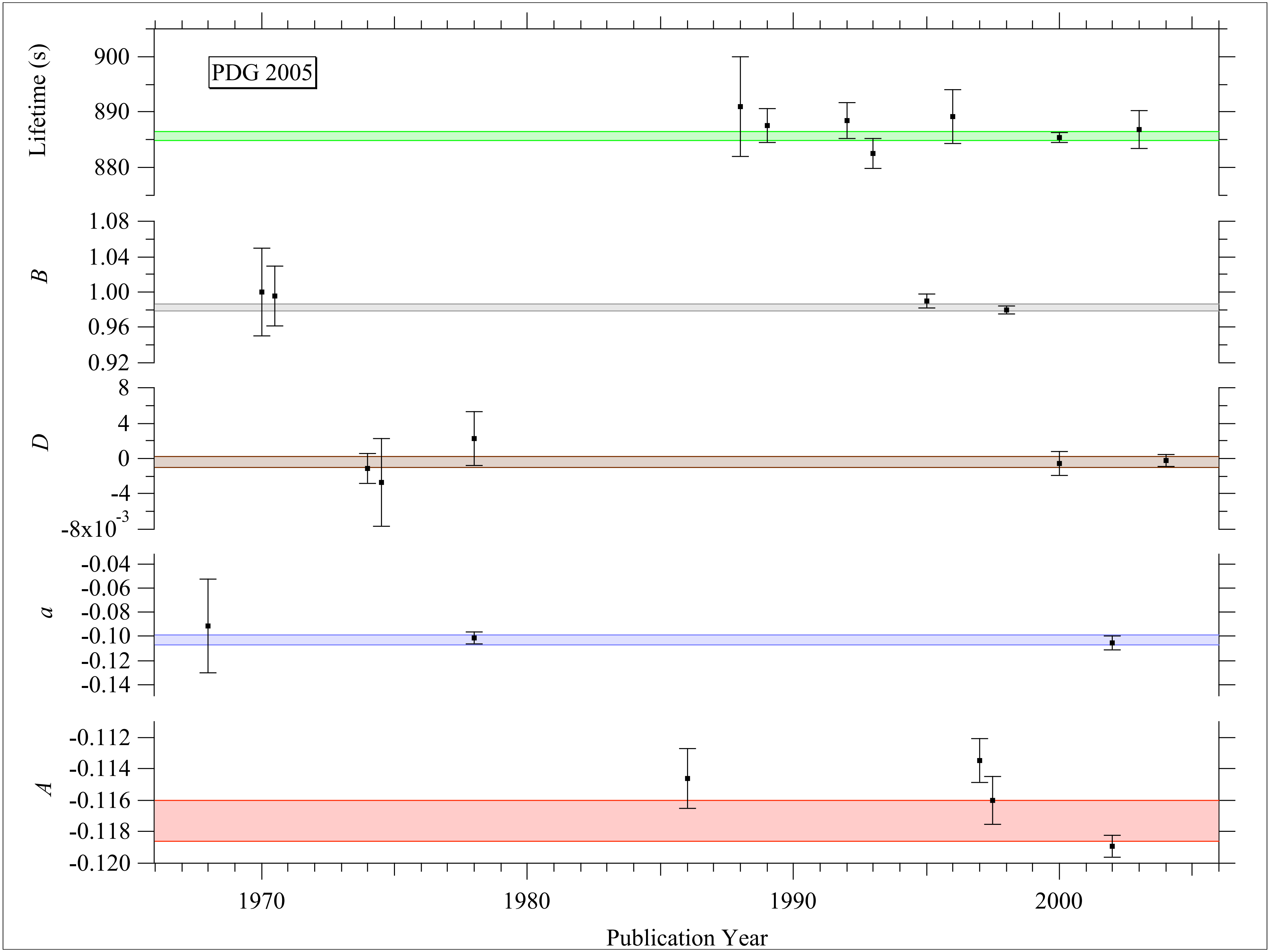
$$A = -2\frac{|\lambda|^2 - |\lambda|cos\phi}{1+3|\lambda|^2} = (-0.1173 \pm 0.0013)$$

Triple correlation

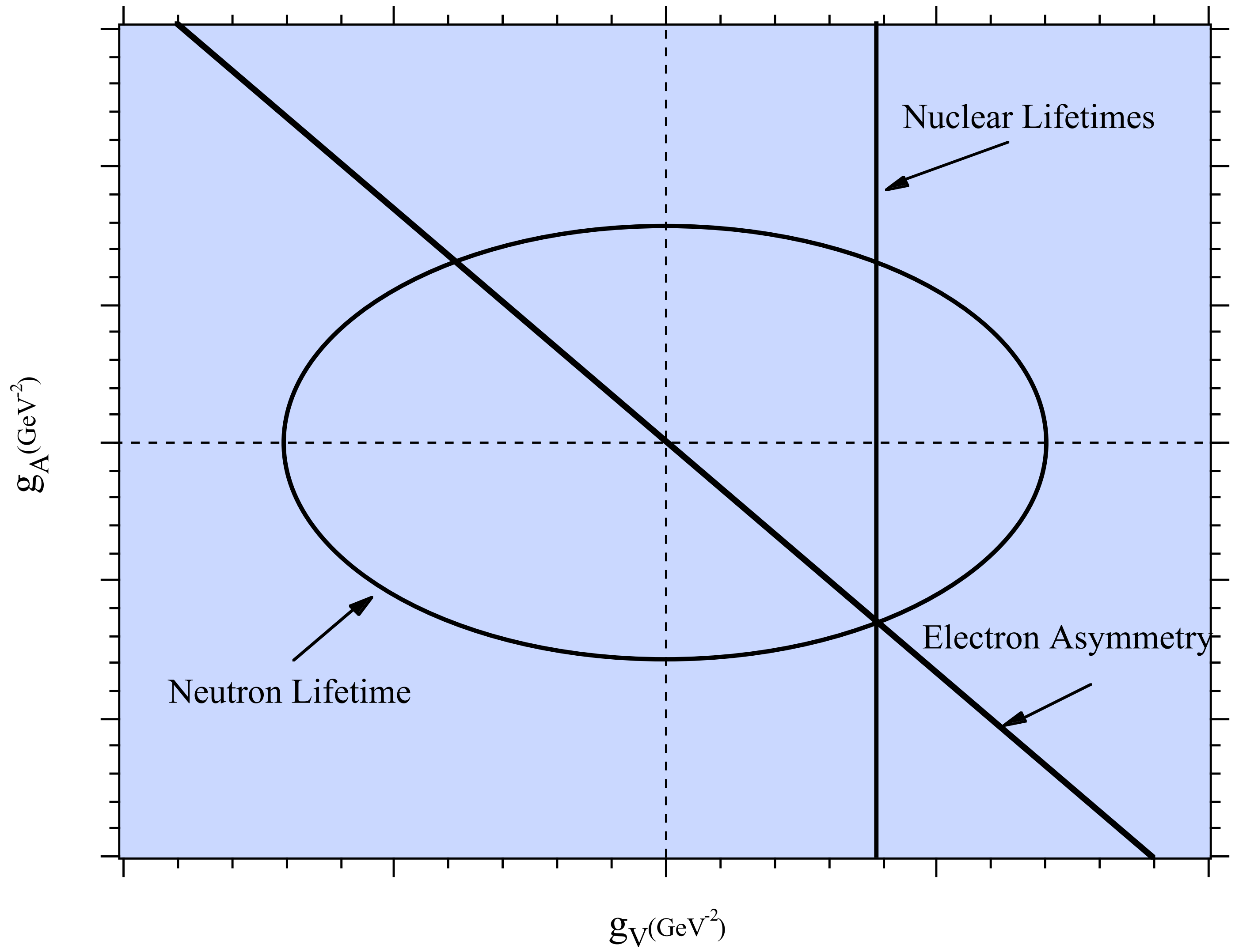
$$D = 2\frac{|\lambda|sin\phi}{1+3|\lambda|^2} = (-4 \pm 6)\times 10^{-4}$$

PDG, 2006 update

Jackson, Treiman, Wyld, *Nucl. Phys.* **4**, 206 (1957)


PDG 2005
Lifetime (s)
900
890
880
B
1.08
1.04
1.00
0.96
0.92
D
8
4
0
-4
-8x10^-3
a
-0.04
-0.06
-0.08
-0.10
-0.12
-0.14
A
-0.112
-0.114
-0.116
-0.118
-0.120
1970
1980
1990
2000
Publication Year

Standard Model Test



CKM Quark Mixing Matrix

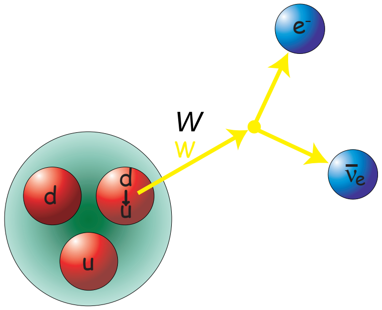
CKM matrix represents a rotation of the quark mass eigenstates to the weak eigenstates.

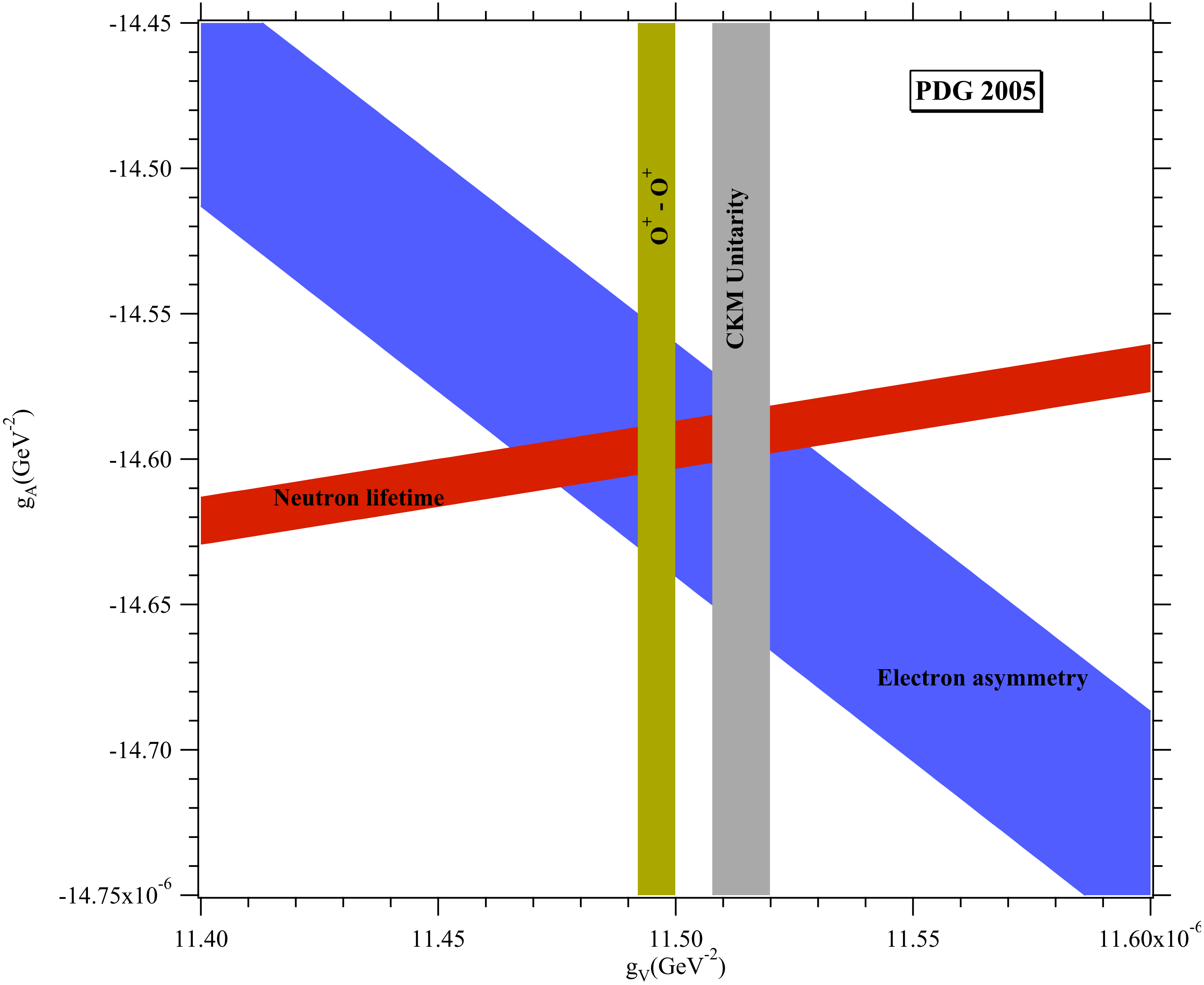
$$\begin{pmatrix} d_w \\ s_w \\ b_w \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

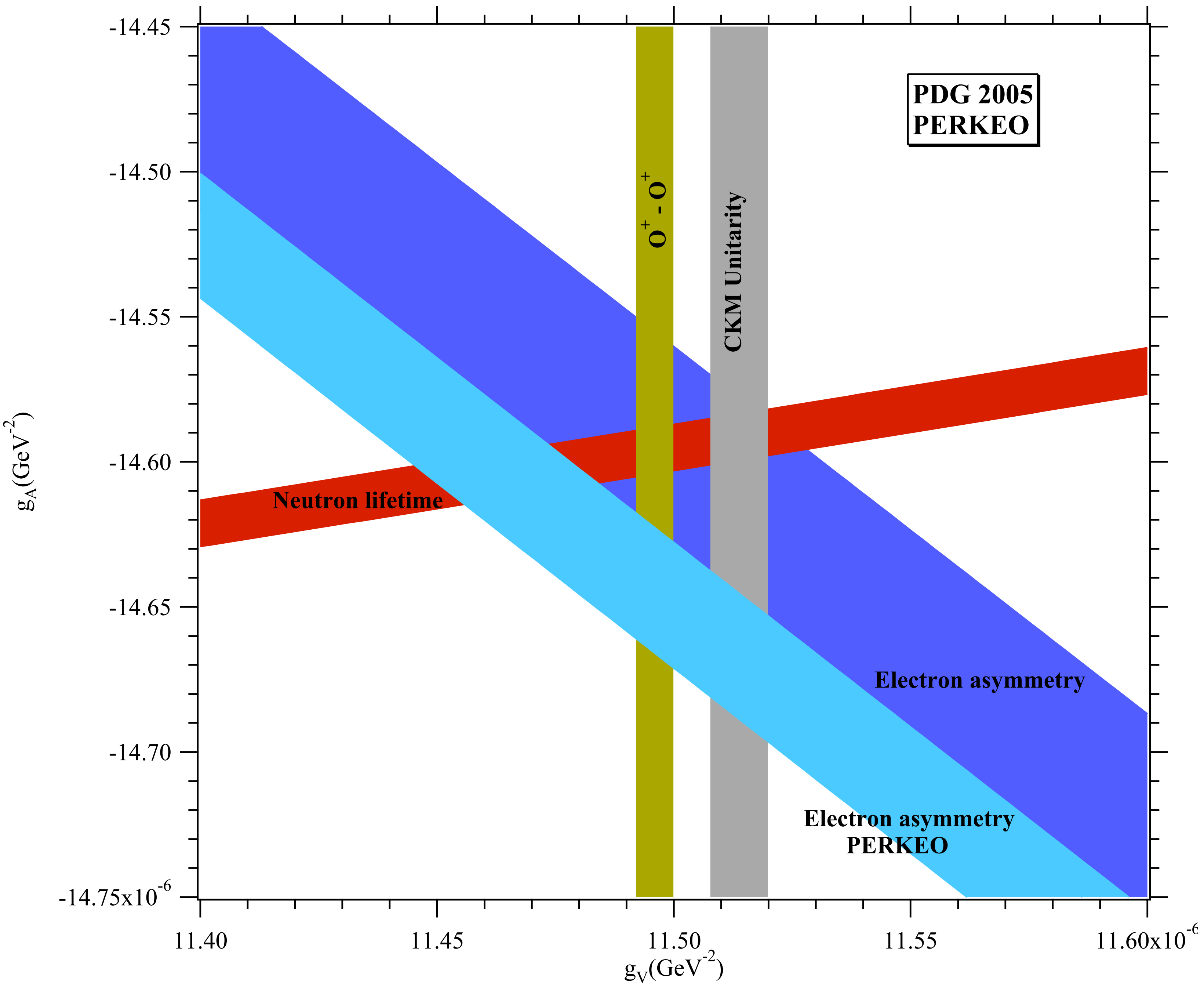
- Unitarity requires $|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$ (unless...)

