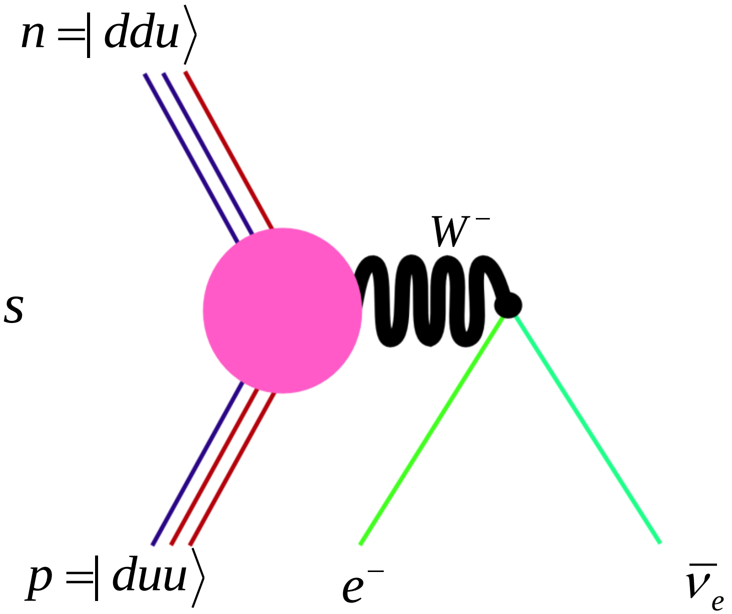
Measuring The Neutron Lifetime to 1 s and Why You Should Care

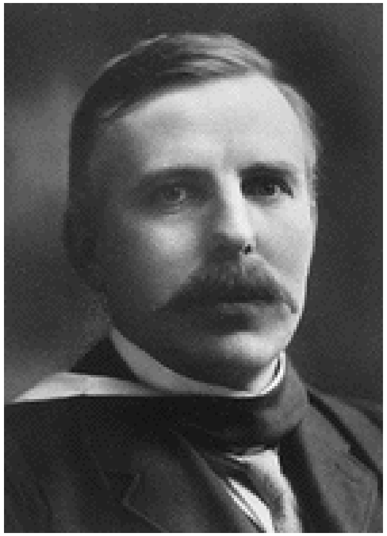
$$\tau_n = \frac{G_F^2}{G_V^2 + 3G_A^2} 4908.7(1.9)s$$



Jonathan Mulholland
University of Tennessee
03/17/2015 UVA Nuc Seminar
Charlottesville, VA

First, a neutron history lesson

(courtesy of G. L. Greene)



Ernest Rutherford

1920: Noting that atomic number does not correspond to atomic weight, Rutherford suggests that, in addition to "bare" protons, the nucleus contains some tightly bound "proton-electron pairs"

"Such an atom would have very novel properties. Its external field would be practically zero, except very close to the nucleus, **and in consequence it should be able to move freely through matter. Its presence would probably be difficult to detect by the spectroscope, and it may be impossible to contain it in a sealed vessel.**

Bakerian Lecture, 1920

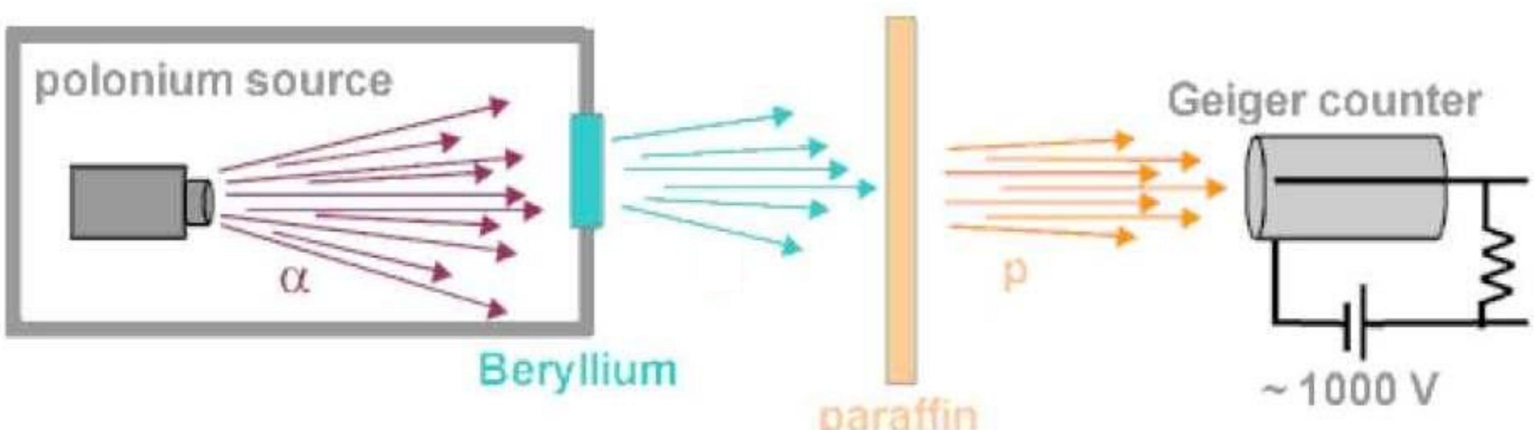
Marie Curie

1930: Bothe and Becker discover a penetrating, neutral radiation when alpha particles hit a beryllium target

1931: Mme Curie shows that they are not gamma rays and have sufficient momentum to eject protons from paraffin

Walter Bothe

$$\alpha + {}^{9}\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + n$$



James Chadwick

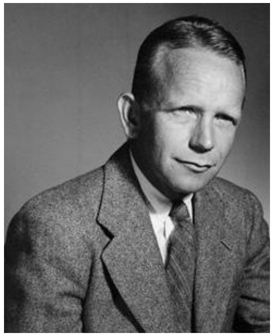
1932: Chadwick replaced the paraffin with a variety of other targets (nitrogen, oxygen, helium, and argon) and, by measuring the recoil energies of the ejected particles, determined the mass of the neutral particle:

$$M_n = 1.15 \pm 10\%\ \mathrm{u}$$

Chadwick claimed this was Rutherford's "neutron" stating:

"It is, of course, possible to suppose that the neutron may be an elementary particle… **This view has little to recommend it at present.**"

J. Chadwick, Proc. Roy. Soc., A 136 692 (1932)



Kenneth Bainbridge

1933: Bainbridge makes precision measurements of the atomic masses of the proton and deuteron using the mass spectrograph

Maurice Goldhaber

1934: Chadwick and Goldhaber make the first "precision" measurement of the neutron mass by looking at the photo-disassociation of the deuteron:

$$h\nu + D_1^2 > H_1^1 + n_0^1$$

Using 2.62 MeV gammas from Thorium and determining the recoil energy of the protons, they determined:

$$M_n = 1.0080 \pm 0.0005 \text{ u}$$

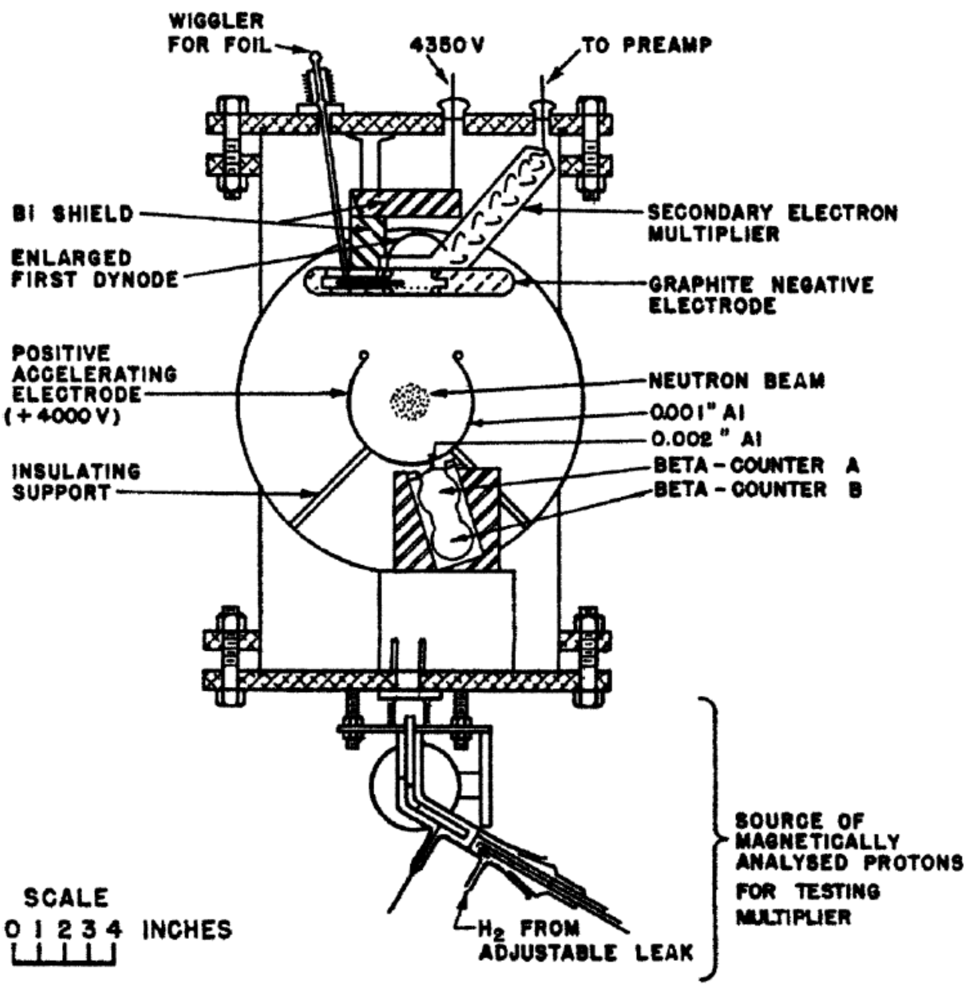
$$M_n > M_p + M_e$$

"If the neutron is definitely heavier than the hydrogen atom, then one must conclude that **a free neutron is unstable**, i.e., it can change spontaneously into a proton+electron+neutrino"