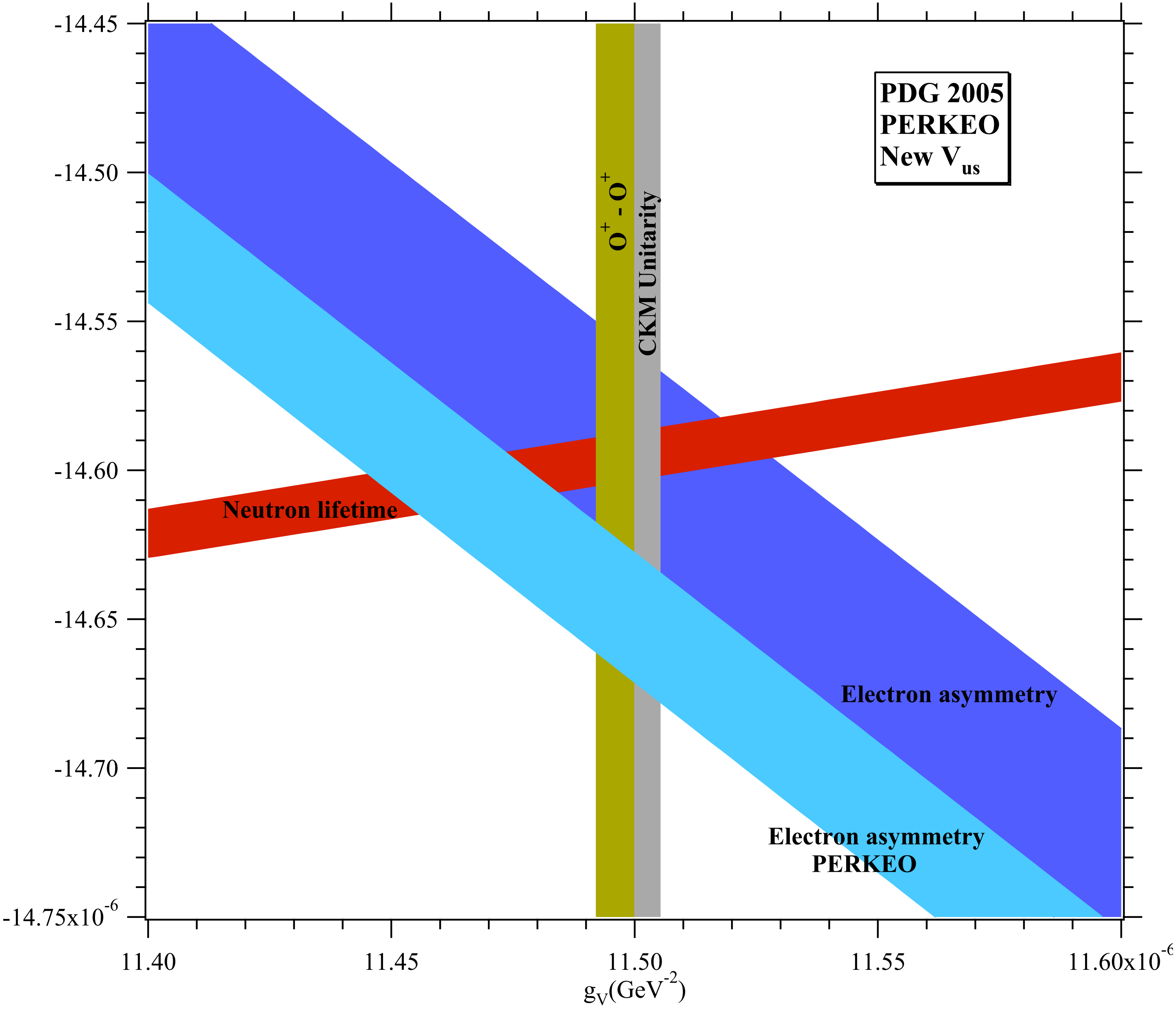
- $|V_{us}|$ obtained from kaon decay experiments; theoretical question on calculation of form factor $f_+(0)$.

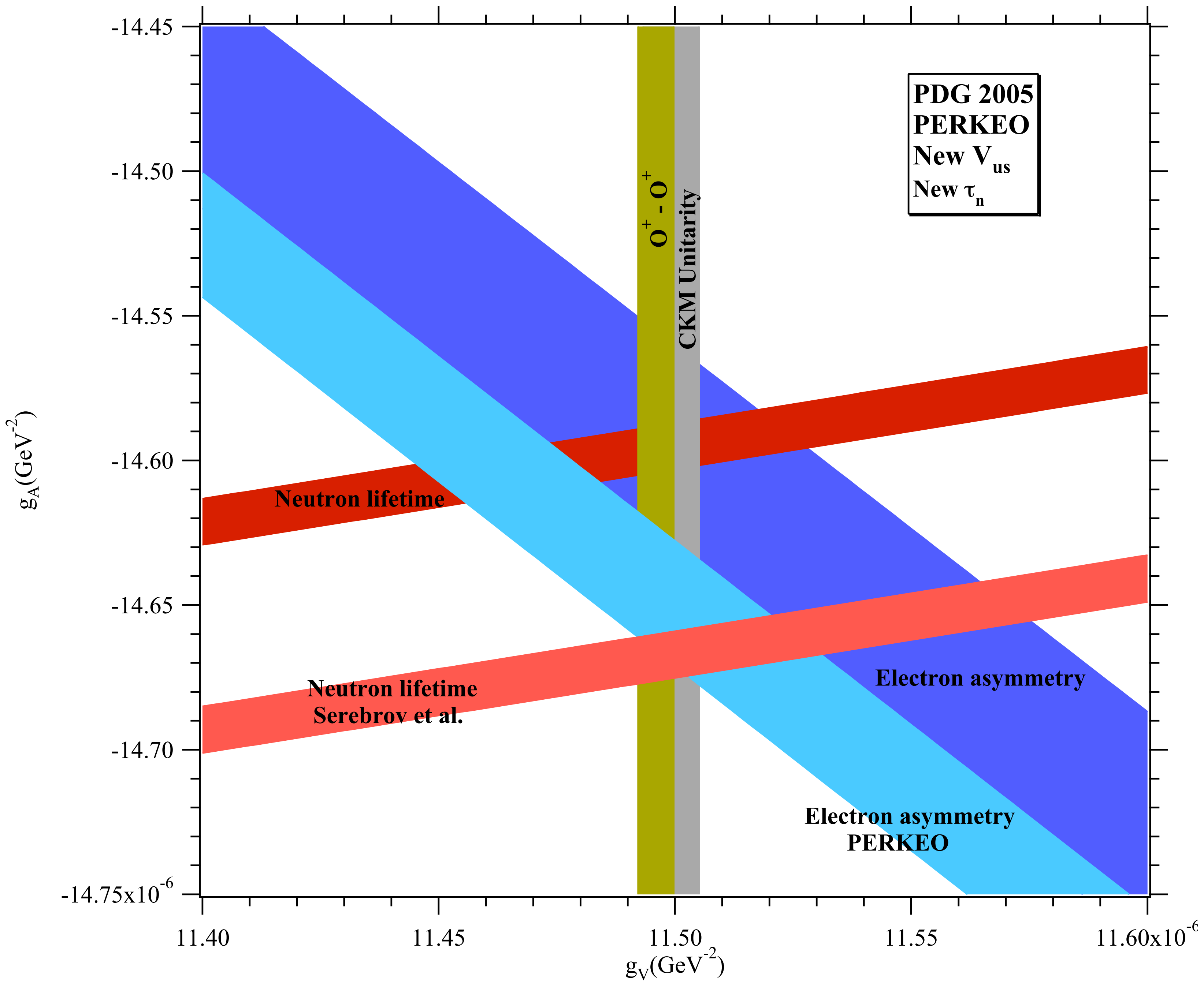
- $|V_{ud}|$ obtained from
  1. nuclear lifetimes,
  2. pion beta decay, and
  3. neutron beta decay.




PDG 2005
$0^+ - 0^+$
CKM Unitarity
Neutron lifetime
Electron asymmetry
$g_A(GeV^{-2})$
-14.45
-14.50
-14.55
-14.60
-14.65
-14.70
-14.75x10^{-6}
11.40
11.45
11.50
11.55
11.60x10^{-6}
$g_V(GeV^{-2})$


PDG 2005
PERKEO
$0^+ - 0^+$
CKM Unitarity
Neutron lifetime
Electron asymmetry
Electron asymmetry
PERKEO
-14.45
-14.50
-14.55
-14.60
-14.65
-14.70
-14.75x10^{-6}
$g_A(\mathrm{GeV}^{-2})$
11.40
11.45
11.50
11.55
11.60x10^{-6}
$g_V(\mathrm{GeV}^{-2})$


PDG 2005
PERKEO
New V_us
0+ - 0+
CKM Unitarity
Neutron lifetime
Electron asymmetry
Electron asymmetry PERKEO
g_A(GeV^-2)
-14.45
-14.50
-14.55
-14.60
-14.65
-14.70
-14.75x10^-6
11.40
11.45
11.50
11.55
11.60x10^-6
g_V(GeV^-2)



PDG 2005
PERKEO
New V_{us}
New τ_n
$0^+ - 0^+$
CKM Unitarity
Neutron lifetime
Neutron lifetime
Serebrov et al.
Electron asymmetry
Electron asymmetry
PERKEO
-14.45
-14.50
-14.55
-14.60
-14.65
-14.70
-14.75x10^{-6}
$g_A(\mathrm{GeV}^{-2})$
11.40
11.45
11.50
11.55
11.60x10^{-6}
$g_V(\mathrm{GeV}^{-2})$

$|V_{ud}|$ Comparison

Nuclear decays: $|V_{ud}|_{0+} = 0.97377 \pm 0.00027$

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

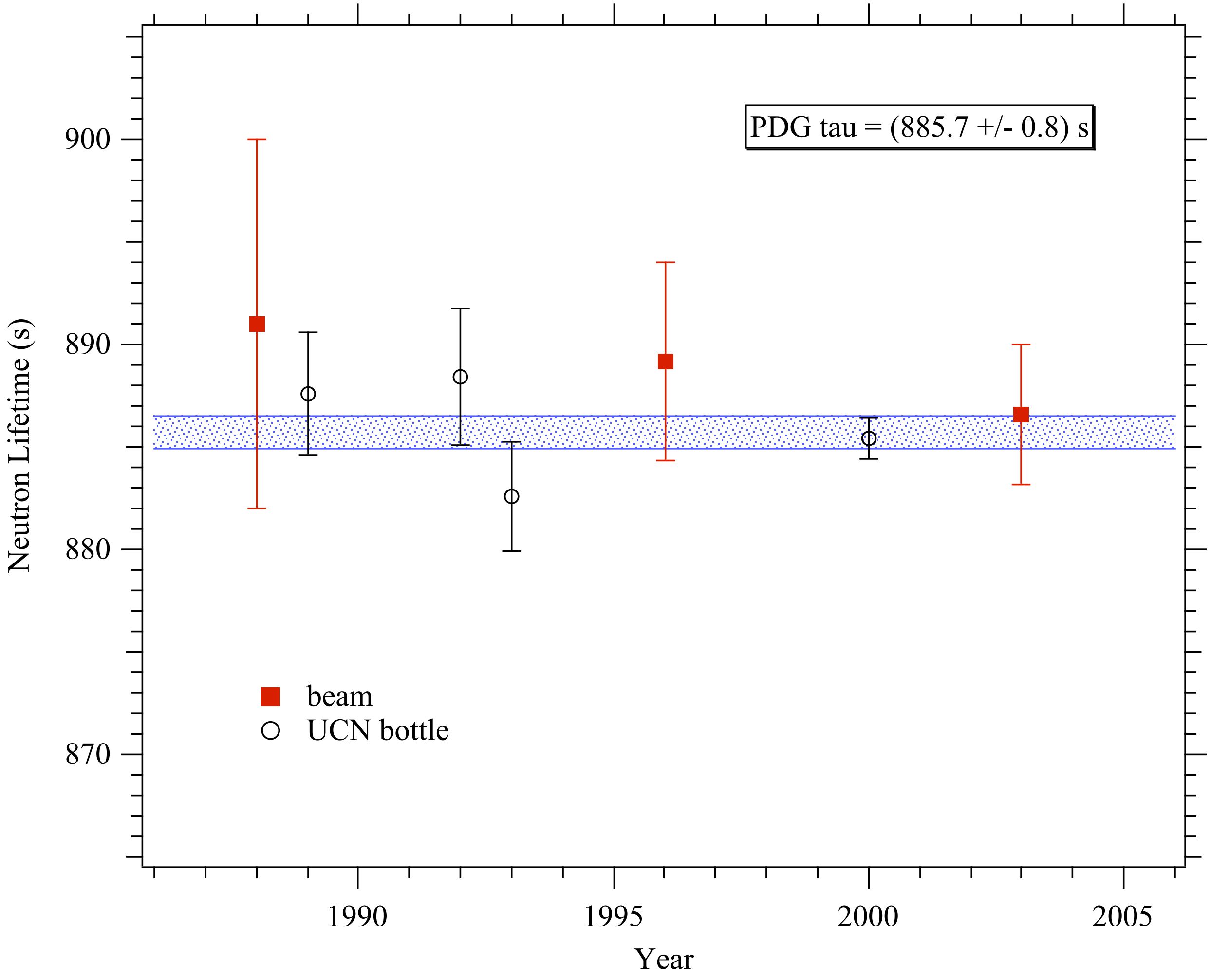
Neutron decay: $|V_{ud}|_{n} = 0.9745 \pm 0.0016$

Contributions in neutron system (PDG 2006):

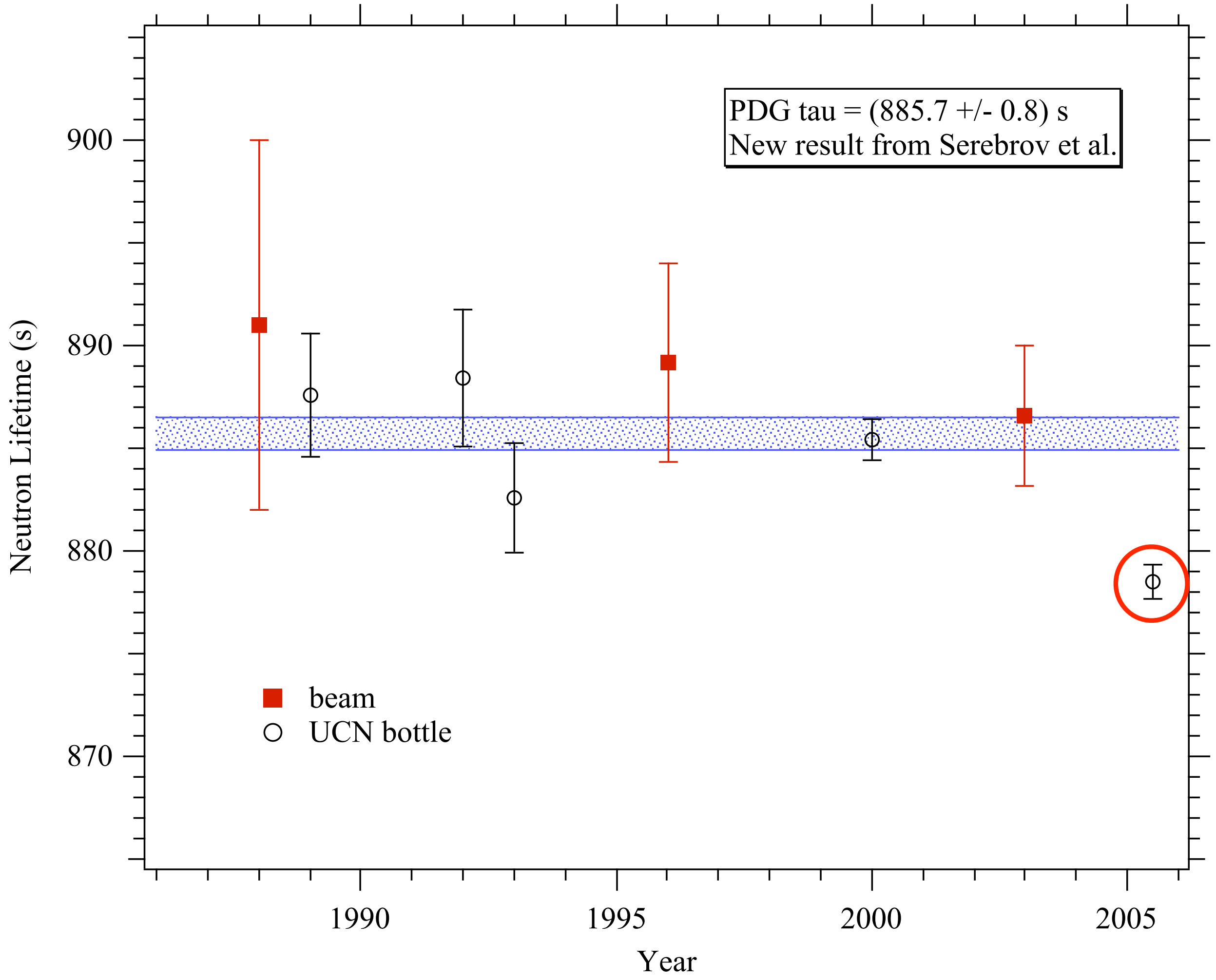
$$\frac{\sigma_\tau}{\tau} = 0.09\%, \ \frac{\sigma_\lambda}{\lambda} = 0.23\%, \ \text{and} \ \frac{\sigma_{th.}}{th.} = 0.04\%$$

Significant improvements are feasible.

Status of the Neutron Lifetime



Status of the Neutron Lifetime



The Exponential Decay Law: $N = N_0 e^{-\lambda t}$

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:

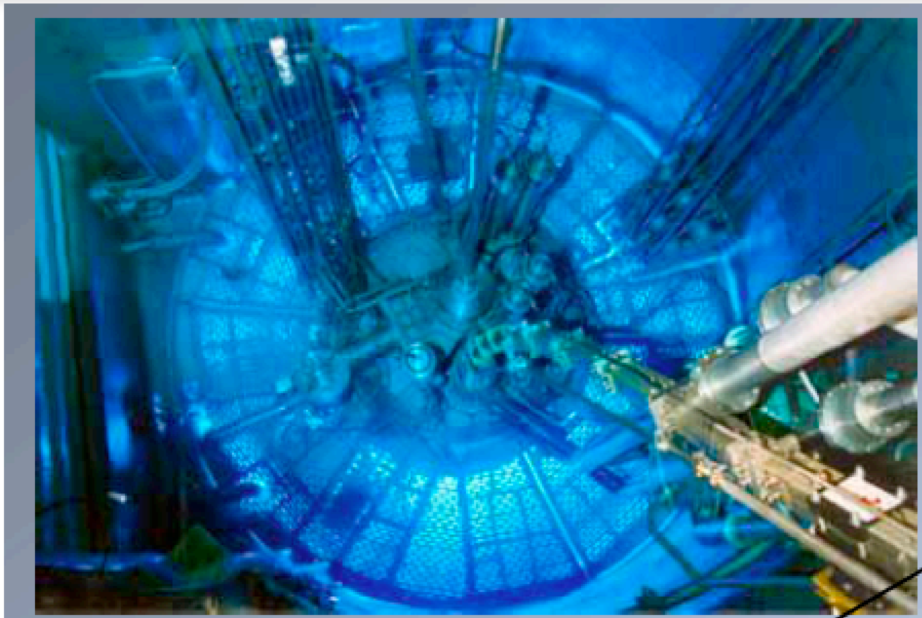
$$ln(N/N_0) = -\lambda t$$

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

In a nutshell ...

Technique	*Detection*	*Issues*	*Approach*
(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	“cleaning”; spectrum measurement
(2’) UCN magnetic confinement	neutron and/or proton monitor	UCN energy distribution; orbits (spin flip)	“cleaning”; spectrum measurement
(3) UCN in He-4 (or vacuum)	monitor decay electrons	signal and background	more signal, less background

UCN/VCN Facility PF2 at ILL



Neutron turbine
A. Steyerl (TUM - 1985)

Vertical guide tube

Cold source

Reactor core

MamBo I at ILL

Mampe, Ageron, Bates, Pendlebury, and Steyerl (1989)

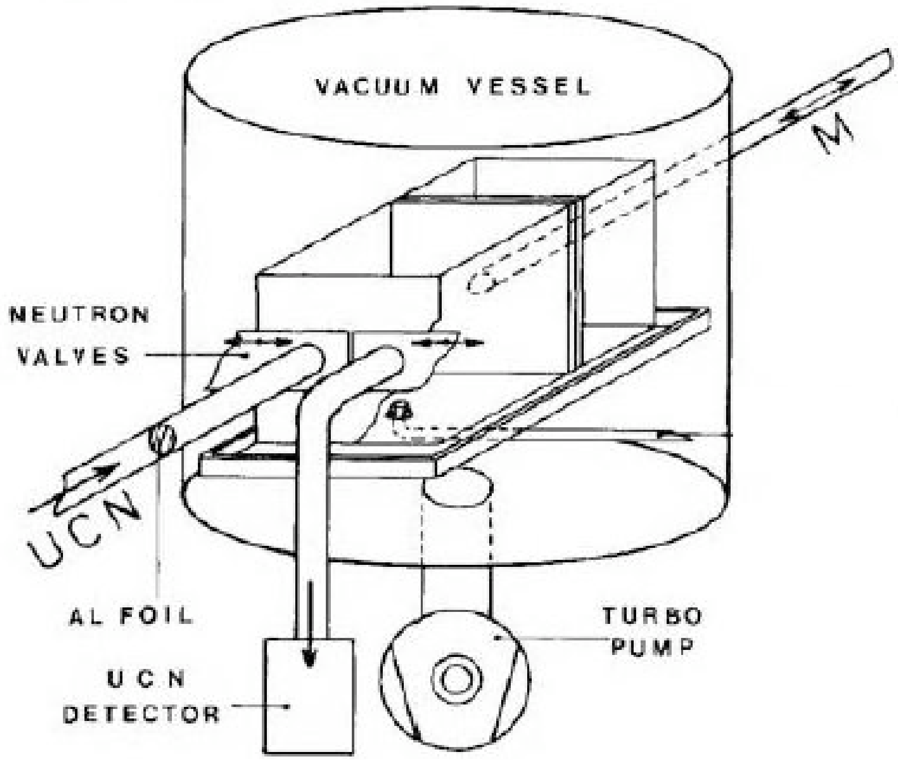


FIG. 1. Sketch of the apparatus.

$$\lambda_{st} = \lambda_n + \lambda_{loss} + \ \ldots$$

Vary *A* and *V* of confinement and extrapolate to infinite *V*.

MamBo I at ILL

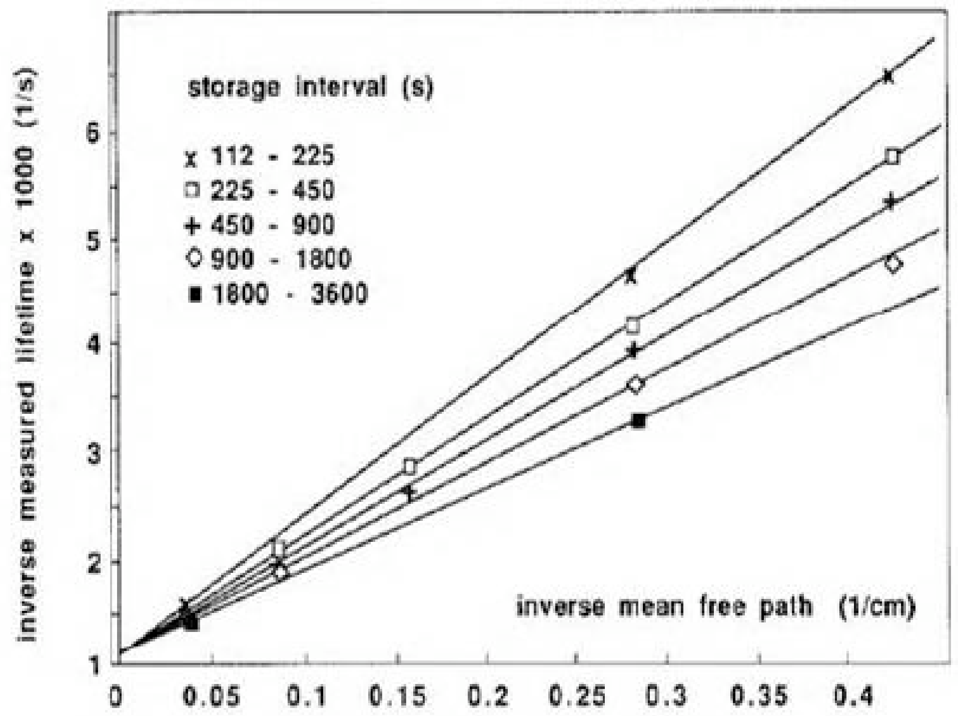
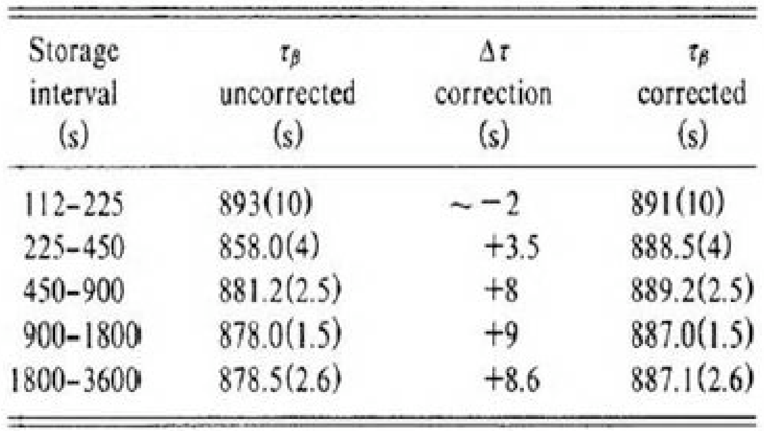


FIG. 2. Measured inverse bottle lifetimes as a function of the bottle inverse mean free path and for different storage intervals, from a 10-d run. The error bars are smaller than the data points.

TABLE I. Results of τ_β for different storage intervals.



Storage interval (s)	τ_β uncorrected (s)	$\Delta\tau$ correction (s)	τ_β corrected (s)
112–225	893(10)	~ −2	891(10)
225–450	858.0(4)	+3.5	888.5(4)
450–900	881.2(2.5)	+8	889.2(2.5)
900–1800	878.0(1.5)	+9	887.0(1.5)
1800–3600	878.5(2.6)	+8.6	887.1(2.6)

Additional corrections for gravity, filling and counting time, ...

$$\lambda_n = (887.6 \pm 3)\, s$$

Mampe et al., *Phys. Rev. Lett.* **63** (1989)

UCN Gravitational Trap Experiment

**A. Serebrov[1,3], V. Varlamov[1], A. Kharitinov[1], A. Fomin[1],
Yu. Pokotilovski[2], P. Geltenbort[4], J. Butterworth[4],
I. Krasnoschekova[1], M. Lasakov[1], K. Schechenbach[5],
R. Taldaev[1], A. Vassiljev[1], and O. Zherebtov[1]**

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):

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

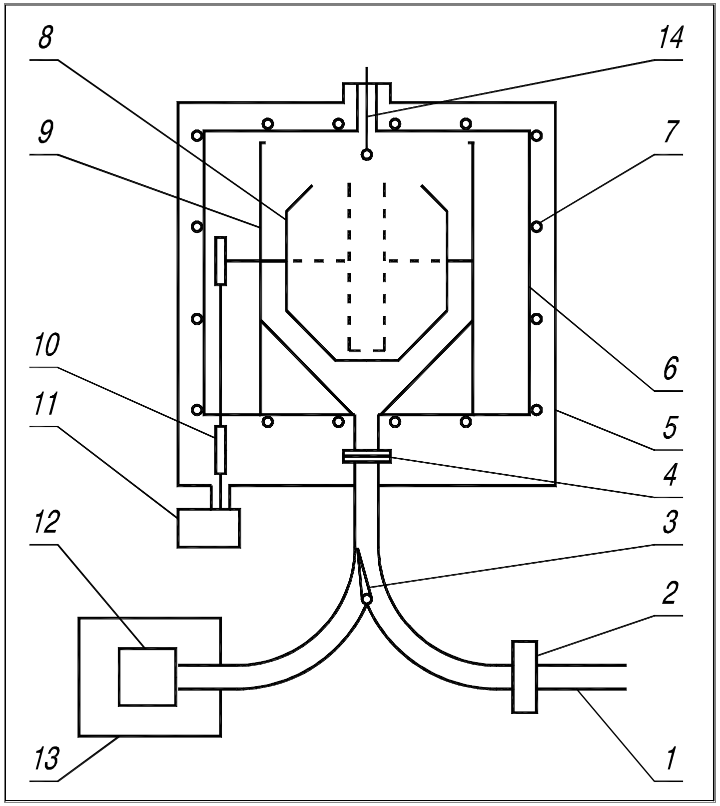
where $\eta = -Im(V_F)/Re(V_F) = \text{wall loss coefficient}$

$\gamma = \text{loss-weighted collision frequency}$

- 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

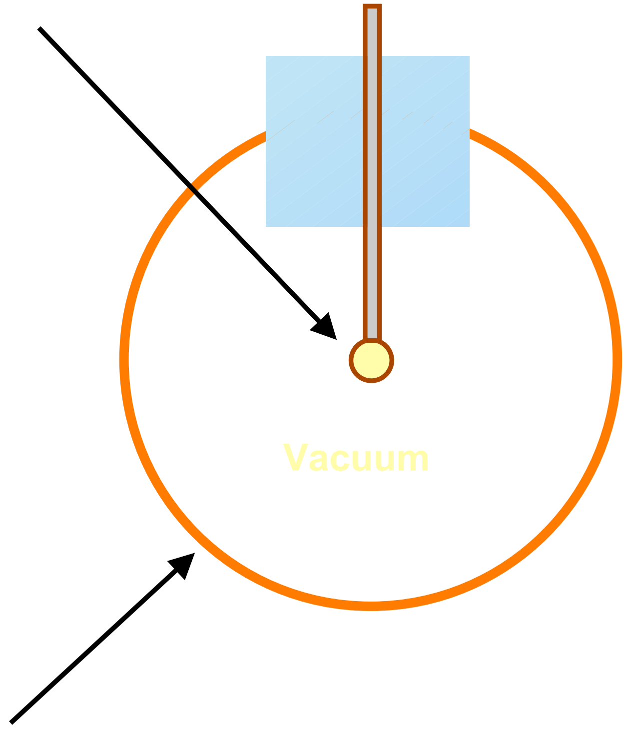
Gravitrap UCN storage



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

Low temperature fomblin oil

LTF evaporator is heated to +140^{0}C



Trap surface is cooled to about -150^{0}C

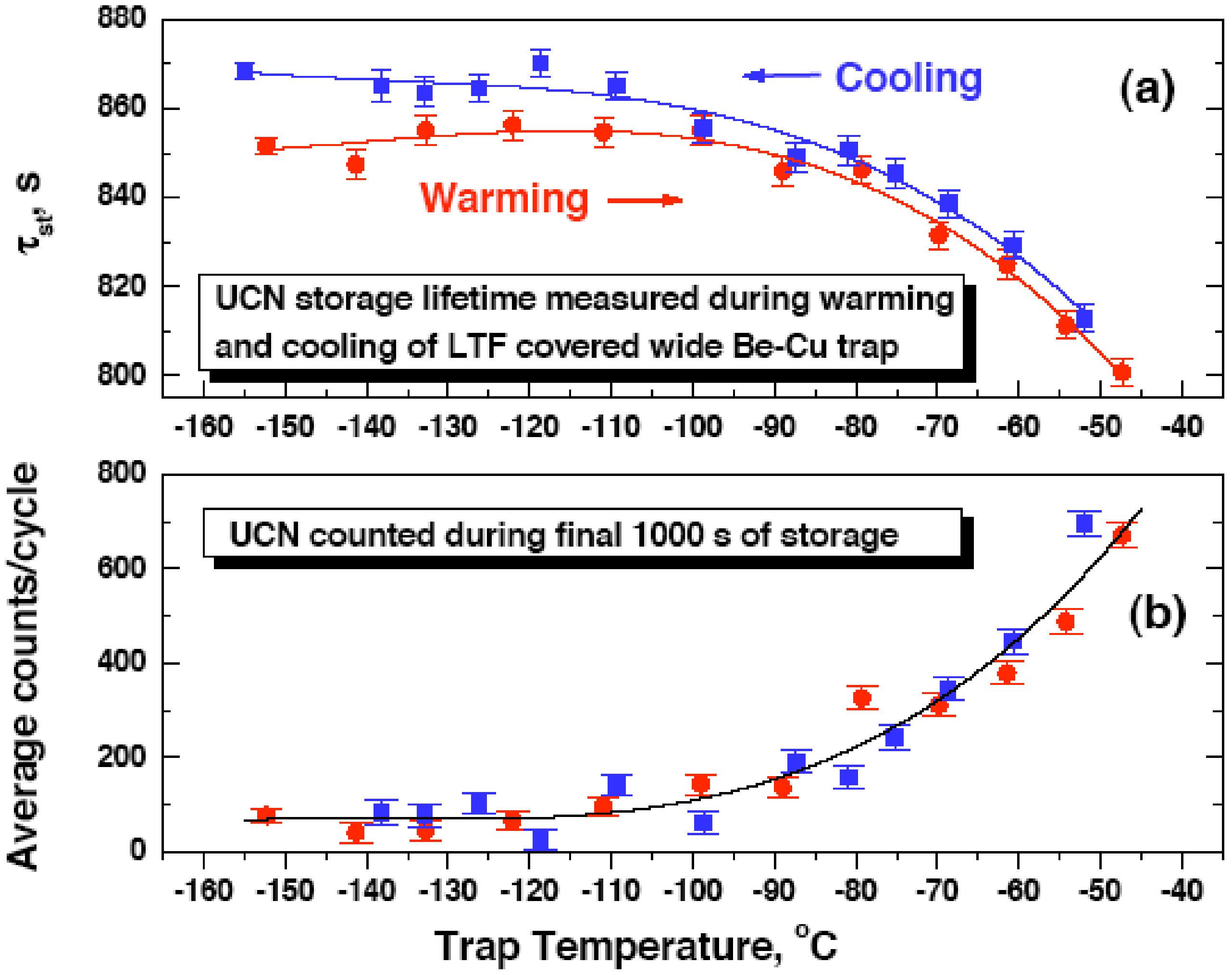
- Why fomblin?
  - Contains only C, O, and F (no H)
  - small neutron capture X-section
  - at low temp, inelastic scattering is small
  - liquid fills in gaps
  - uniform films by vapor deposition
- Calculation by Pokotilovski of

$$\eta = 2 \times 10^{-6}$$

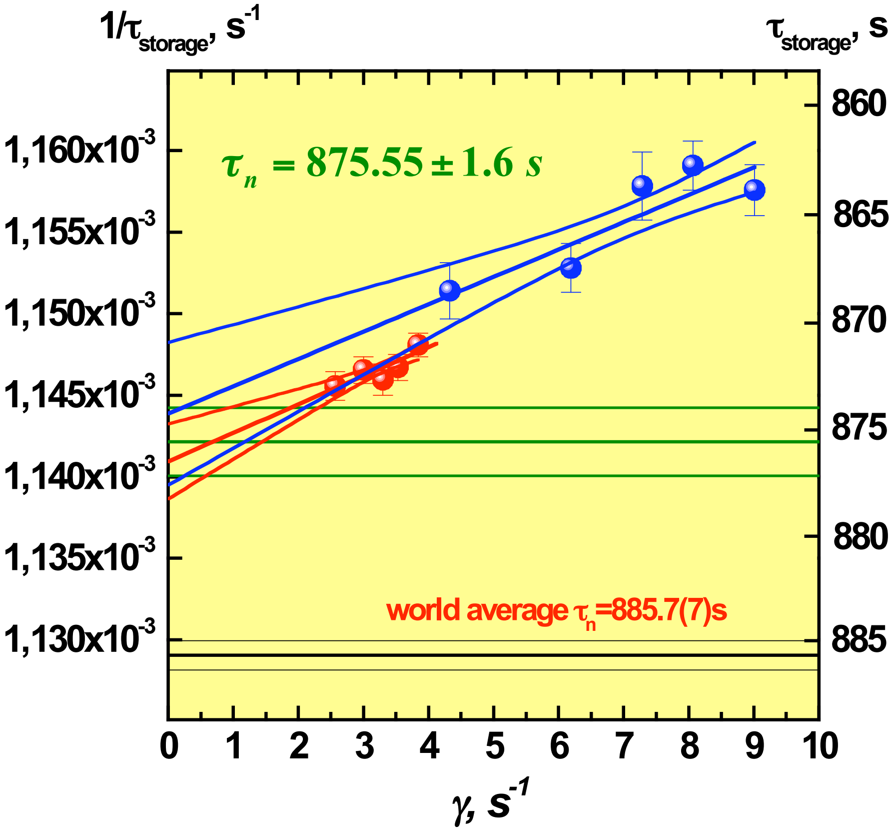
See INT talk next week.