Chadwick and Goldhaber, Nature, 134 237 (1934)

First Observation of Free Neutron Decay

In 1948 by Snell and Miller at the Graphite Reactor at Oak Ridge, TN



Background has a large contribution from the beam—background must be suppressed.

Rate in each beta counter: 75,000 cpm

Coincidence rate for both beta counters: 1,500 cpm

Electron-proton coincidences: 1 cpm

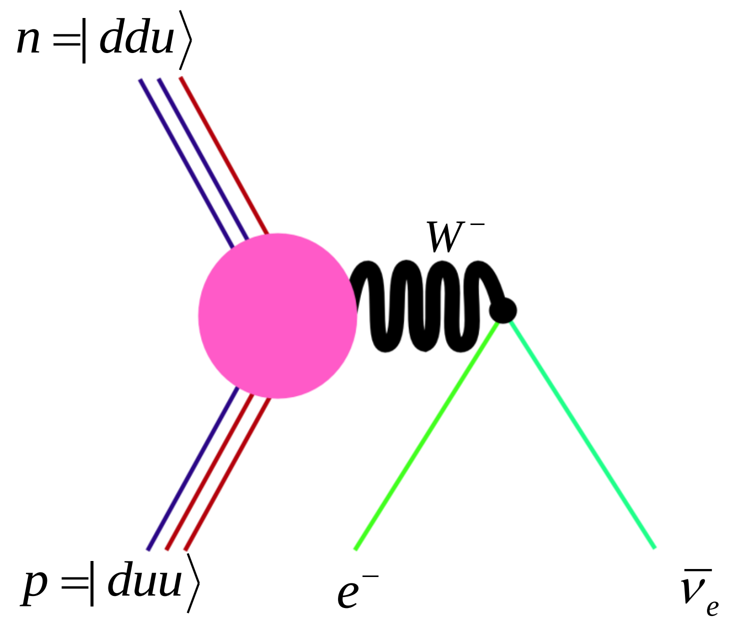
Restricting time-of-flight: 0.67±0.05 cpm

Estimated $t_{1/2}$= 9 – 25 min.

Snell, A. H., and L. Miller, 1948, Phys. Rev. 74, 1217

A Long Lived Particle

Lifetime of about 15 minutes
It basically lives forever!
(for scattering experiments)



Beta decay is mediated by the Weak Interaction

$$M = \left[G_V \bar{p}\gamma_\mu n - G_A \bar{p}\gamma_5\gamma_\mu n\right]\cdot\left[\bar{e}\gamma_\mu(1+\gamma_5)\nu\right]$$

$$\tau_n = \frac{G_F^2}{G_V^2 + 3G_A^2} 4908.7(1.9)s$$

The ratio λ is related to the strong interaction within the parton, connecting weak physics to parton structure.

$$\lambda = G_A / G_V$$

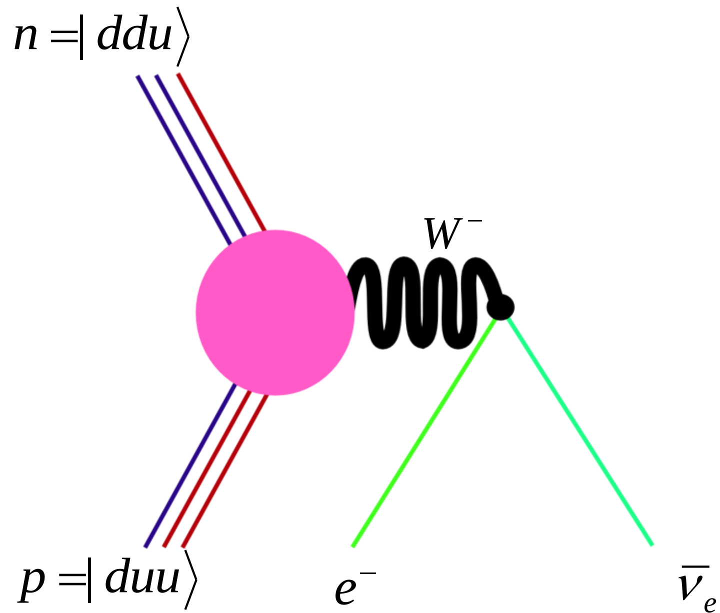
Image: www.lns.mit.edu

$$\int_0^1 dx\left[g_1^p(x) - g_1^n(x)\right] = \frac{1}{6}|\lambda|$$

Bjorken sum rule: connection to spin structure

So Many Things to Measure!

Decaying into a proton, electron, and anti-neutrino… where did they all go and which way was the neutron looking?



$$\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto p_e E_e (E_0 - E_e)^2$$

$$\times \left[1 + b\frac{m_e}{E_e} + a\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \langle \vec{\sigma}_n \rangle \cdot \left(A\frac{\vec{p}_e}{E_e} + B\frac{\vec{p}_\nu}{E_\nu} + D\frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right]$$

To leading order all those correlations are given by lambda:

$$\lambda \equiv \frac{g_A}{g_V} \qquad a = \frac{1-\lambda^2}{1+3\lambda^2} \qquad A = -2\frac{\lambda(\lambda+1)}{1+3\lambda^2} \qquad B = 2\frac{\lambda(\lambda-1)}{1+3\lambda^2}$$

Hundredth of a Percent Level τ_n and V_{ud}

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

Measurements of *ft* values for superallowed $0^+ \rightarrow 0^+$ β-decay :

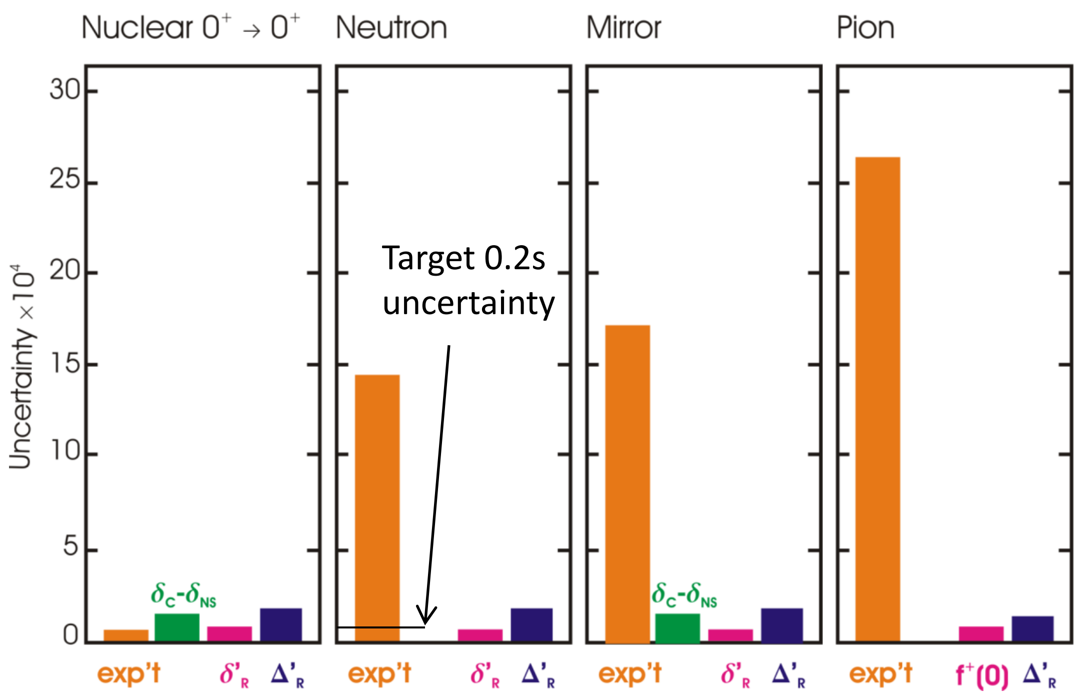
$$|V_{ud}|^2 = \frac{2984.48(5)s}{ft(1+RC)}$$

Best determination of V_{ud} !
But the technique is limited by nuclear structure corrections

Measurements of τ_n and β-decay angular correlation coefficients :

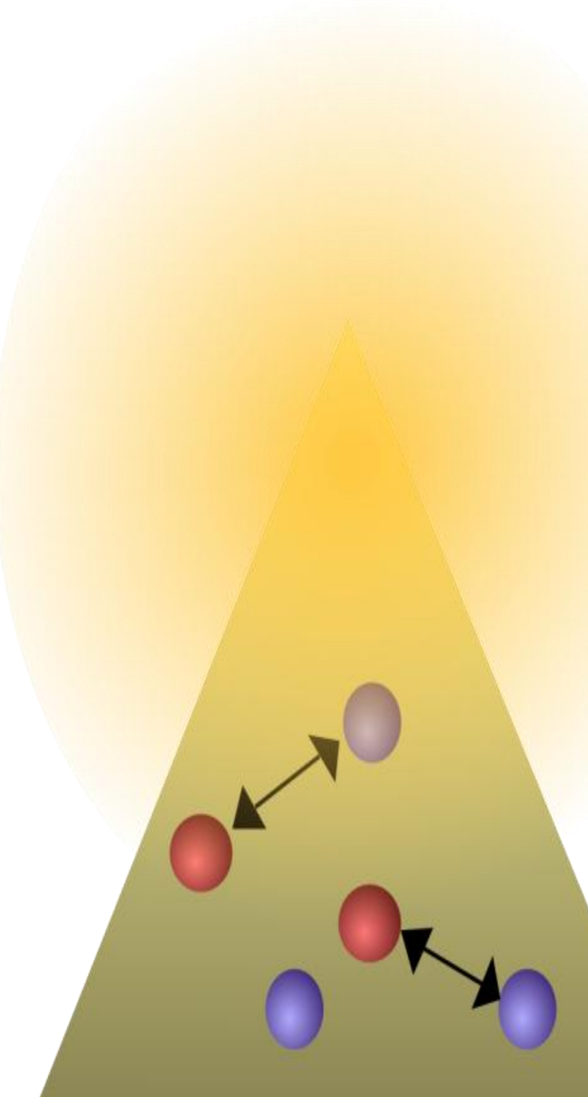
$$|V_{ud}|^2 = \frac{4908.7(1.9)s}{\tau_n(1+3\lambda^2)}$$

A measurement in the 10^{-4} range can probe BSM physics. Neutron decay based V_{ud} determinations are unconstrained by nuclear structure corrections.



Hardy and Towner, Ann. Phys. 525, 443 (2013)

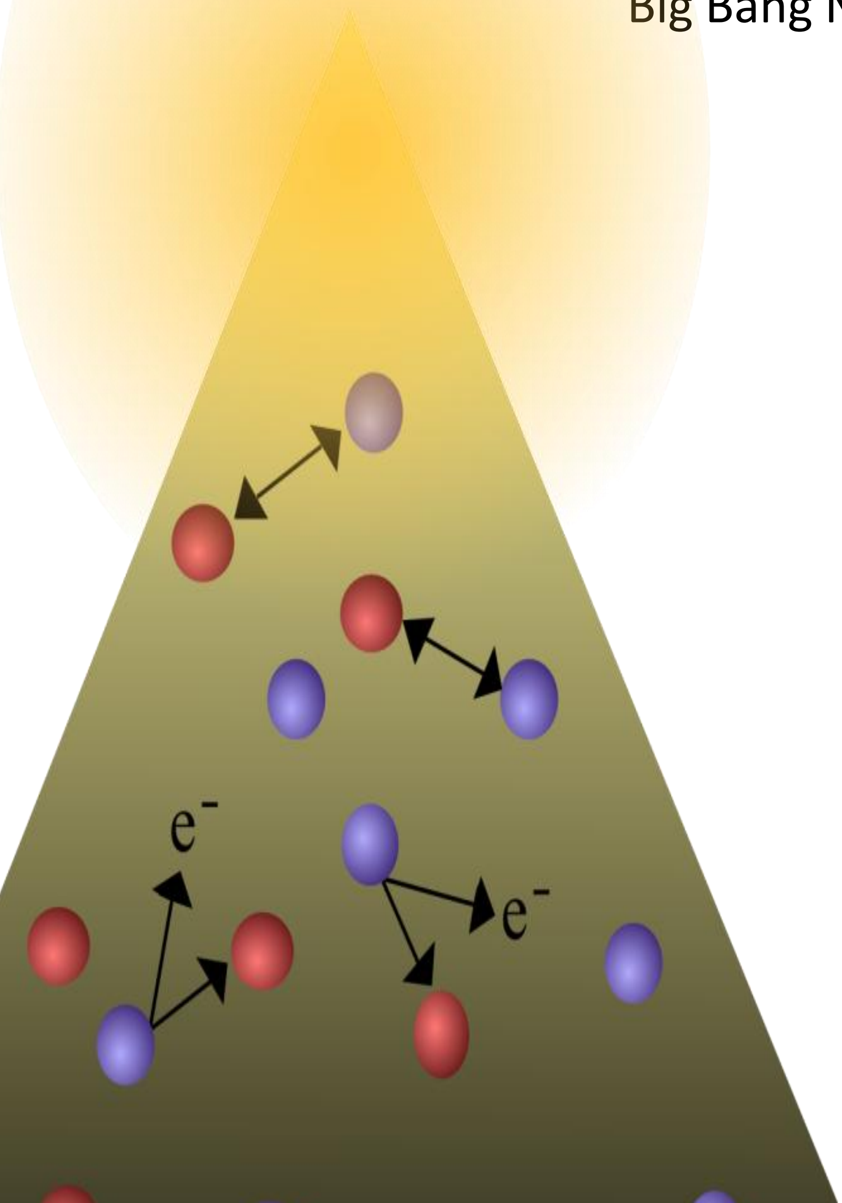
The Early Universe



Time	Temperature	
$t = 0$	T = A LOT	The Beginning
$t = 10^{-43}$s	$T = 10^{32}$K	2 forces : gravity and GUT
$t = 10^{-35}$s	$T = 10^{27}$K	Inflation
$t = 10^{-12}$s	$T = 10^{15}$K	4 forces – no more unification
$t = 10^{-7}$s	$T = 10^{12}$K	We have protons, neutrons, positrons, and electrons

The Early Universe

Big Bang Nucleosynthesis



After the quark-gluon phase transition around $t \sim 3\times10^{-5}s$, while $t < 1s$ protons and neutrons were held in thermal equilibrium by these reactions:

$$n + e^{+} \leftrightarrow p + \overline{\nu}_e \qquad n + \nu_e \leftrightarrow p + e^{-}$$

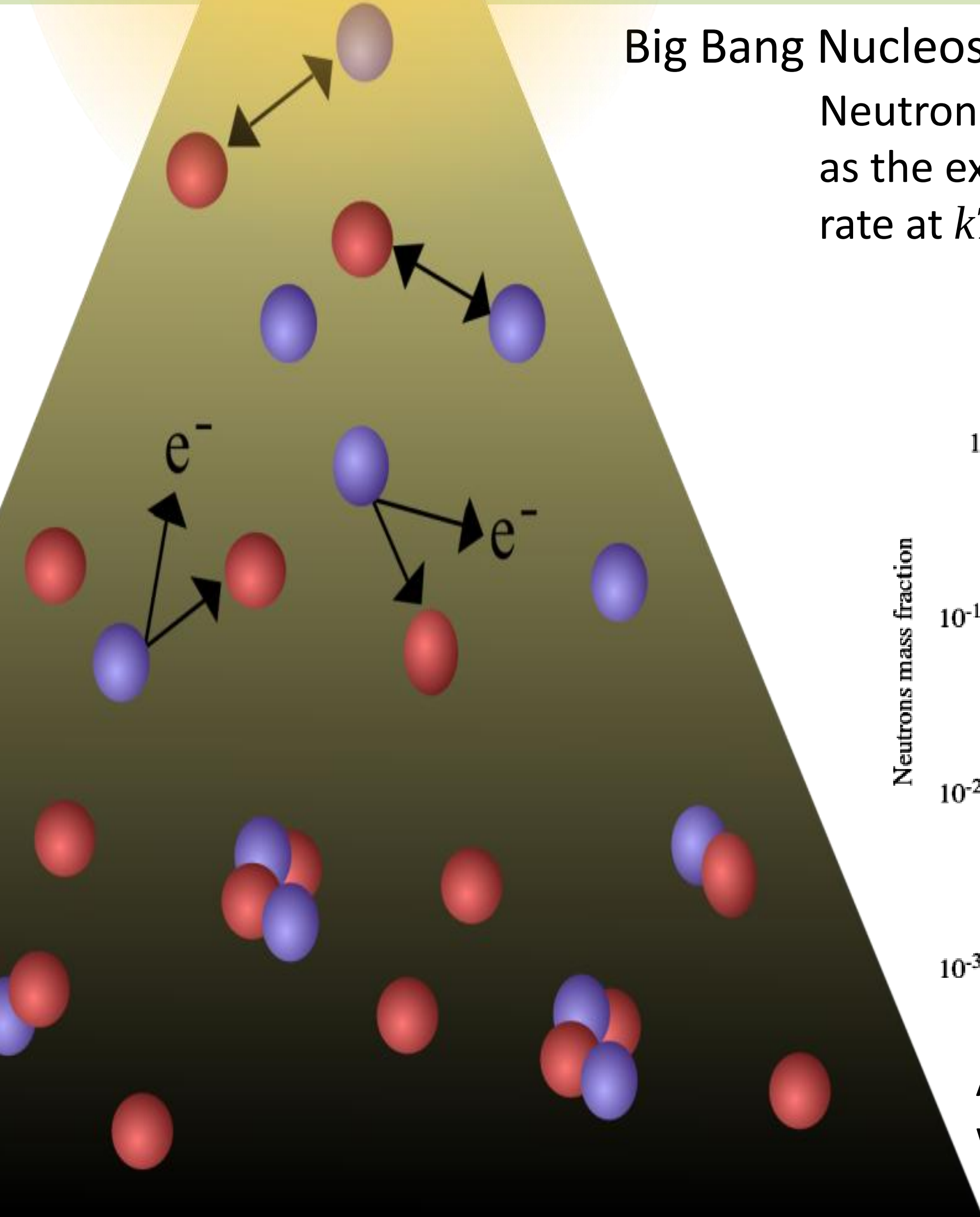
$$n \rightarrow e^{-} + p + \overline{\nu}_e$$