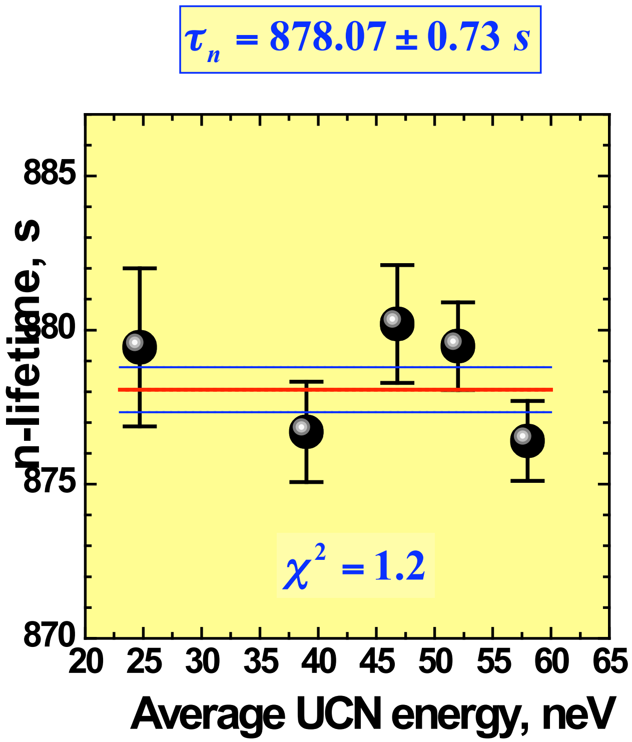
Pokotolovski, *JETP* 9**6** (2003)

Temperature dependence

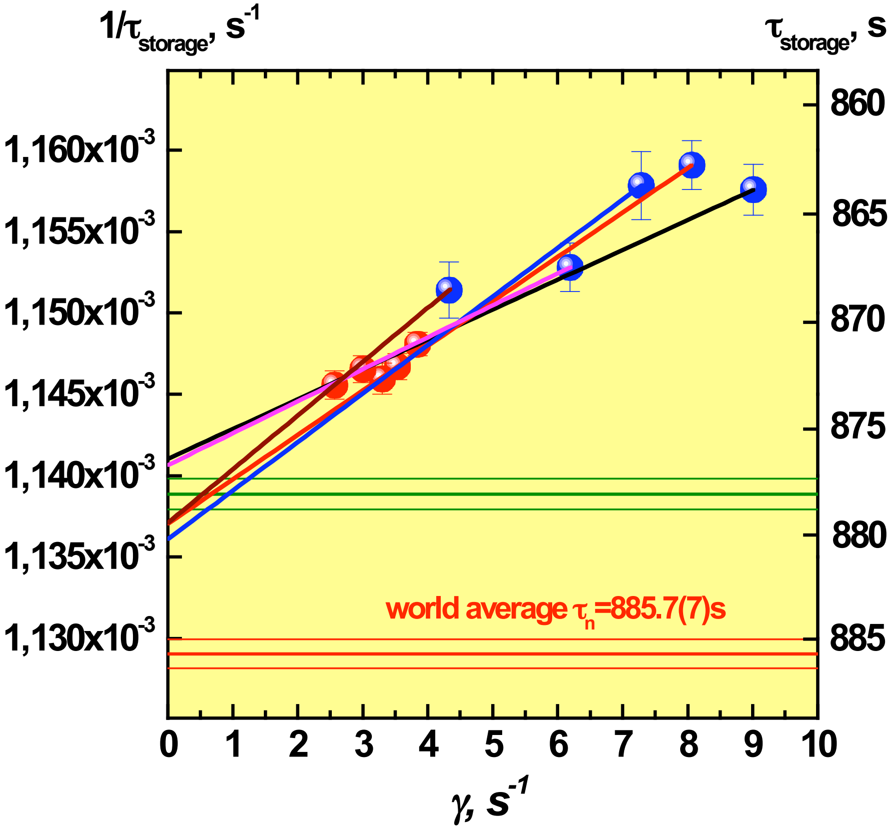


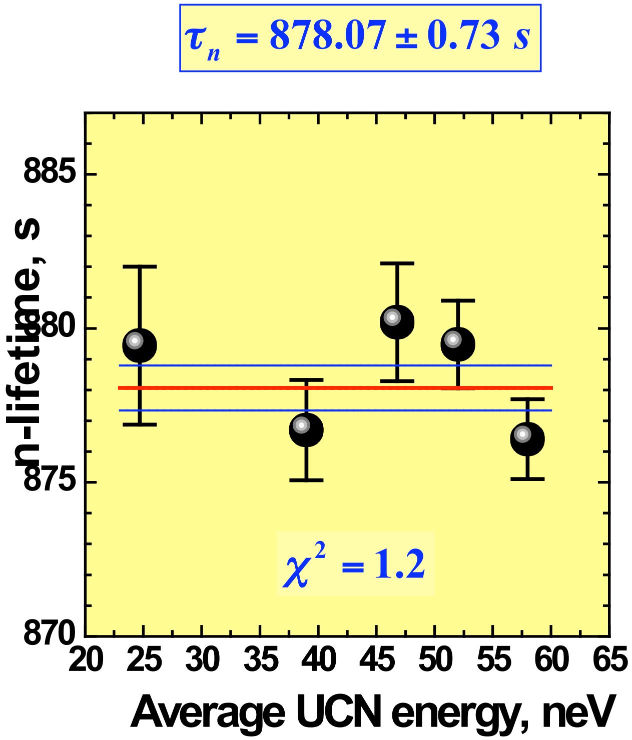
Extrapolation (E)



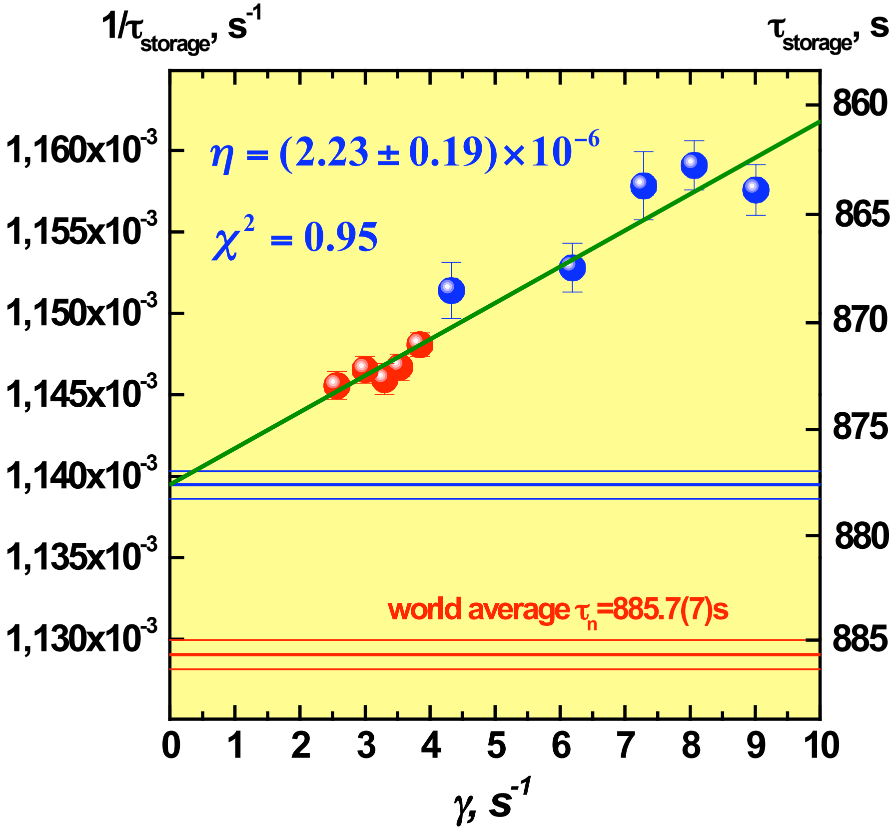


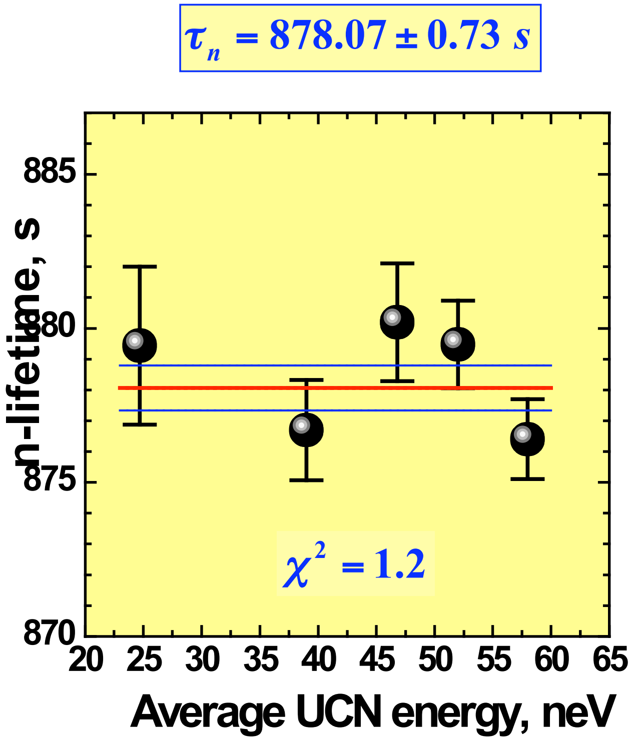
Extrapolation (size)





Extrapolation (E + size)





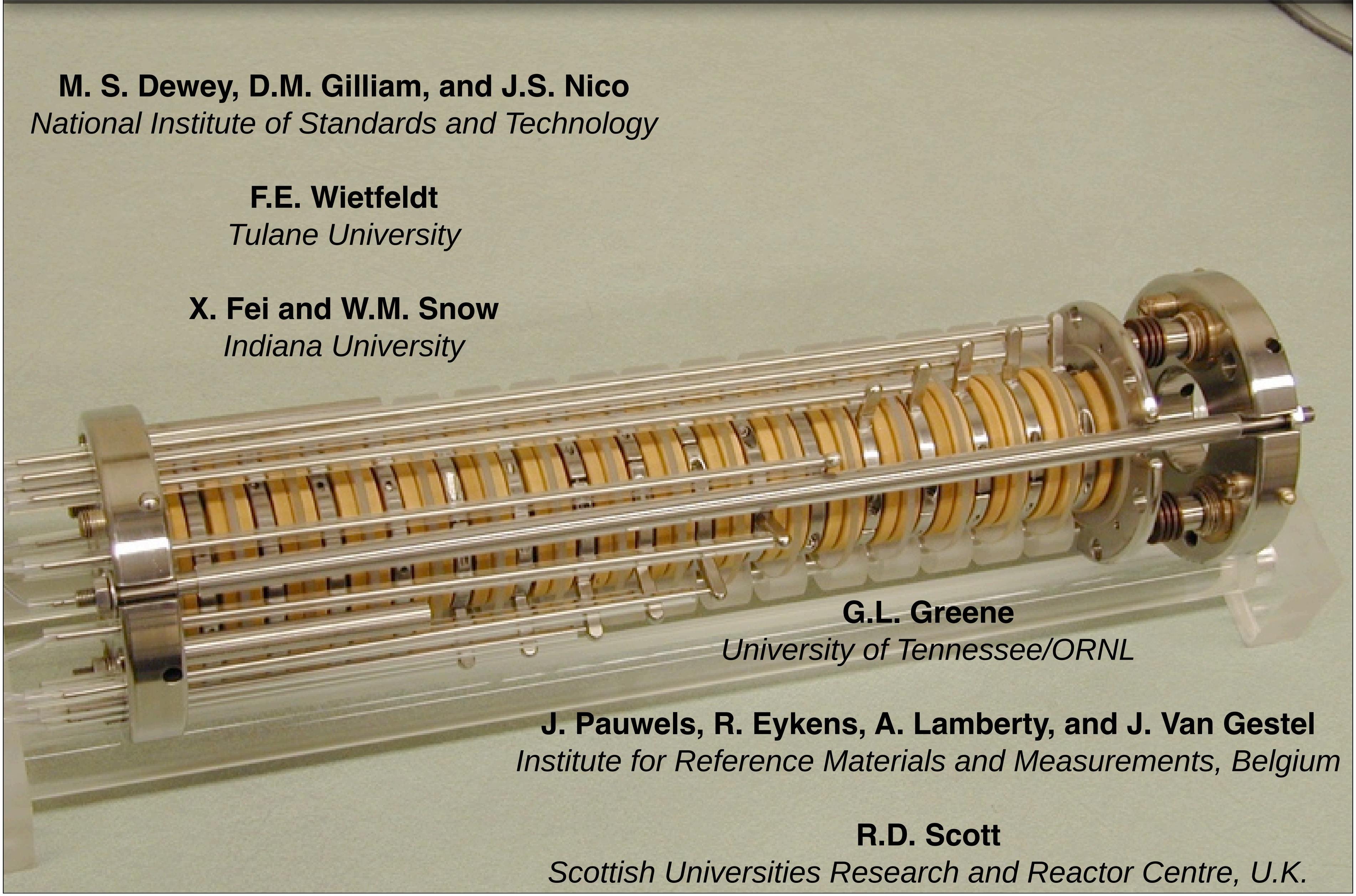
Result and Systematics

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 uncertaities	0	0.104
Uncertaities of traps sizes(1mm)	0	0.058
Influence of the residual gas	0.40	0.024
Uncertaity of LTF critical energy (20 neV)	0	0.004
Total systematic effect	0.40	0.30

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

Serebrov et al, *Phys. Lett. B* **605** (2005) p.72

Proton Trap Experiment



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

F.E. Wietfeldt
Tulane University

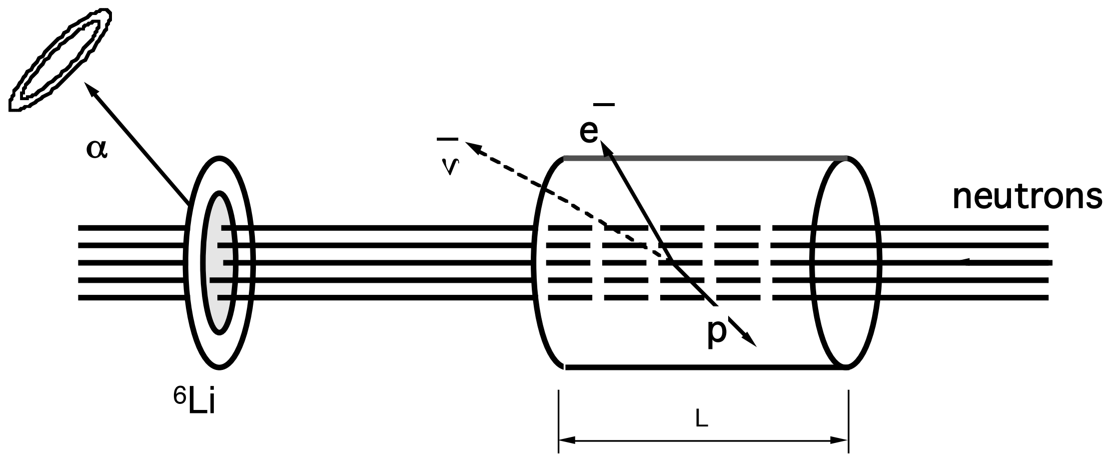
X. Fei and W.M. Snow
Indiana University

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.

The “in-beam” Method



$$\dot{N}_p = -\frac{dN}{dt} = N\lambda$$

Neutron rate is proportional to the alpha rate:

$$\dot{N}_n = k\dot{N}_\alpha = \epsilon_\Omega \int\int \left(\frac{\rho t N_A}{M}\right)\sigma_0 v_0 \frac{I(v)}{v}\, dAdv = \epsilon_\Omega \left(\frac{\rho t N_A}{M}\right)\sigma_0 v_0 \int\int \frac{I(v)}{v}\, dAdv$$

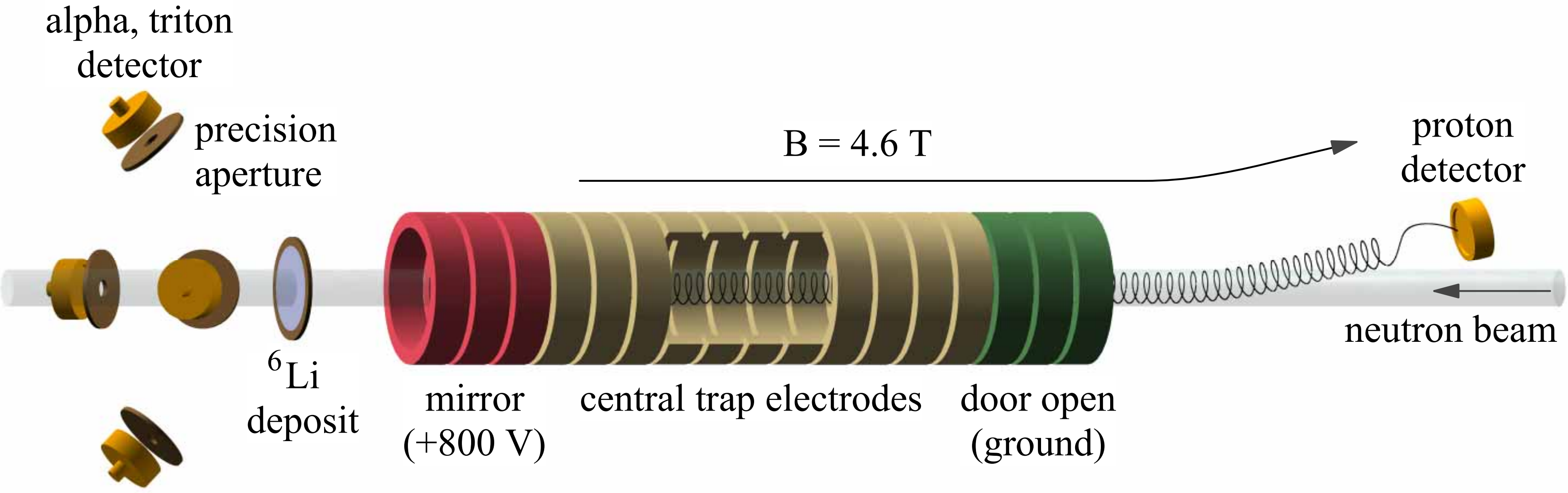
Mean number of neutrons passing a fiducial volume:

$$N = \int_0^L dz \int\int \frac{I(v)}{v}\, dAdv = L \int\int \frac{I(v)}{v}\, dAdv \Longrightarrow \dot{N}_\alpha = k\frac{N}{L}$$

$$\tau = \frac{N}{\dot{N}_p} = \frac{\dot{N}_\alpha L}{k\dot{N}_p} \quad \text{where} \quad k = \epsilon_\Omega \frac{\rho t N_A}{M}\sigma_0 v_0$$