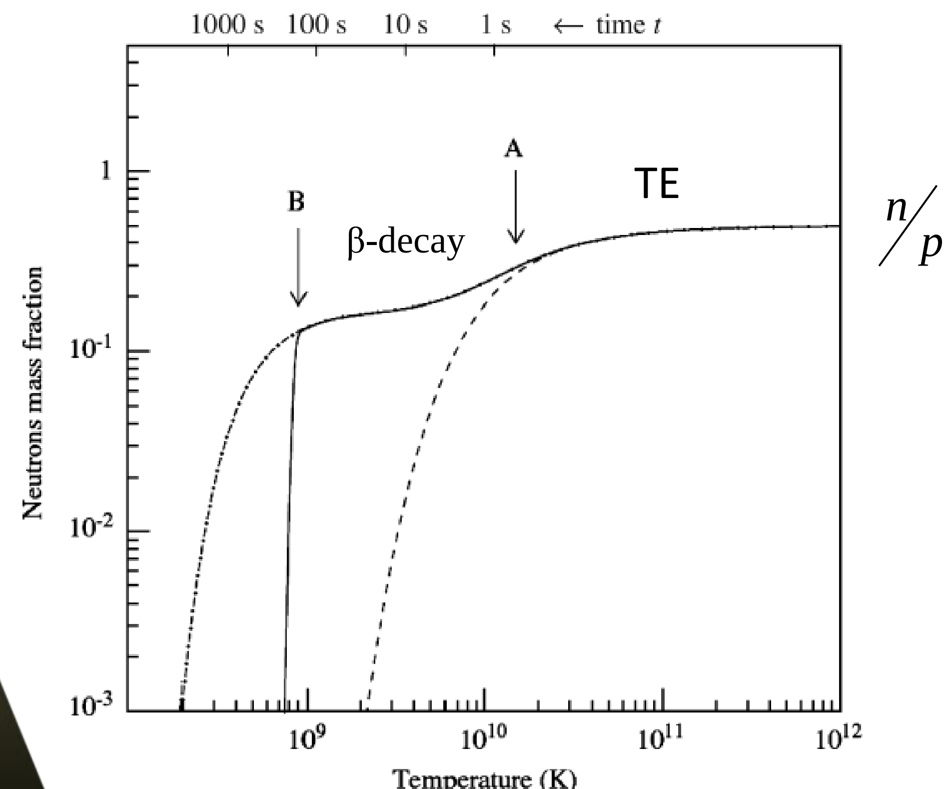
$$\frac{n}{p} = e^{-\Delta m/kT} \qquad \Delta m = 1.293\, MeV/c^2$$

The Early Universe

Big Bang Nucleosynthesis

Neutrons and protons fall out of thermal contact as the expansion rate beats the weak interaction rate at $kT_f \approx 0.7\,\mathrm{MeV}$





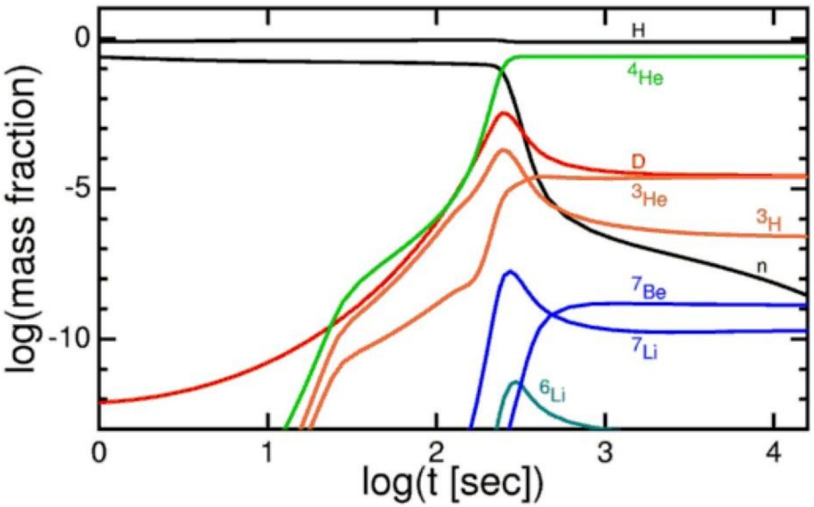
At “B”, neutrons are bound up into mostly ^4He with smaller amounts of ^2H, ^3He, and ^7Li

plot: D Dubbers, M Schmidt Rev Mod Phys **V 83** 1111 (2011)

The Early Universe

Early Element Abundance: Big Bang Nucleosynthesis

The lighter element abundance (^2H, ^3H, ^3He, ^7Li, and ^7Be) predictions are all dependent on Y_p .



Burles et al. 1999

The early ^4He abundance, Y_p can be calculated with just three parameters:

N_ν : number of neutrino species

$$\Delta Y_p / Y_p = +0.17\,\Delta N_\nu / N_\nu$$

$\eta = n_b/n_\gamma$: ratio of baryon density to photon density (WMAP)

$$\Delta Y_p / Y_p = +0.039\,\Delta\eta / \eta$$

τ_n : neutron lifetime

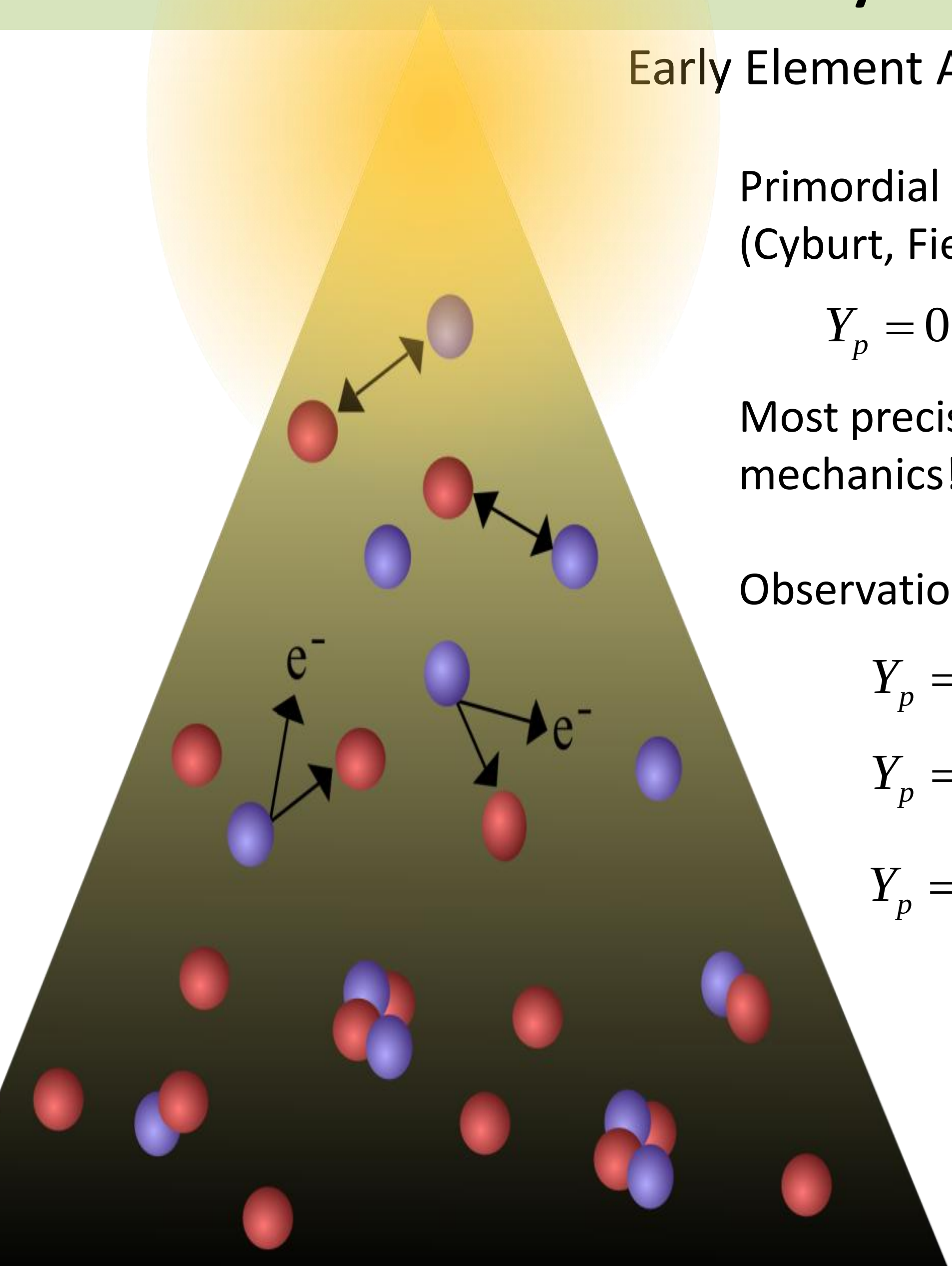
$$\Delta Y_p / Y_p = +0.72\,\Delta\tau_n / \tau_n$$

Uncertainty in the lifetime dominates the predictions of Y_p by BBN

D Dubbers, M Schmidt Rev Mod Phys **V 83** 1111 (2011)

The Early Universe

Early Element Abundance



Primordial Helium abundance via BBN:
(Cyburt, Fields, and Olive 2008)

$$Y_p = 0.2486 \pm 0.0002 \quad (0.08\%)$$

Most precise astrophysical prediction outside of orbital mechanics!

Observations are catching up to predictions

$$Y_p = 0.2516 \pm 0.0011$$

Izotov, Thuan, & Stasinska 2007
Porter HeI emmissivities

$$Y_p = 0.2561 \pm 0.0108$$

Aver, Olive, Skillman 2010
extragalactic H II regions

$$Y_p = 0.2565 \pm 0.005$$

Izotov & Thuan 2010
low-Z extragalactic HII regions

Measurement of lifetime to 1 s gives

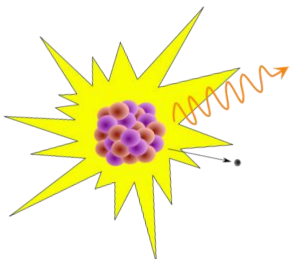
$$0.72 \Delta\tau_n / \tau_n = 0.08\%$$

But do we know τ_n to 1s?

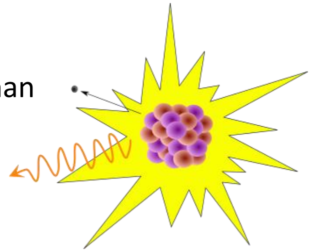
references at http://www.pas.rochester.edu/~emamajek/memo_Yp.html

How to Measure τ_n ... $N(t) = N_0 e^{-t/\tau_n}$

Direct Observation of Exponential Decay:



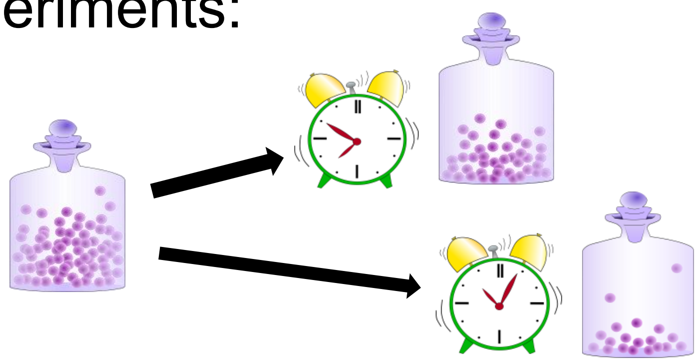
Similar in principle to Freshman Physics Majors measuring radionuclide half lives -- only a lot harder.



Observe the decay rate of N_0 neutrons and the slope of

$$\ln\left(\frac{\partial N(t)}{\partial t}\right) \text{ is } -1/\tau_n$$

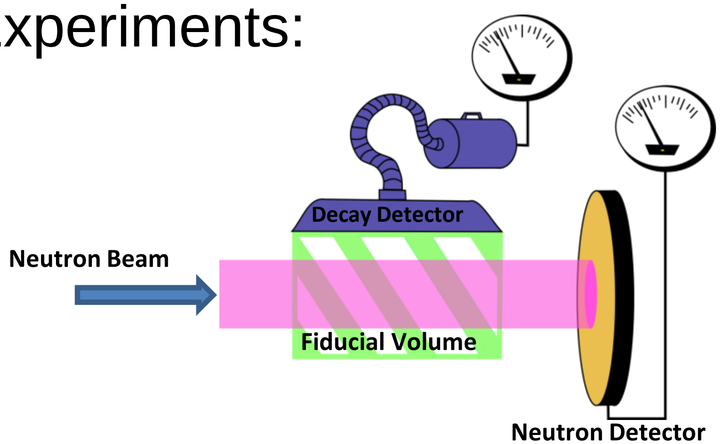
"Bottle" Experiments:



Form two identical ensembles of neutrons and then count how many are left after different times.

$$\frac{N(t_1)}{N(t_2)} = e^{-(t_1 - t_2)/\tau_n}$$

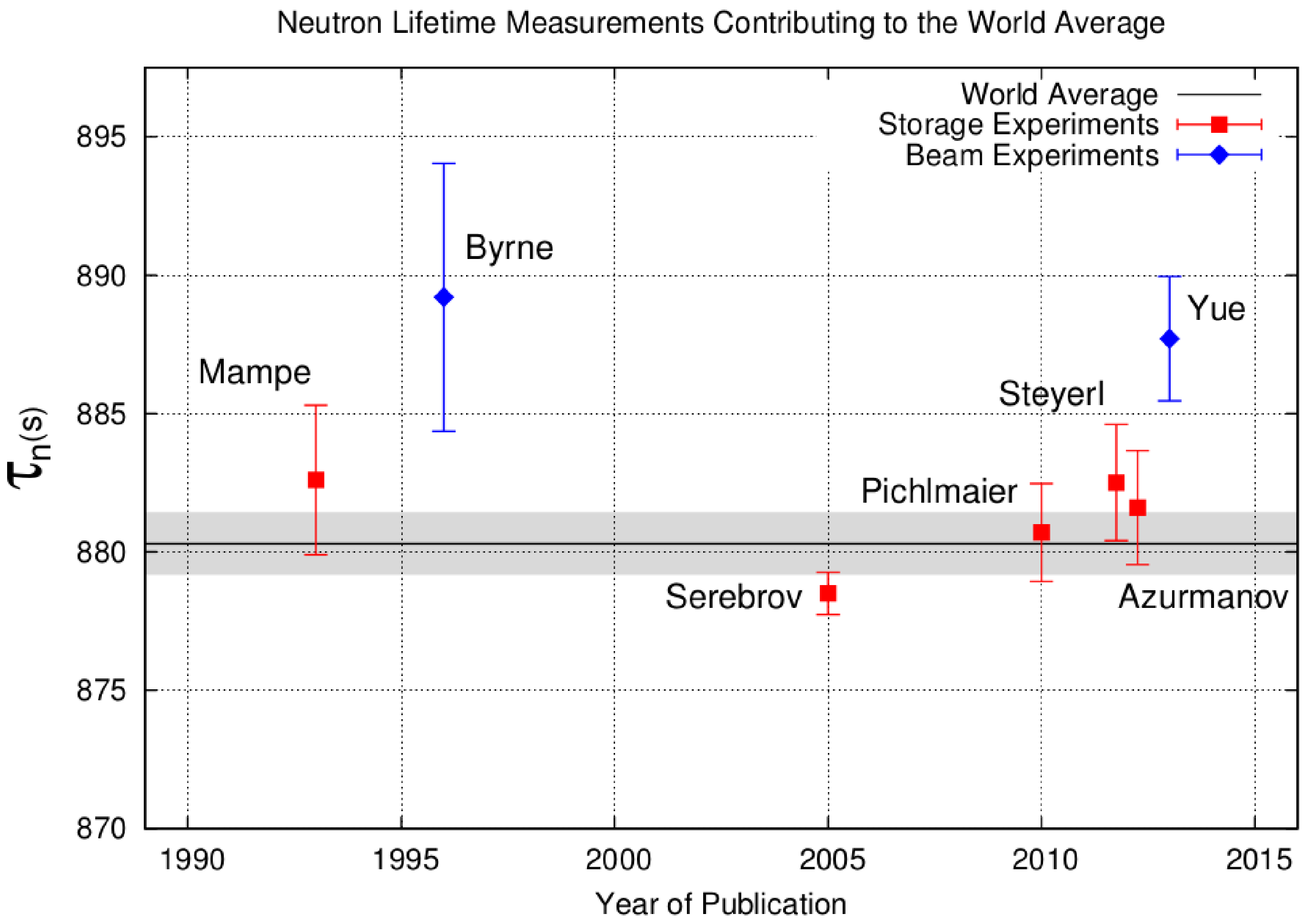
Beam Experiments:



Decay rates within a fiducial volume are measured for a beam of well known fluence.

$$\frac{\partial N(t)}{\partial t} = -N/\tau_n$$

The State of the Neutron Lifetime

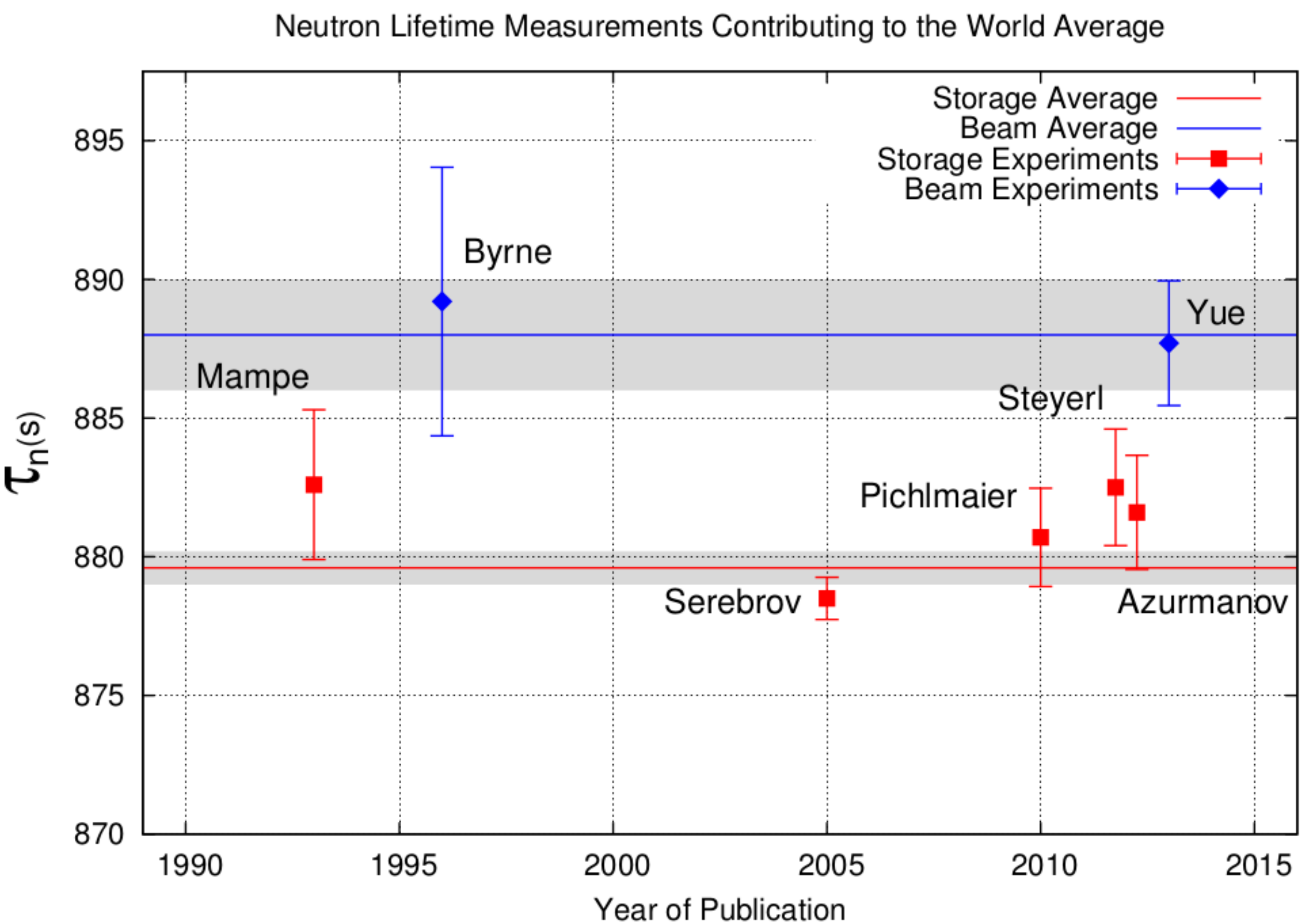


World Average

$$\tau_n = 880.3 \pm 1.1 s$$

see PDG for references

The State of the Neutron Lifetime



Beam Average

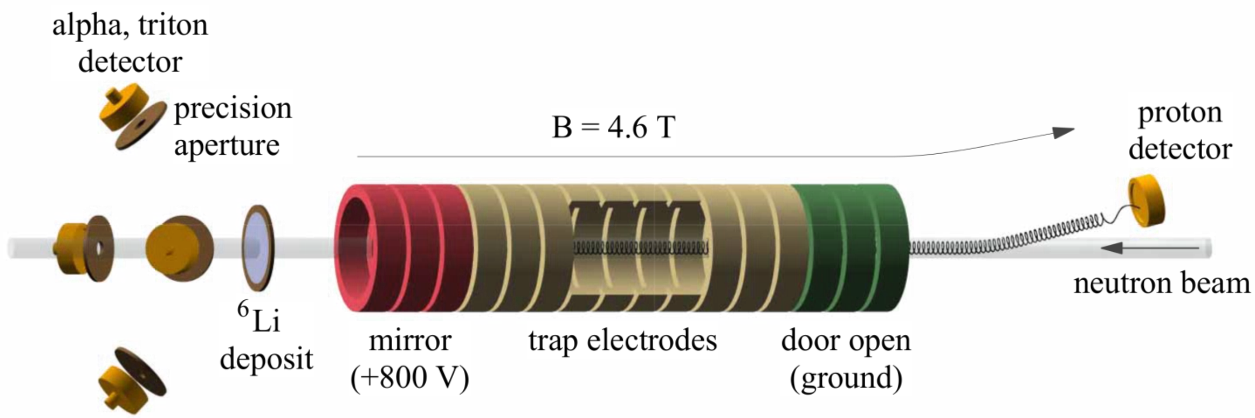
$$\tau_n = 888.0 \pm 2.1s$$

Storage Average

$$\tau_n = 879.6 \pm 0.8s$$

see PDG for references

Sussex-ILL-NIST Beam Experiments



graphic by F Wietfeldt

PHYSICAL REVIEW C **71**, 055502 (2005)

Measurement of the neutron lifetime by counting trapped protons in a cold neutron beam

J. S. Nico, M. S. Dewey, and D. M. Gilliam
National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA

F. E. Wietfeldt
Tulane University, New Orleans, Louisiana 70118, USA

X. Fei and W. M. Snow
Indiana University and Indiana University Cyclotron Facility, Bloomington, Indiana 47408, USA

G. L. Greene
University of Tennessee/Oak Ridge National Laboratory, Knoxville, Tennessee 37996, USA

J. Pauwels, R. Eykens, A. Lamberty, and J. Van Gestel
European Commission, Joint Research Centre, Institute for Reference Materials and Measurements, B-2440 Geel, Belgium

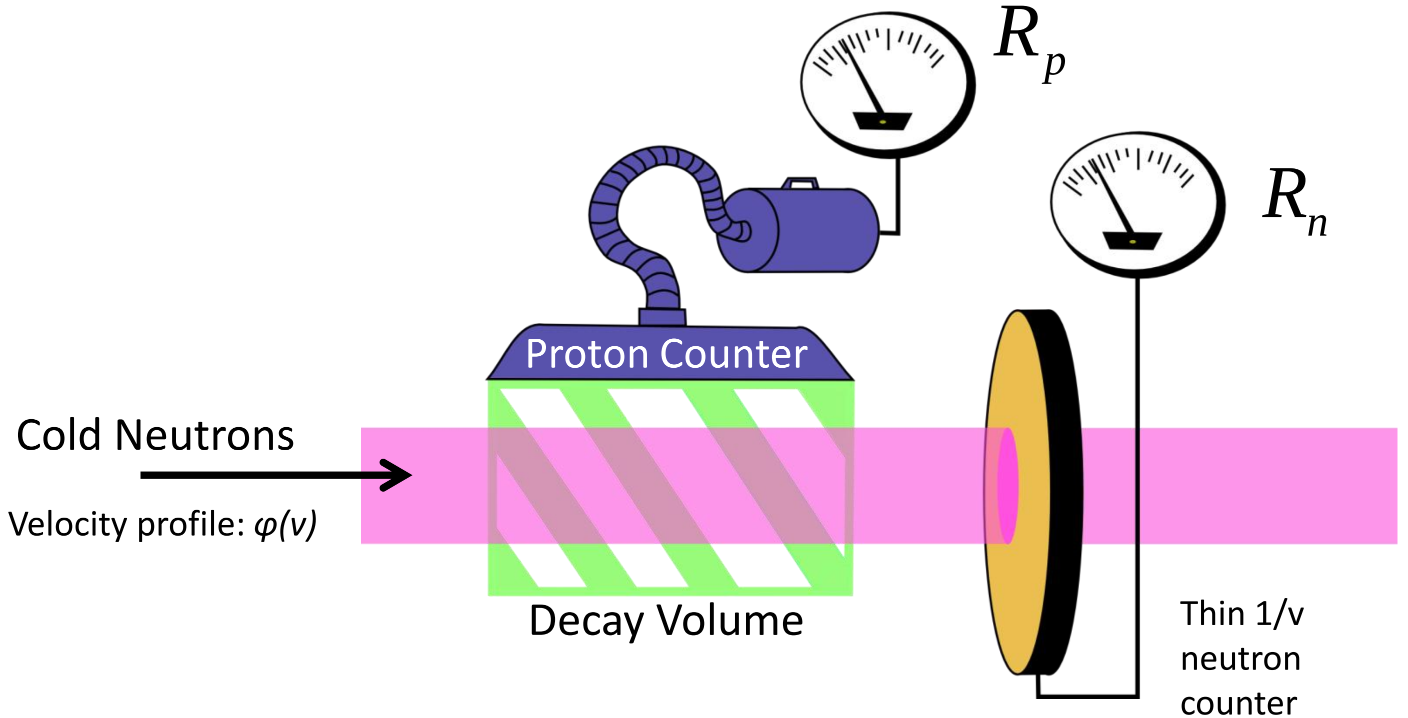
R. D. Scott
Scottish Universities Research and Reactor Centre, East Kilbride G75 0QU, United Kingdom