The “in-beam” Method

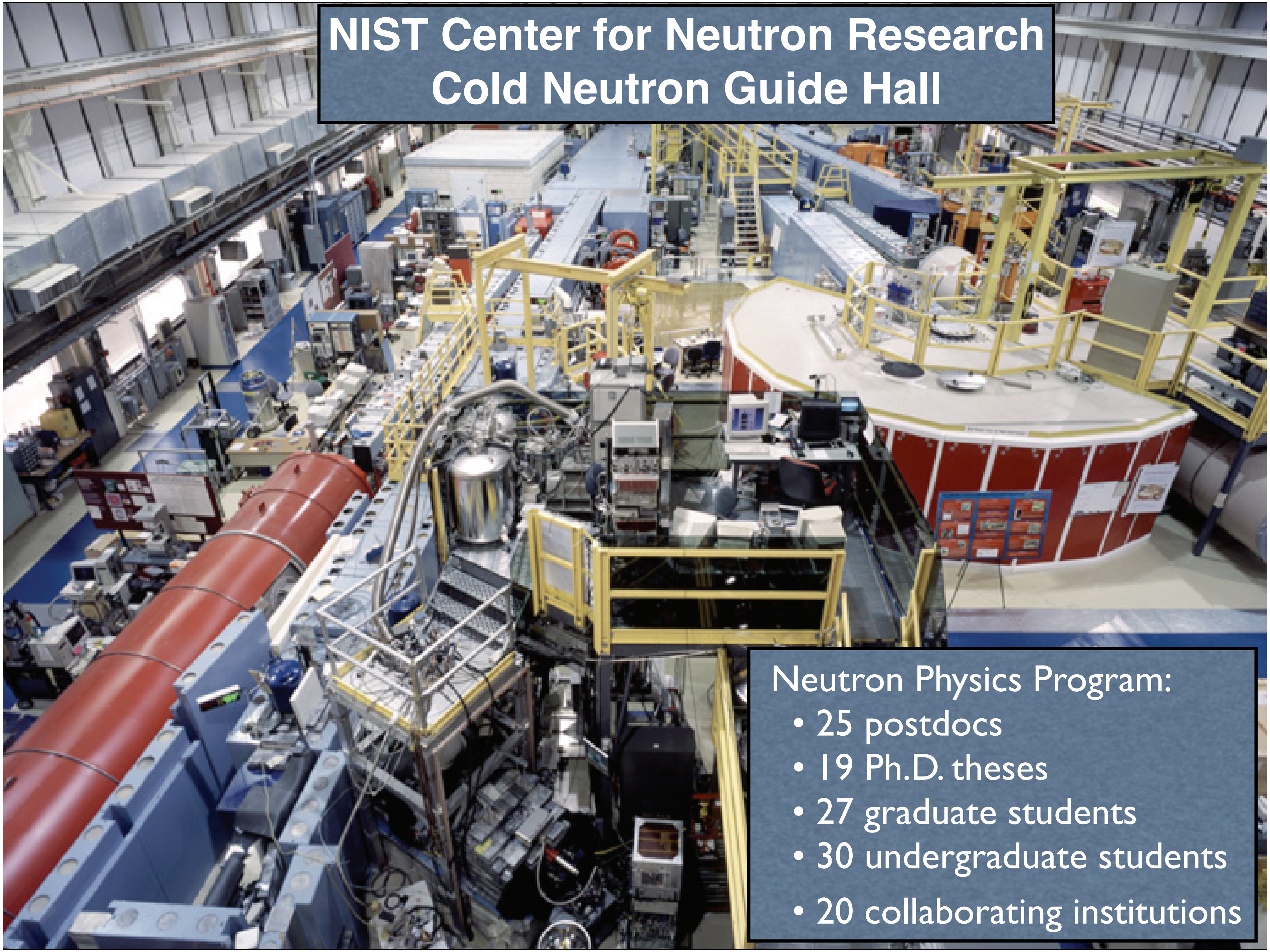
$$\tau = \frac{\dot{N}_{\alpha+t}}{\dot{N}_p}\left(\frac{\varepsilon_p}{\varepsilon_o v_o}\right)\left(nl + L_{end}\right)$$



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

Byrne et al., *Nucl. Instrum. Meth. A* **284** (1989)

NIST Center for Neutron Research
Cold Neutron Guide Hall



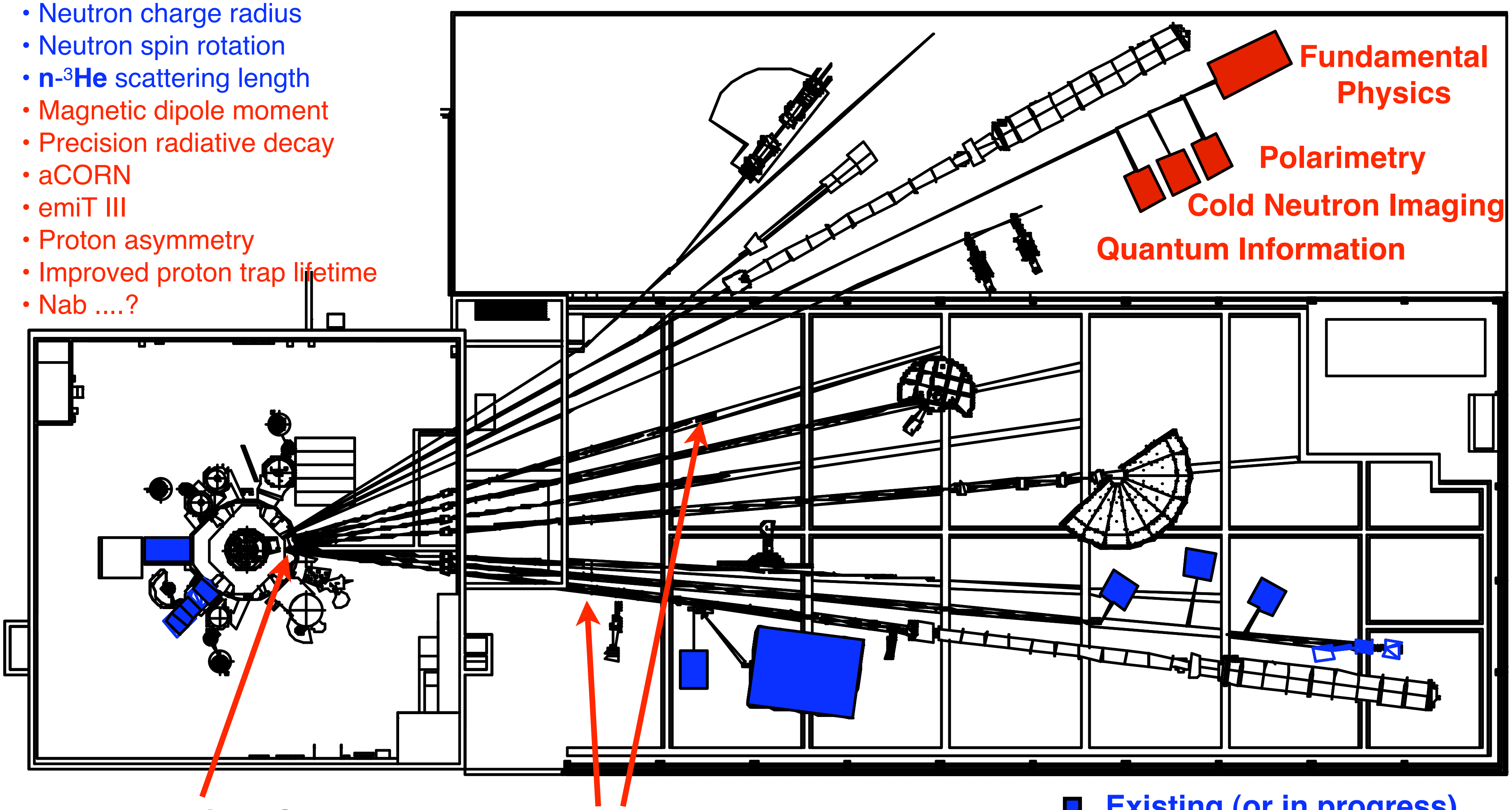
Neutron Physics Program:

- 25 postdocs
- 19 Ph.D. theses
- 27 graduate students
- 30 undergraduate students
- 20 collaborating institutions

Neutron Physics Expansion at NIST

Physics Program:

- UCN n lifetime
- Absolute neutron fluence (τ_n)
- Neutron charge radius
- Neutron spin rotation
- **n-^{3}He** scattering length
- Magnetic dipole moment
- Precision radiative decay
- aCORN
- emiT III
- Proton asymmetry
- Improved proton trap lifetime
- Nab ....?



Proposed New Guide Hall (conceptual design)

Fundamental Physics

Polarimetry

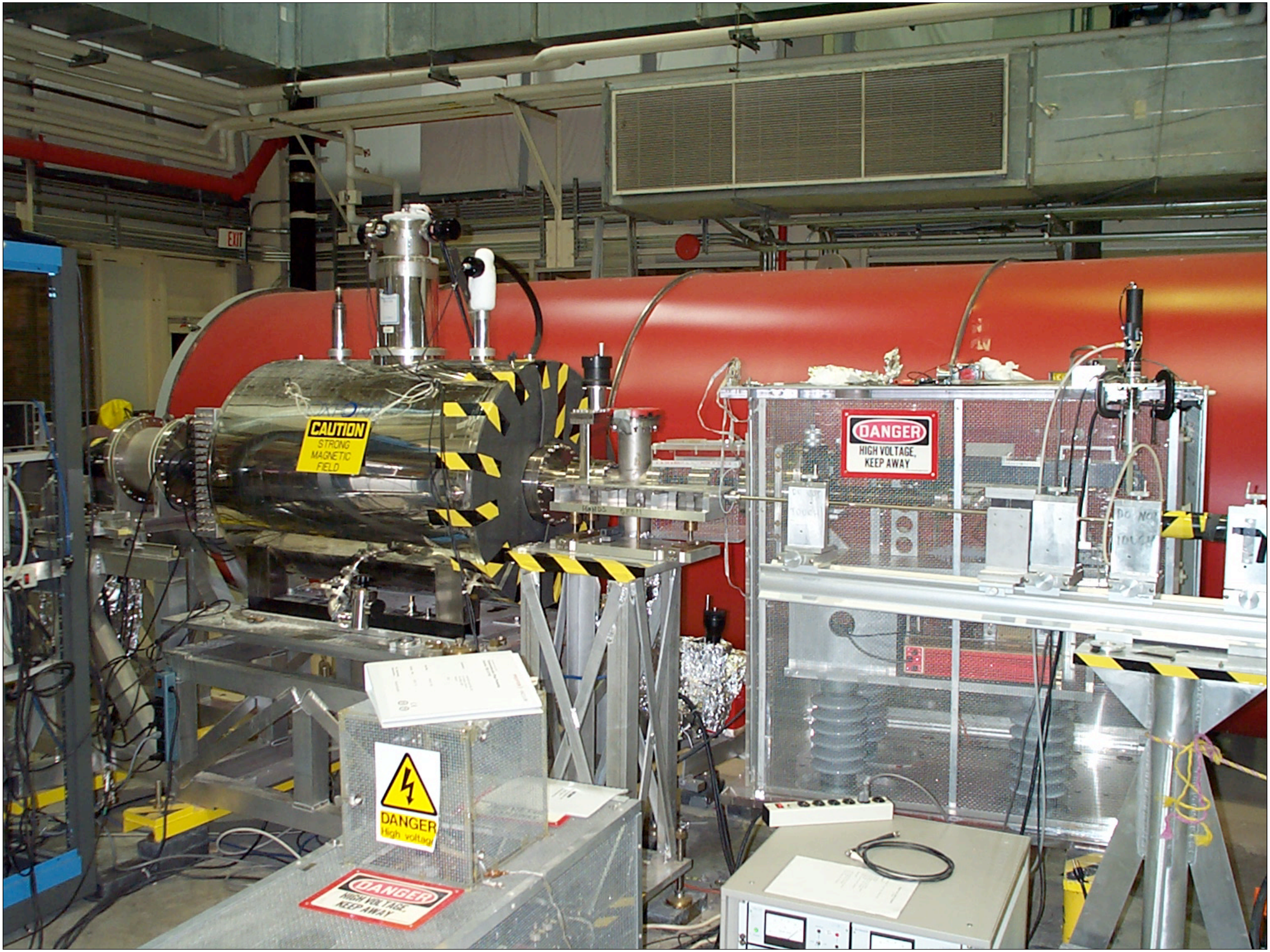
Cold Neutron Imaging

Quantum Information

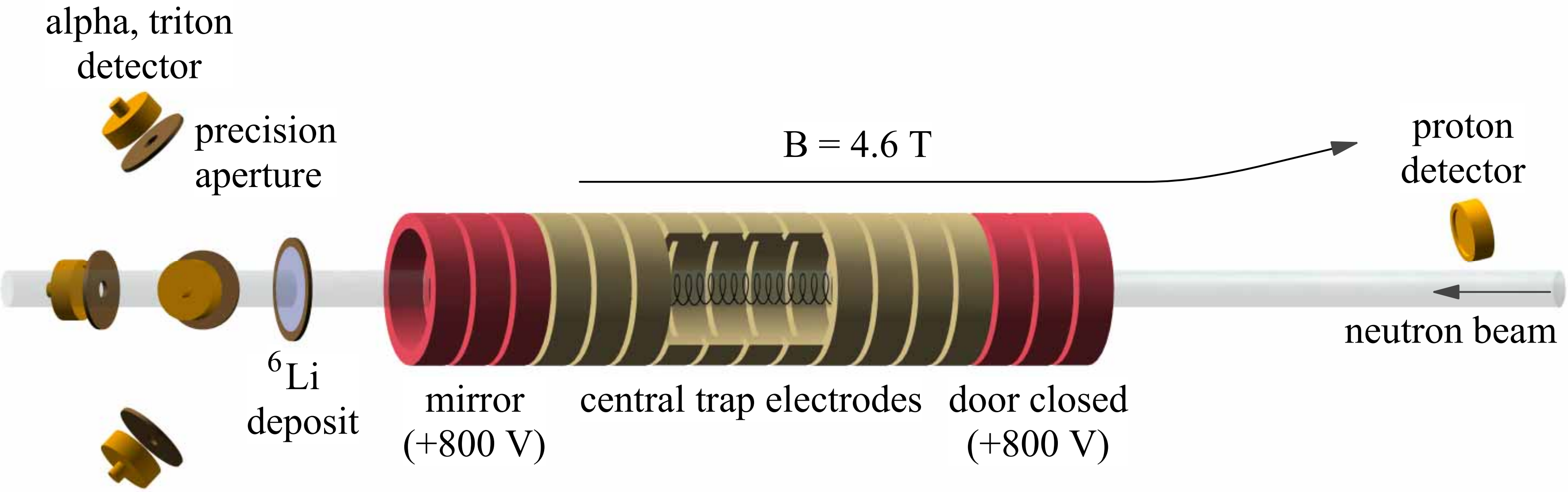
Upgrade Cold Source (liquid deuterium, x~1.5)

Upgrade Existing Guides

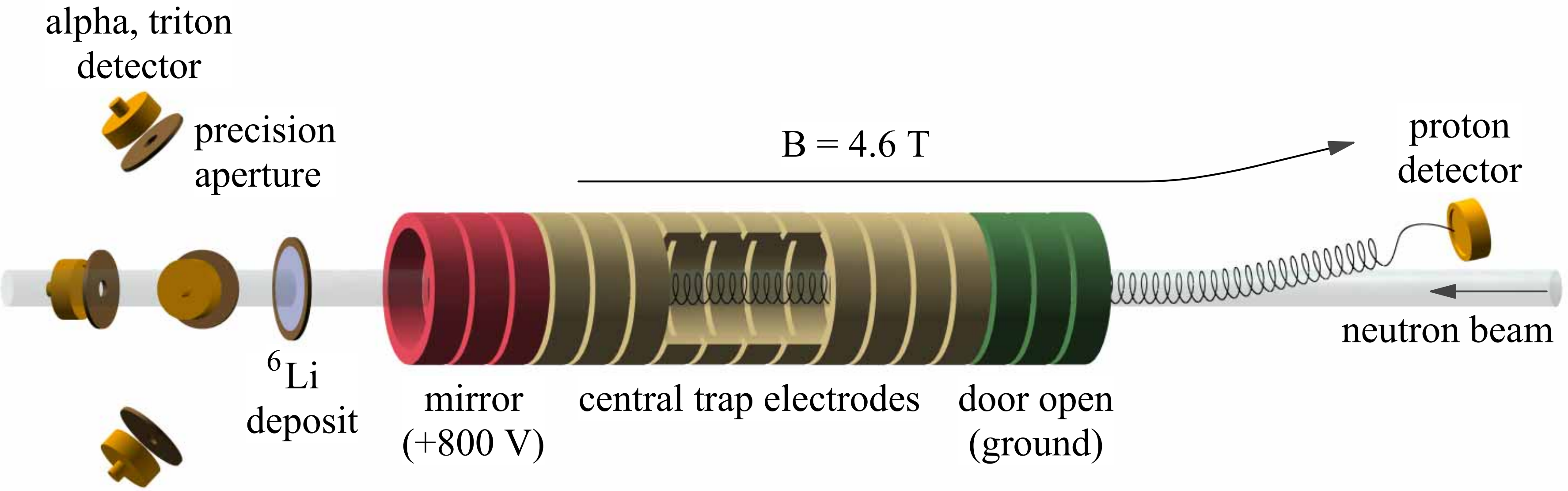
🟦 **Existing (or in progress)**
🟥 **Proposed**


EXIT
CAUTION
STRONG MAGNETIC FIELD
DANGER
HIGH VOLTAGE, KEEP AWAY
DO NOT TOUCH
DANGER
High voltage
DANGER
HIGH VOLTAGE, KEEP AWAY

Trapping Cycle - 10 ms

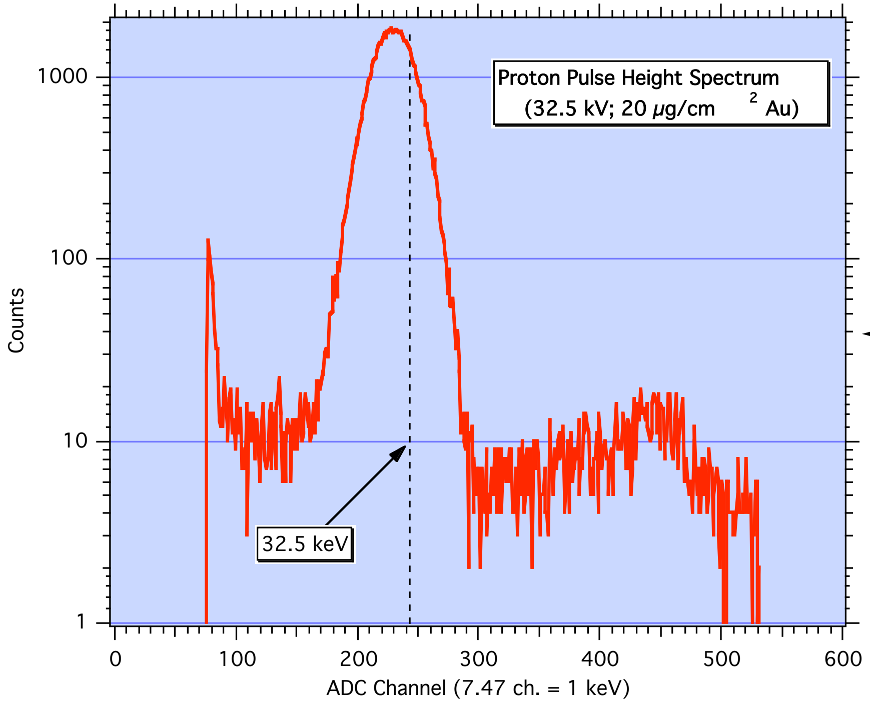


Counting Cycle - 100 *μ*s

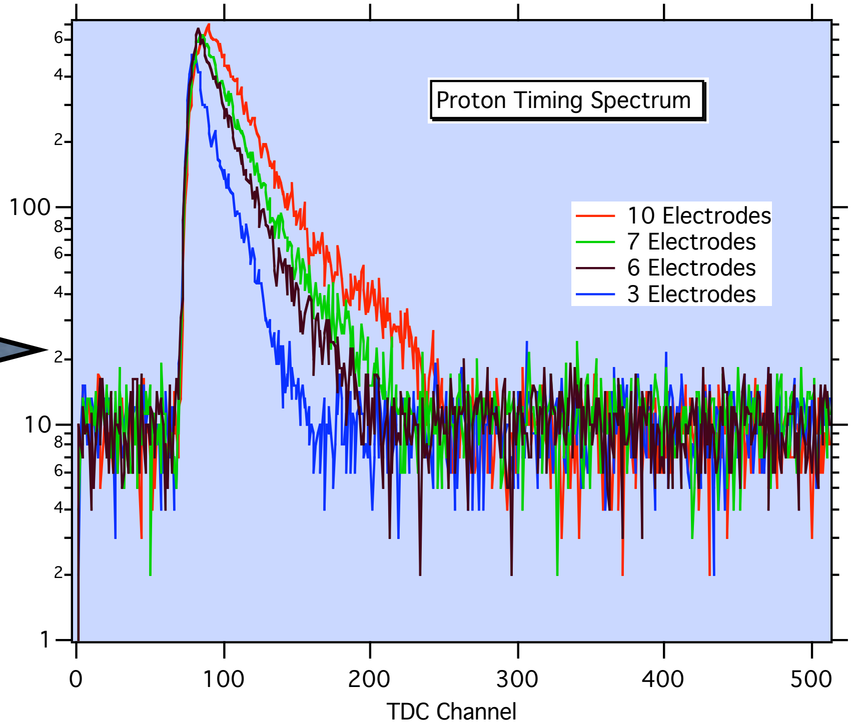


Proton Counting

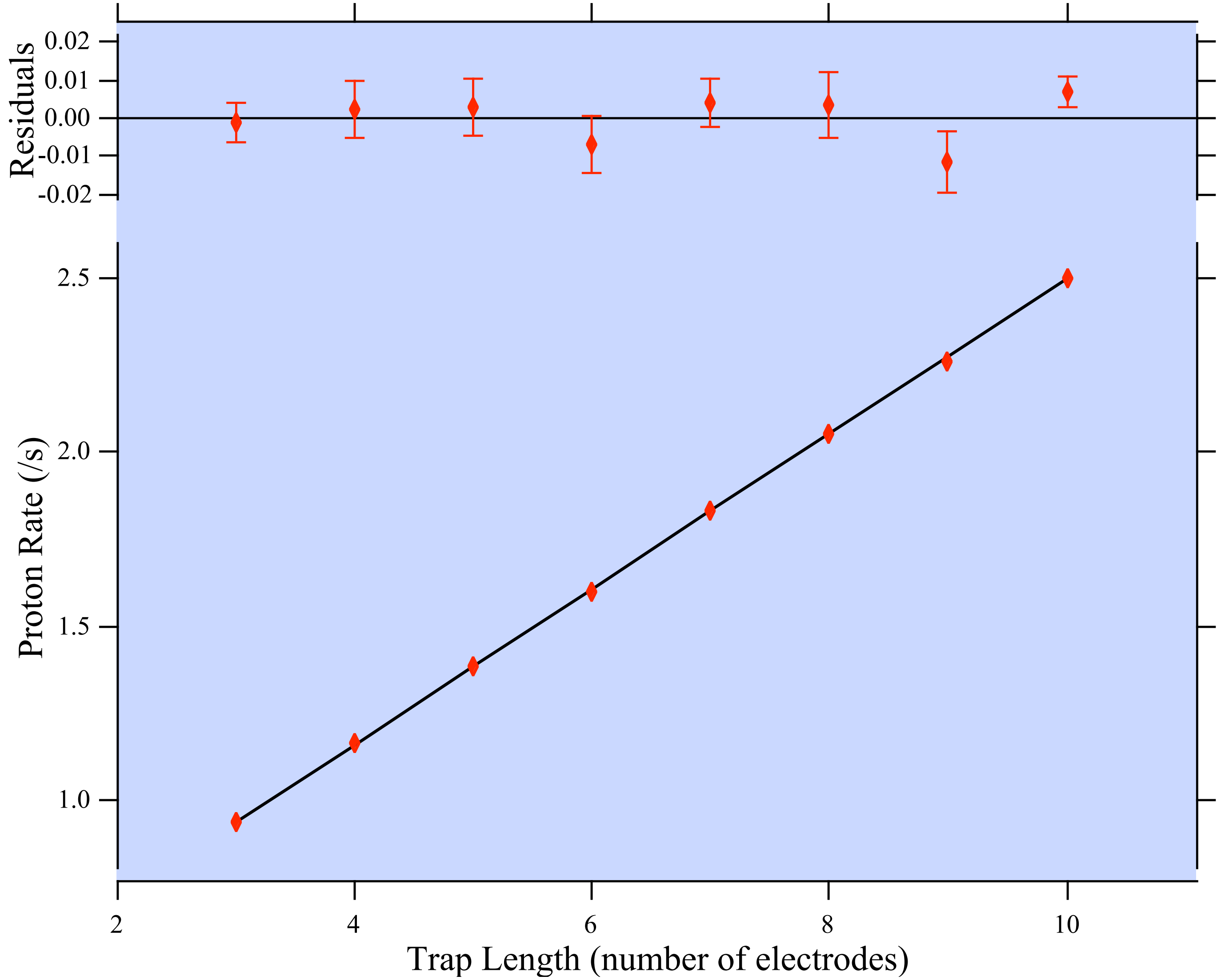
Energy Spectrum



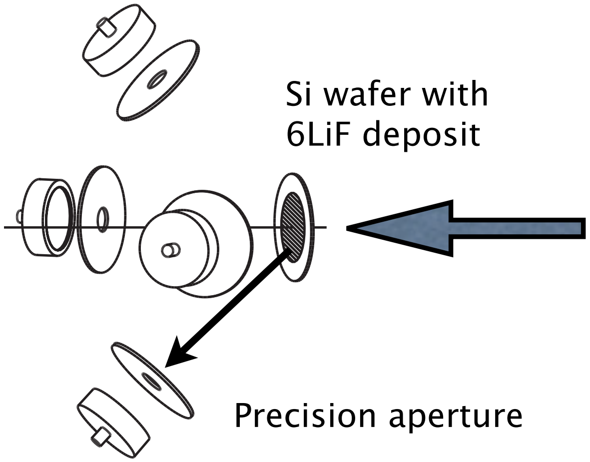
Timing Spectra



Extrapolation in Electrode Length



Neutron Counting



Si wafer with 6LiF deposit

Precision aperture

Silicon detector

areal density of deposit

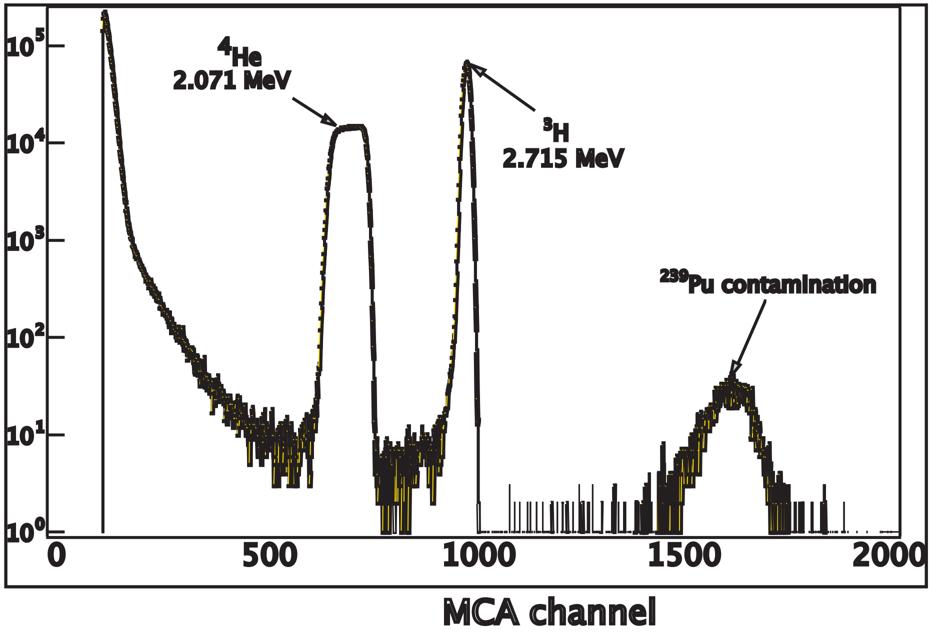
$$\epsilon = \frac{\sigma_{Li}}{4\pi}\int\int \Omega(x,y)\rho(x,y)\Theta(x,y)dxdy$$

solid angle

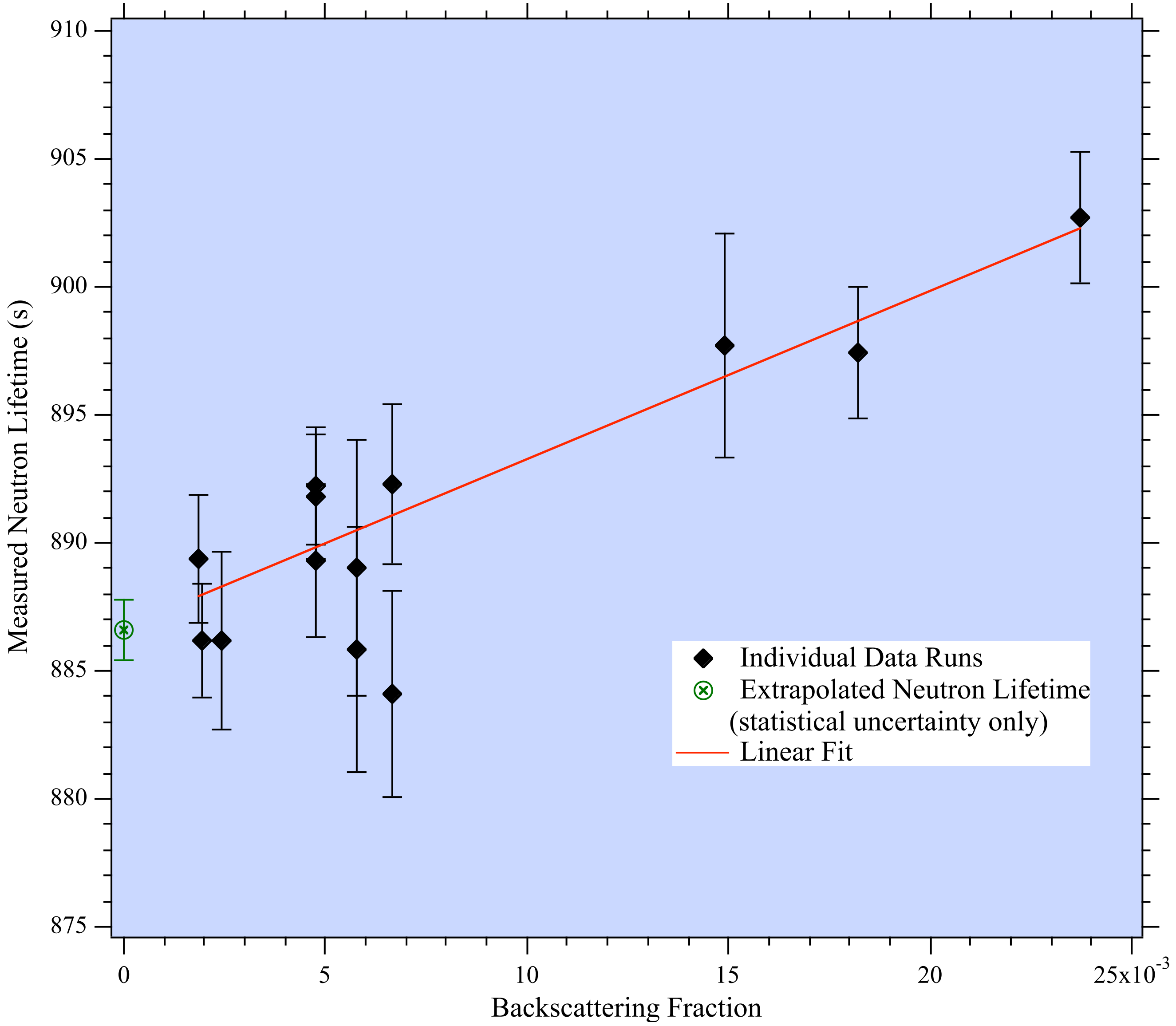
beam profile

- n+^{6}Li reaction products (alpha + triton) produced isotropically.

- Detect small fraction but with known efficiency



Result: Extrapolation in Backscattering



Systematics

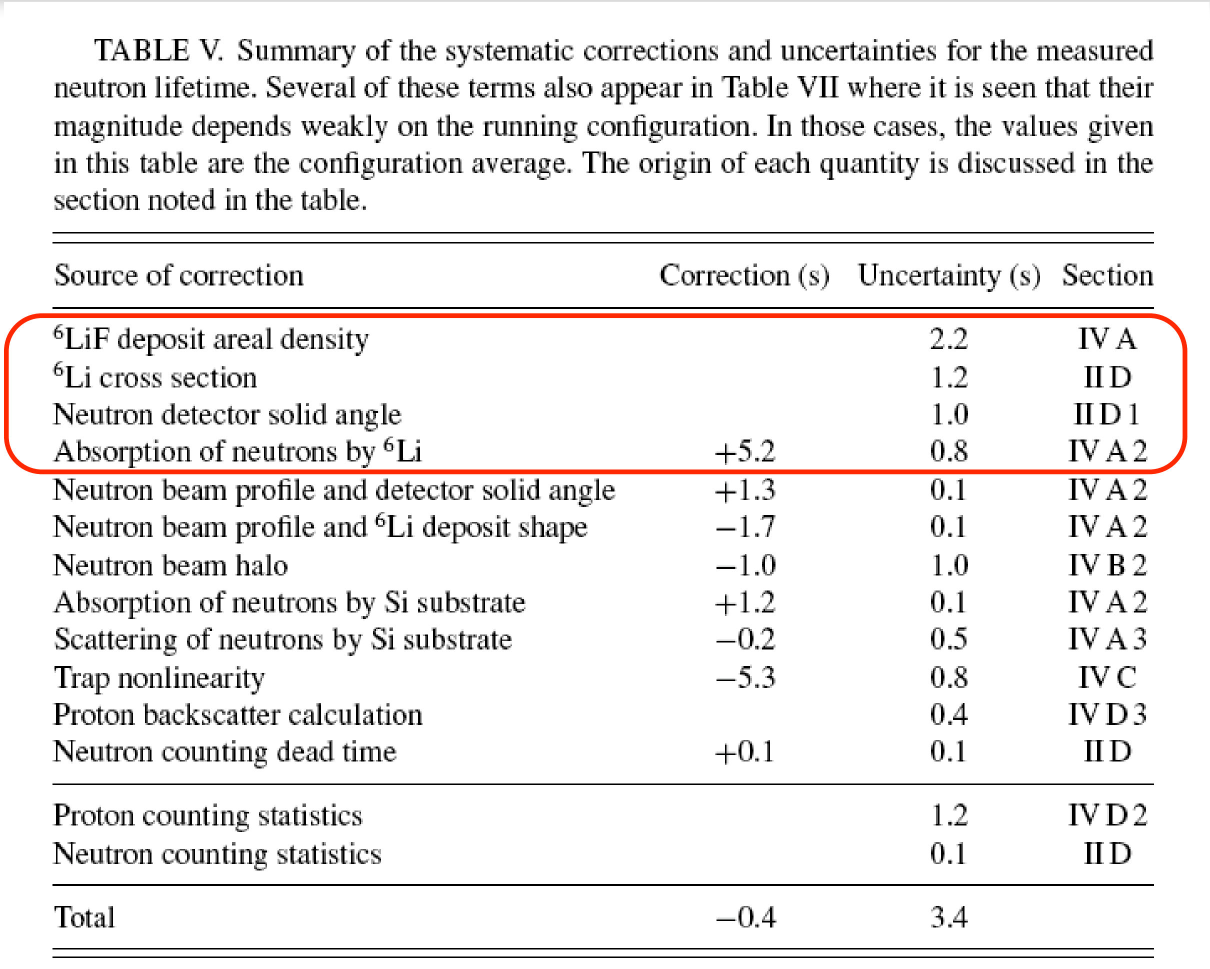


TABLE V. Summary of the systematic corrections and uncertainties for the measured neutron lifetime. Several of these terms also appear in Table VII where it is seen that their magnitude depends weakly on the running configuration. In those cases, the values given in this table are the configuration average. The origin of each quantity is discussed in the section noted in the table.