(Received 16 November 2004; published 25 May 2005)

A measurement of the neutron lifetime τ_n performed by the absolute counting of in-beam neutrons and their decay protons has been completed. Protons confined in a quasi-Penning trap were accelerated onto a silicon detector held at a high potential and counted with nearly unit efficiency. The neutrons were counted by a device with an efficiency inversely proportional to neutron velocity, which cancels the dwell time of the neutron beam in the trap. The result is $\tau_n = (886.3 \pm 1.2[\text{stat}] \pm 3.2[\text{sys}])$ s, which is the most precise measurement of the lifetime using an in-beam method. The systematic uncertainty is dominated by neutron counting, in particular, the mass of the deposit and the ^{6}Li(n,t) cross section. The measurement technique and apparatus, data analysis, and investigation of systematic uncertainties are discussed in detail.

DOI: 10.1103/PhysRevC.71.055502 PACS number(s): 21.10.Tg, 13.30.Ce, 23.40.−s, 26.35.+c

How to Measure τ_n in a Beam



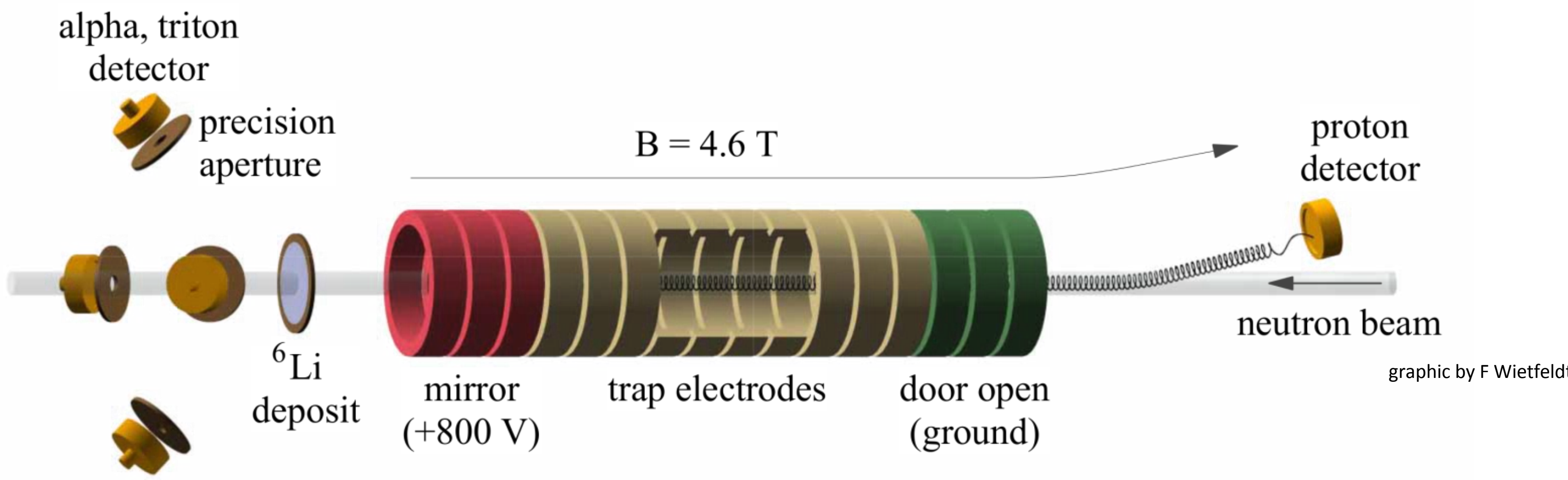
$$R_p = \varepsilon_p \frac{A_{beam} L_{\det}}{\tau_n} \int \frac{\varphi(v)}{v} dv$$

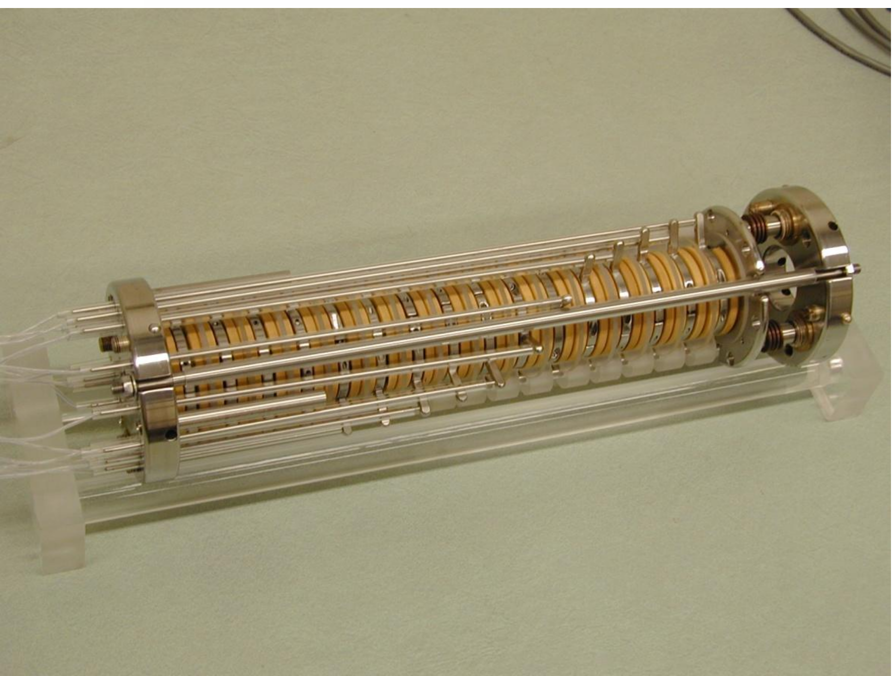
$$\tau_n = \frac{R_n \varepsilon_p L_{\det}}{R_p \varepsilon_{th} v_{th}}$$

FM absorbs neutrons as 1/v
So it's calibrated at thermal velocity

$$R_n = \varepsilon_{th} A_{beam} v_{th} \int \frac{\varphi(v)}{v} dv$$

Sussex-ILL-NIST Beam Experiments





PHYSICAL REVIEW C **71**, 055502 (2005)

Measurement of the neutron lifetime by counting trapped protons in a cold neutron beam

J. S. Nico, M. S. Dewey, and D. M. Gilliam
National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA

F. E. Wietfeldt
Tulane University, New Orleans, Louisiana 70118, USA

X. Fei and W. M. Snow
Indiana University and Indiana University Cyclotron Facility, Bloomington, Indiana 47408, USA

G. L. Greene
University of Tennessee/Oak Ridge National Laboratory, Knoxville, Tennessee 37996, USA

J. Pauwels, R. Eykens, A. Lamberty, and J. Van Gestel
European Commission, Joint Research Centre, Institute for Reference Materials and Measurements, B-2440 Geel, Belgium

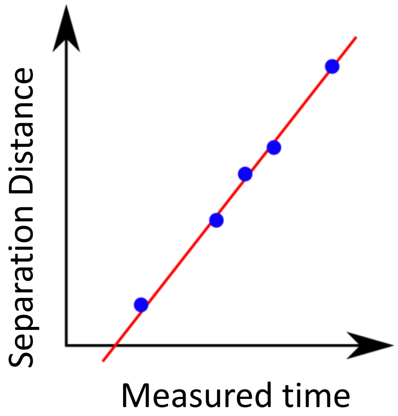
R. D. Scott
Scottish Universities Research and Reactor Centre, East Kilbride G75 0QU, United Kingdom
(Received 16 November 2004; published 25 May 2005)

A measurement of the neutron lifetime τ_n performed by the absolute counting of in-beam neutrons and their decay protons has been completed. Protons confined in a quasi-Penning trap were accelerated onto a silicon detector held at a high potential and counted with nearly unit efficiency. The neutrons were counted by a device with an efficiency inversely proportional to neutron velocity, which cancels the dwell time of the neutron beam in the trap. The result is $\tau_n = (886.3 \pm 1.2[\text{stat}] \pm 3.2[\text{sys}])$ s, which is the most precise measurement of the lifetime using an in-beam method. The systematic uncertainty is dominated by neutron counting, in particular, the mass of the deposit and the ^{6}Li(n,t) cross section. The measurement technique and apparatus, data analysis, and investigation of systematic uncertainties are discussed in detail.