Source of correction	Correction (s)	Uncertainty (s)	Section
^{6}LiF deposit areal density		2.2	IV A
^{6}Li cross section		1.2	II D
Neutron detector solid angle		1.0	II D 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	II D
Proton counting statistics		1.2	IV D 2
Neutron counting statistics		0.1	II D
Total	−0.4	3.4	

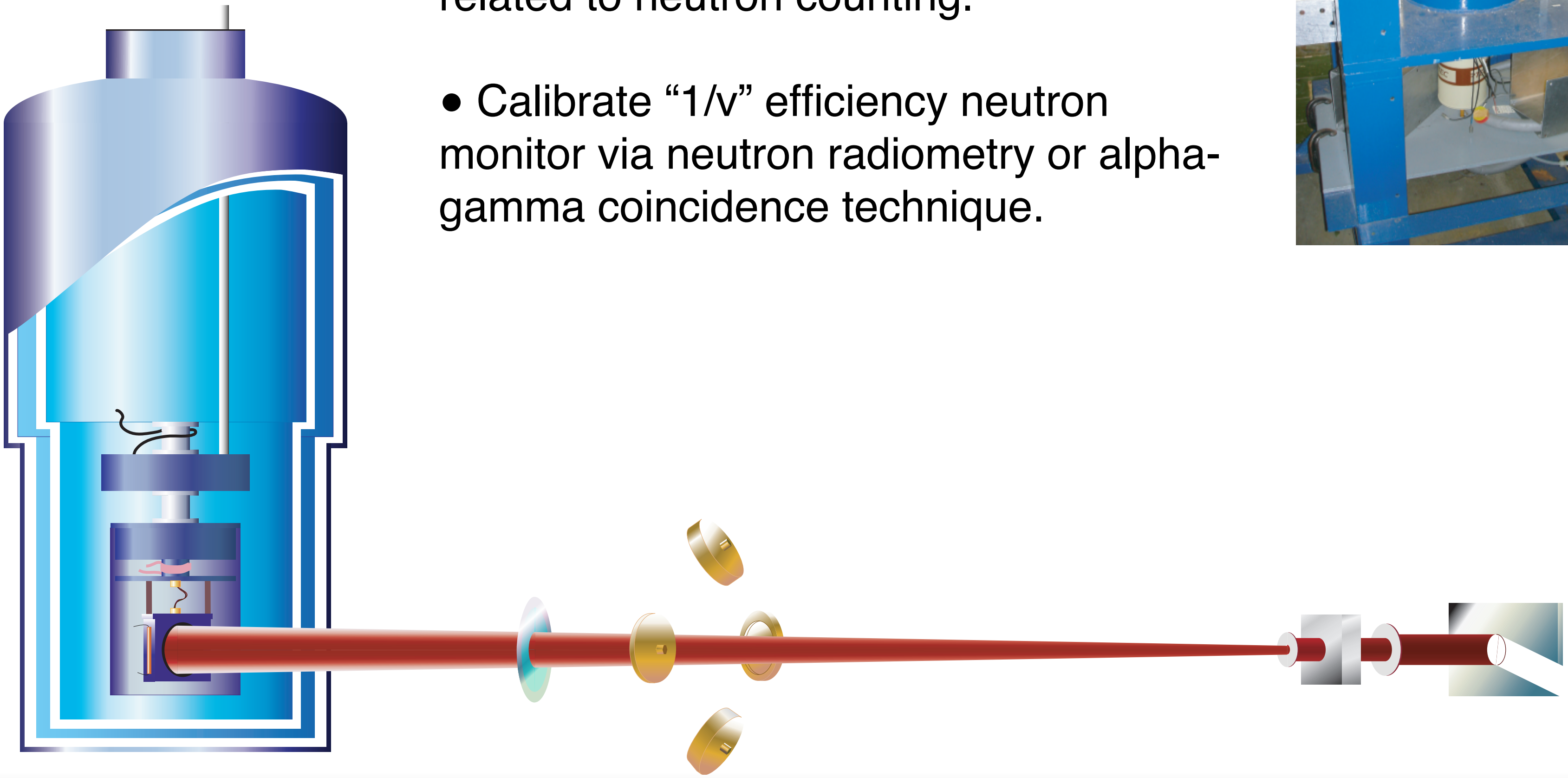
τ = (886.3 ± 1.2[stat] ± 3.2[sys]) s

Dewey et al., *Phys. Rev. Lett.* **91** (2003) and JSN et al., *Phys. Rev. C* **71** (2005)

Neutron Counting

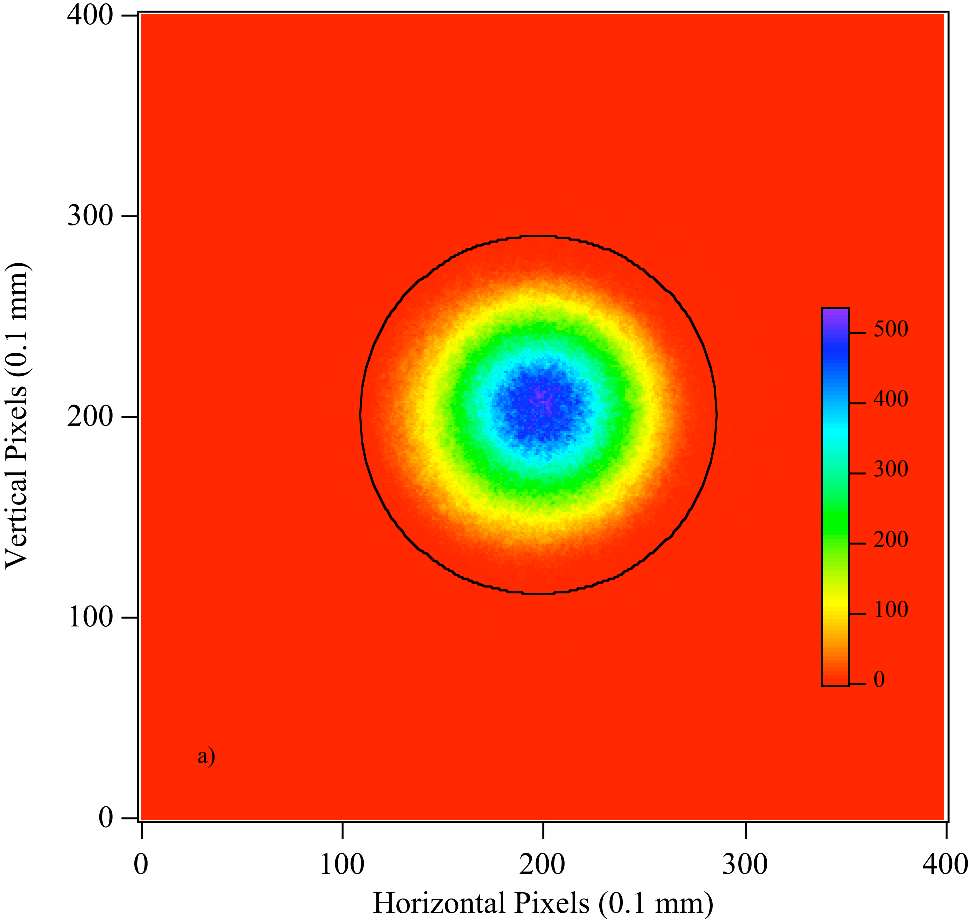
- Uncertainty dominated by systematics related to neutron counting.

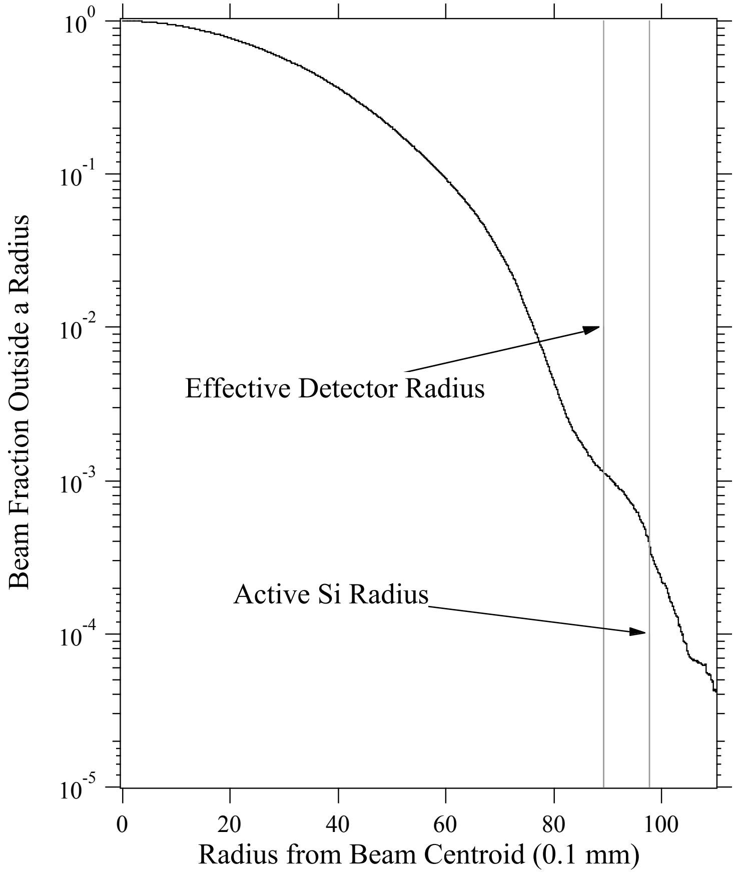
- Calibrate “1/v” efficiency neutron monitor via neutron radiometry or alpha-gamma coincidence technique.



Z. Chowdhuri et al., *Rev. Sci. Instrum.* **74** (2003); J.M. Richardson Ph.D. thesis Harvard University (1993)

Beam Halo Measurement





Effort to Reduce Uncertainty

1. Address reduction of neutron counting systematic.
    - Neutron radiometer LiMg: 0.1% stats; concern with defect formation
    - Neutron radiometer L^{3}He: 2% stats; needs work
    - Absolute fluence with alpha-gamma coincidence technique: online

2. Another round of proton counting??
    - Higher fluence rate (cold source upgrade)
    - Larger area proton detectors
    - Run with multiple neutron counting targets and configurations
    - ....

Neutron counting → 2 s
Proton counting → 1 s

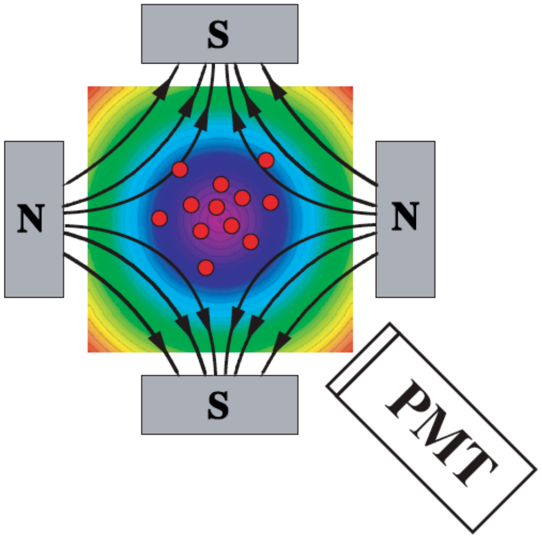
Magnetically Trapped UCN using Superfluid He-4

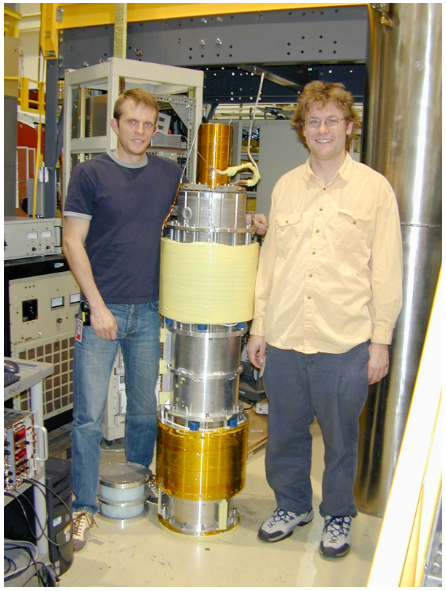
F. Dubose, R. Golub, E. Korobkina, C. O'Shaughnessy, G. Palmquist, Pil-Neyo Seo, P.R. Huffman
North Carolina State University

L. Yang and J.M. Doyle
Harvard University

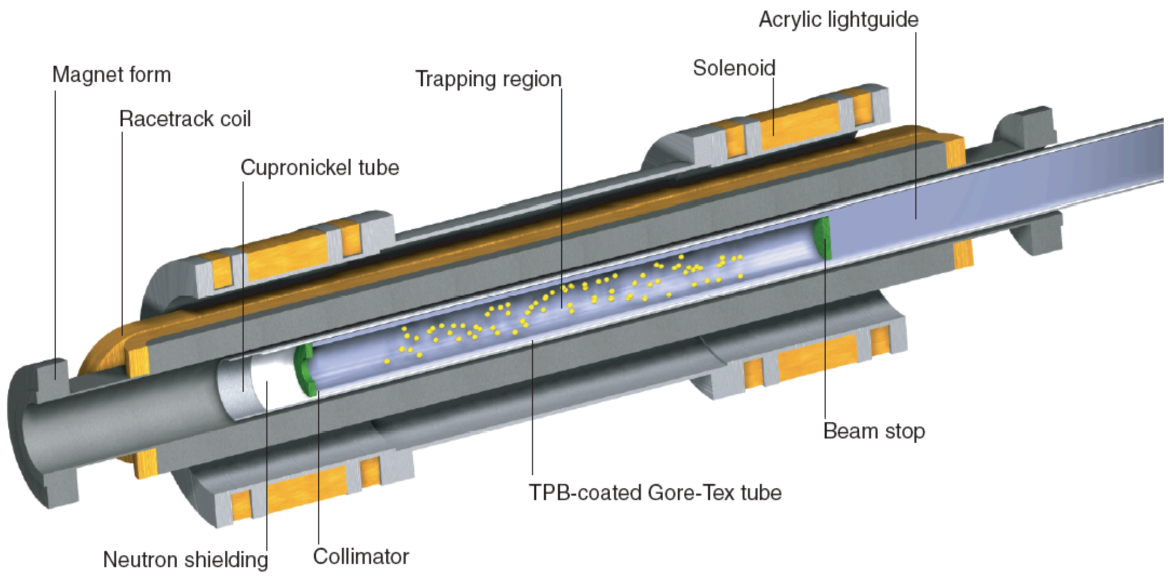
K.J. Coakley, H.P. Mumm, A.K. Thompson, and G.L. Yang
National Institute of Standards and Technology

S.K. Lamoreaux
Yale University





Experiment Overview

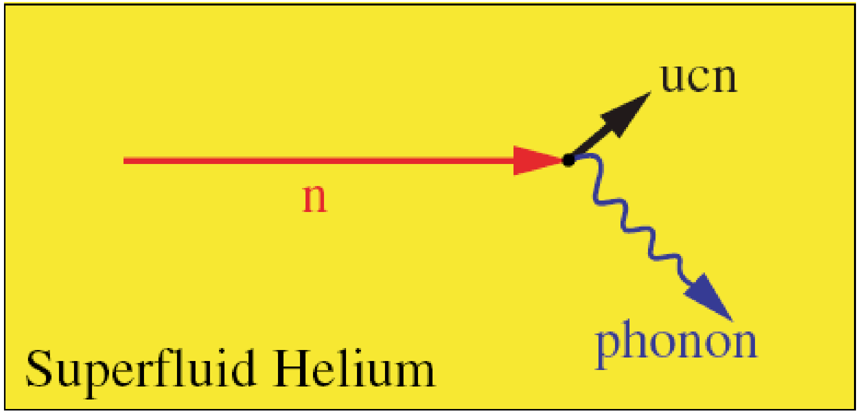


- Confine UCN with a magnetic trap to eliminate wall losses.

- Produce UCN using the superthermal process to increase the UCN density.

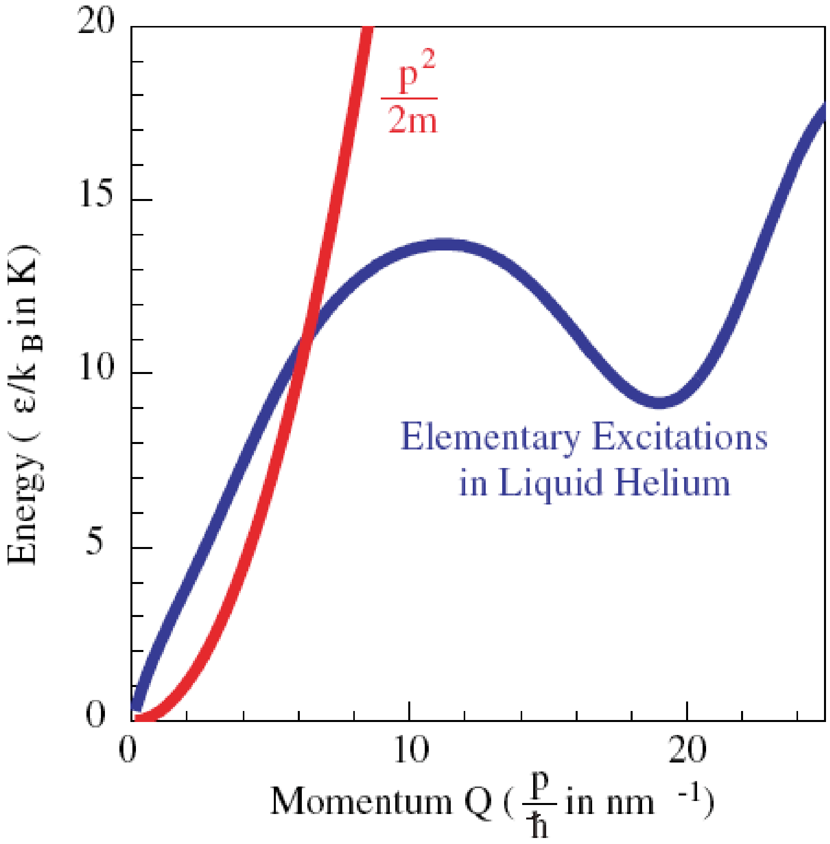
- Detect neutron decay from helium scintillation light, giving continuous monitoring of decays.

Superthermal Process



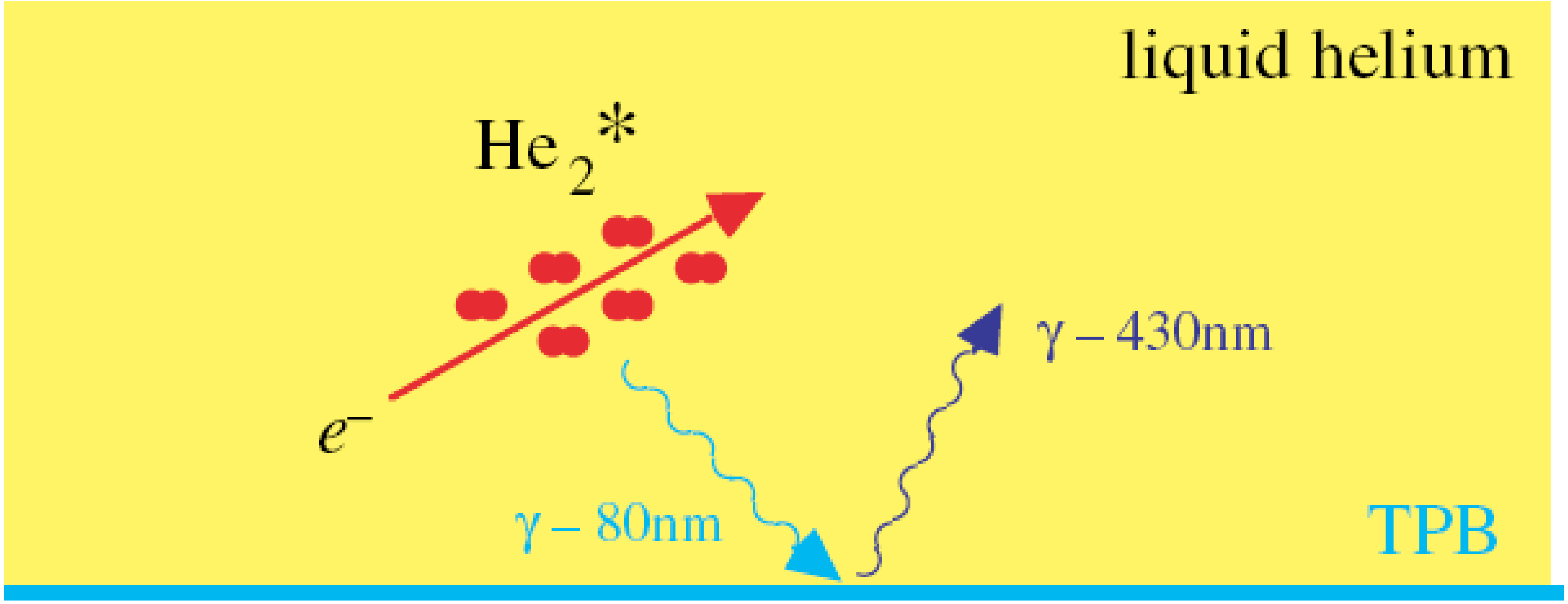
$$\vec{p}_{ucn} = \vec{p}_n - \vec{q}_{phonon}$$

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



Golub and Pendlebury, *Phys*. *Lett*. *A*. **53** (1975)

Detection of Trapped Neutrons



- Neutrons with energy ~0.95 meV (0.89 nm or 12 K) can scatter in liquid helium to near rest by the emission of a single photon.

- Upscattering suppressed by Boltzmann factor ($e^{-(12\text{ K})/T}$)

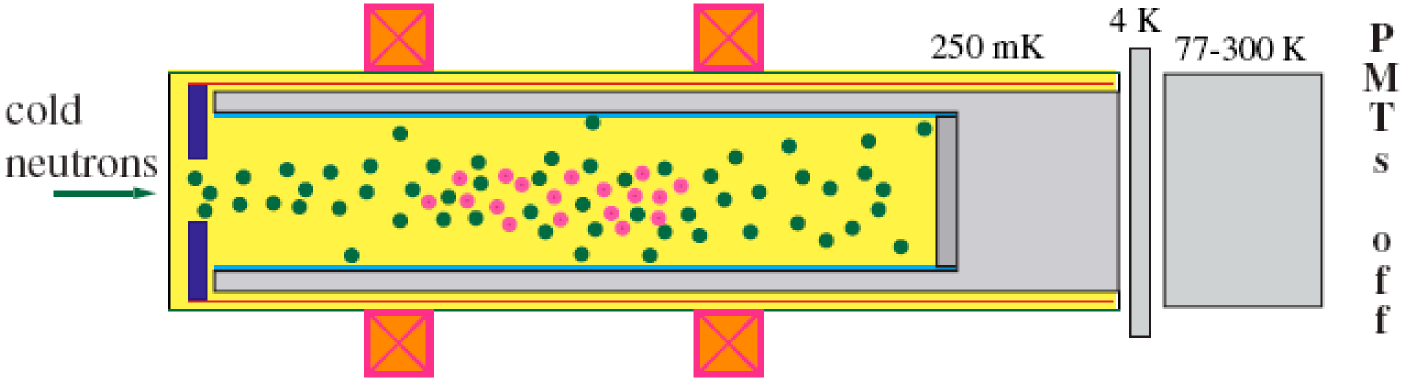
Huffman et al., *Nature* **403** (2000)

Happy Graduate Students

Counting Cycle

1) Loading period

35 minutes



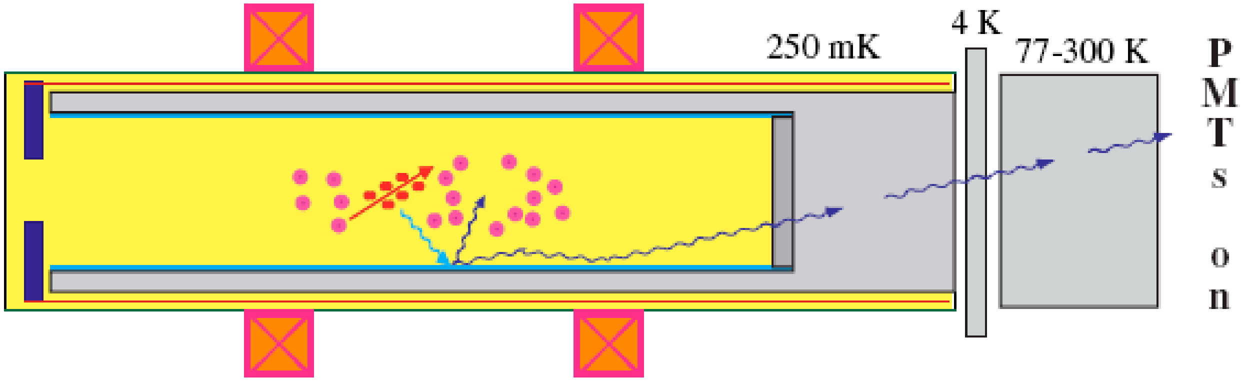
● UCN

● Cold Neutron

2) Turn off Beam

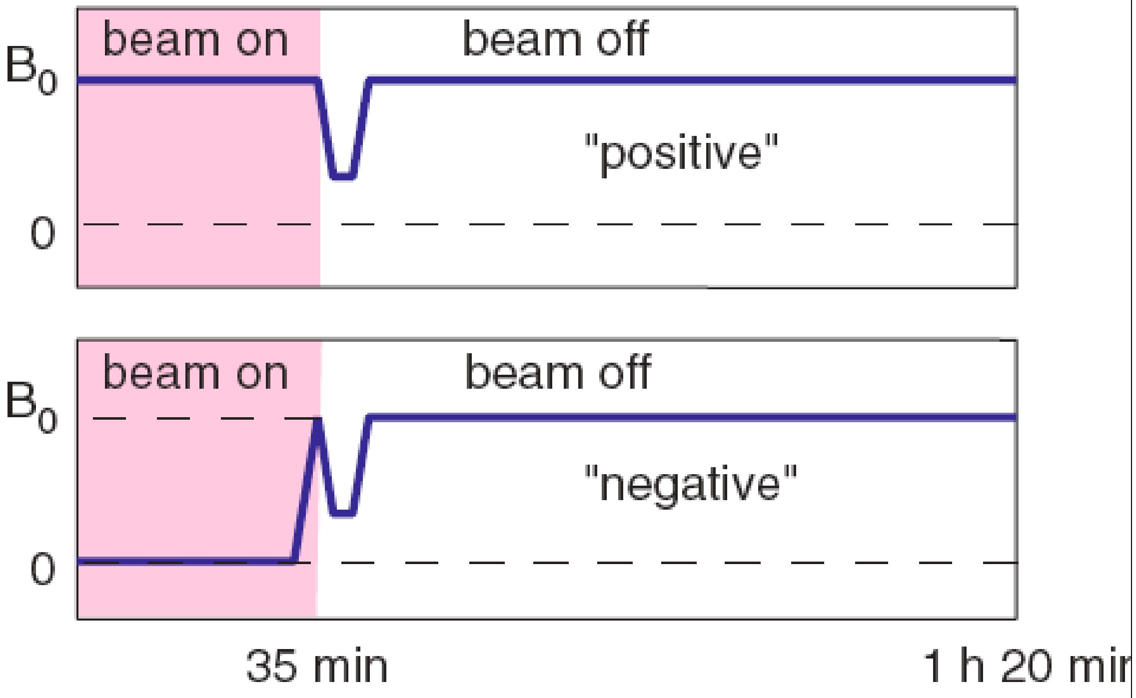
3) Observation period

45 minutes

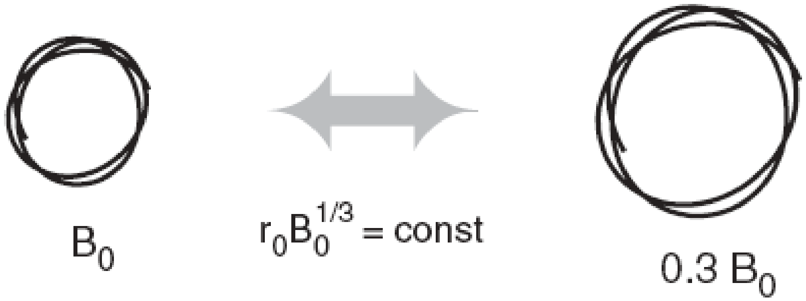


Marginally Trapped Neutrons

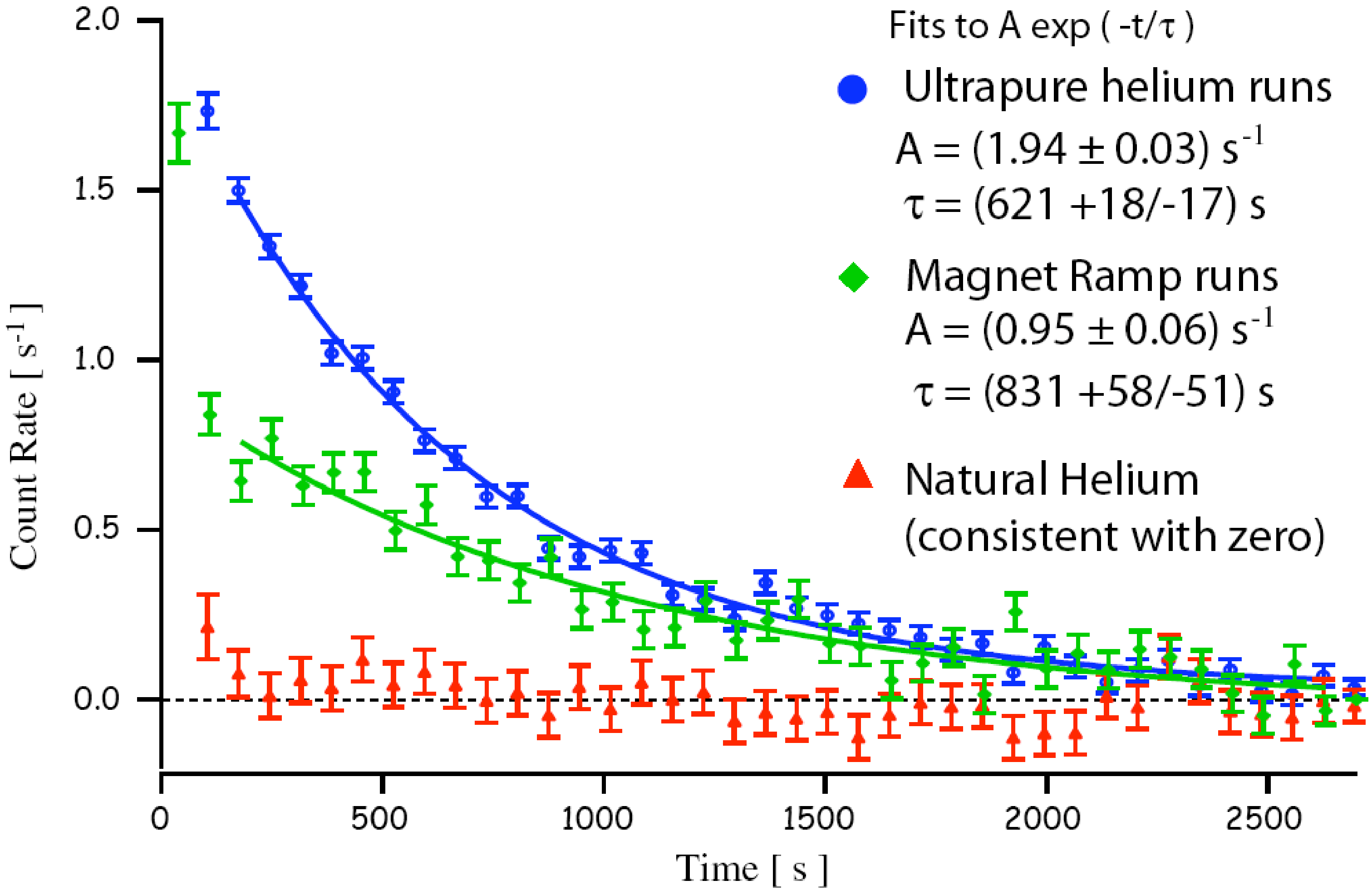
- "Positive" trapping runs
- "Negative" background runs



- Ramp magnet to ~30% B_0 value to eliminate "marginally" trapped neutrons.

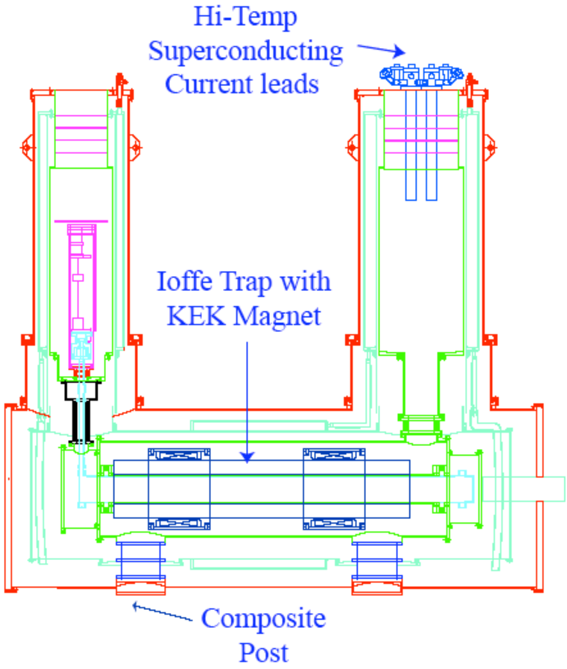


Trapping Data



Improving Measurement Precision

- Larger trap: an accelerator-type quadrupole magnet from KEK (B = 3.1 T, D = 12 cm, L = 75 cm)



- Improved signal-to-background
  - include gamma shield in new cryostat design
  - better light collection (small light guide; low temp light detector)

- Develop techniques for measuring ^{3}He concentration at 10^{-14} level.

More experiments and ideas ...

- ➢ Paul, Zimmer,... (*TU Munich*)
  - Low temperature fomblin bottle

- ➢ Morozov (*Kurchatov Institute, ILL*)
  - Low temperature fomblin bottle

- ➢ Bowman and Penttila (*LANL/ORNL*)
  - UCN in vacuum quadrupole trap
  - Monitor decay electrons

- ➢ Yerozolimsky and Steyerl (*Harvard and Rhode Island*)
  - UCN “accordian-like” trap
  - Coated with low-temperature fomblin oil
- ➢ Pichlmaier (*PSI*)
  - Permanent magnet trap
  - Monitor decays
- ➢ Masuda (*KEK*)
  - Quadrupole bottle
  - Monitor decays

Precision < 1 s

Summary

- *“The most recent result, that of Serebrov 05, is so far from other results that it makes no sense to include it in the average. It is up to workers in this field to resolve this issue. Until this major disagreement is understood our present average of (885.7 ± 0.8) s must be suspect.”*

  \- PDG 2006 -

- New UCN experiments should illuminate the disagreement; results should be imminent (1-2 years). Cold neutron experiment can reduce uncertainty to approximately 1 s and provide distinctly different systematics.

- For neutron decay to directly confront theory, both the lifetime and lambda must be improved. UCNA, PERKEO III, and new experiments to measure electron-antineutrino asymmetry (“little a”) should reduce uncertainty in lambda.

- Addressing CKM unitarity also needs affirmation of $|V_{us}|$ in both experiment and theory.