DOI: 10.1103/PhysRevC.71.055502 PACS number(s): 21.10.Tg, 13.30.Ce, 23.40.−s, 26.35.+c

Galileo and Extrapolating Away End Effects

Galileo in *Two New Sciences:* Proposed a method for measuring the speed of light. Experimenter #1 would open a lantern. Experimenter #2, far away, would open his lantern when he sees the light from experimenter 1. Experimenter #1 would measure the time between opening his lantern and seeing experimenter #2's light.



Credit: Flickr fallen petals

$V_{light} = d_{light} / t_{light}$ but... $t_{measured} = (t_{light} + t_{open})$

$$d(t_{meas}) = V_{light} \times (t_{light} + t_{open})$$

Sussex-ILL-NIST Beam Experiments

$$\frac{R_p}{R_n} = \tau^{-1}\left(\frac{\varepsilon_p}{\varepsilon_{th} v_{th}}\right)(nl + L_{end})$$

Trap Length

R_p : decay proton rate

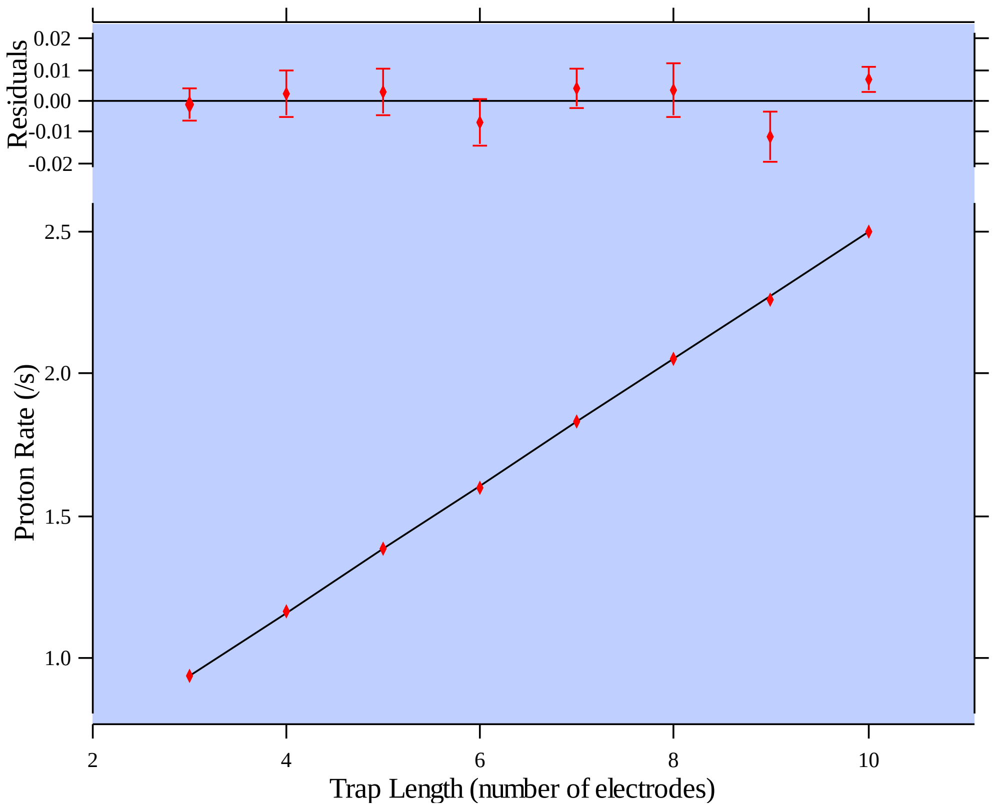
R_n : neutron rate

ε_p : proton detection efficiency

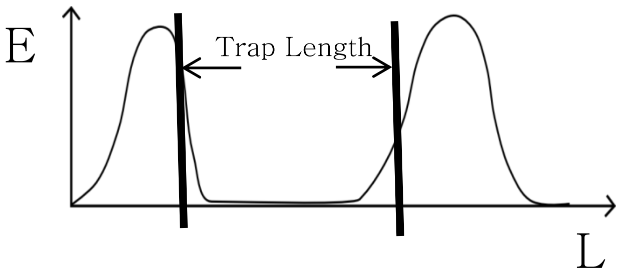
ε_{th} : thermal neutron detection efficiency

nl : number of electrodes times electrode and spacer length

L_{end} : the trap end lengths



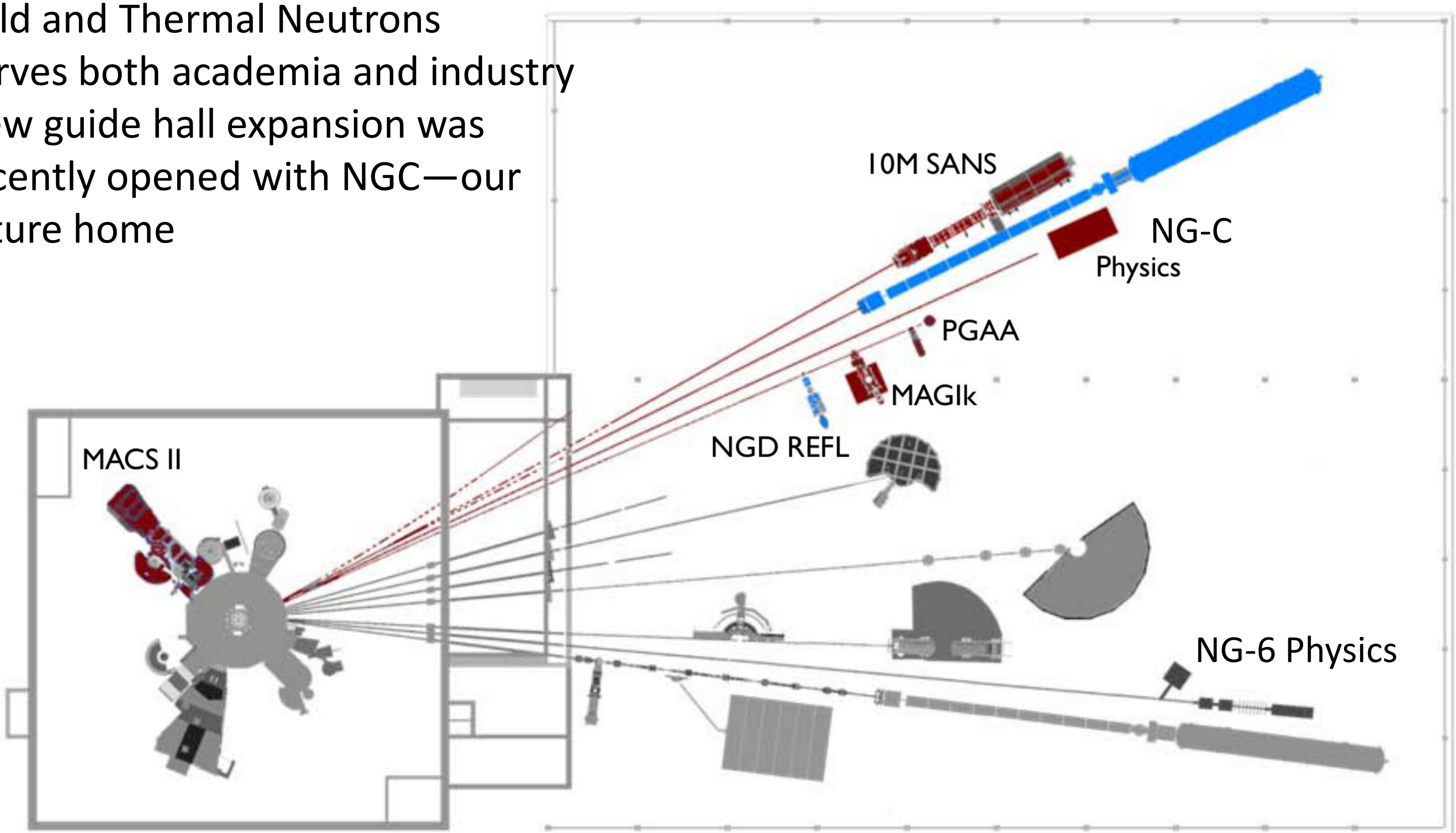
Nico et al Phys Rev C 71 055502 (2005)



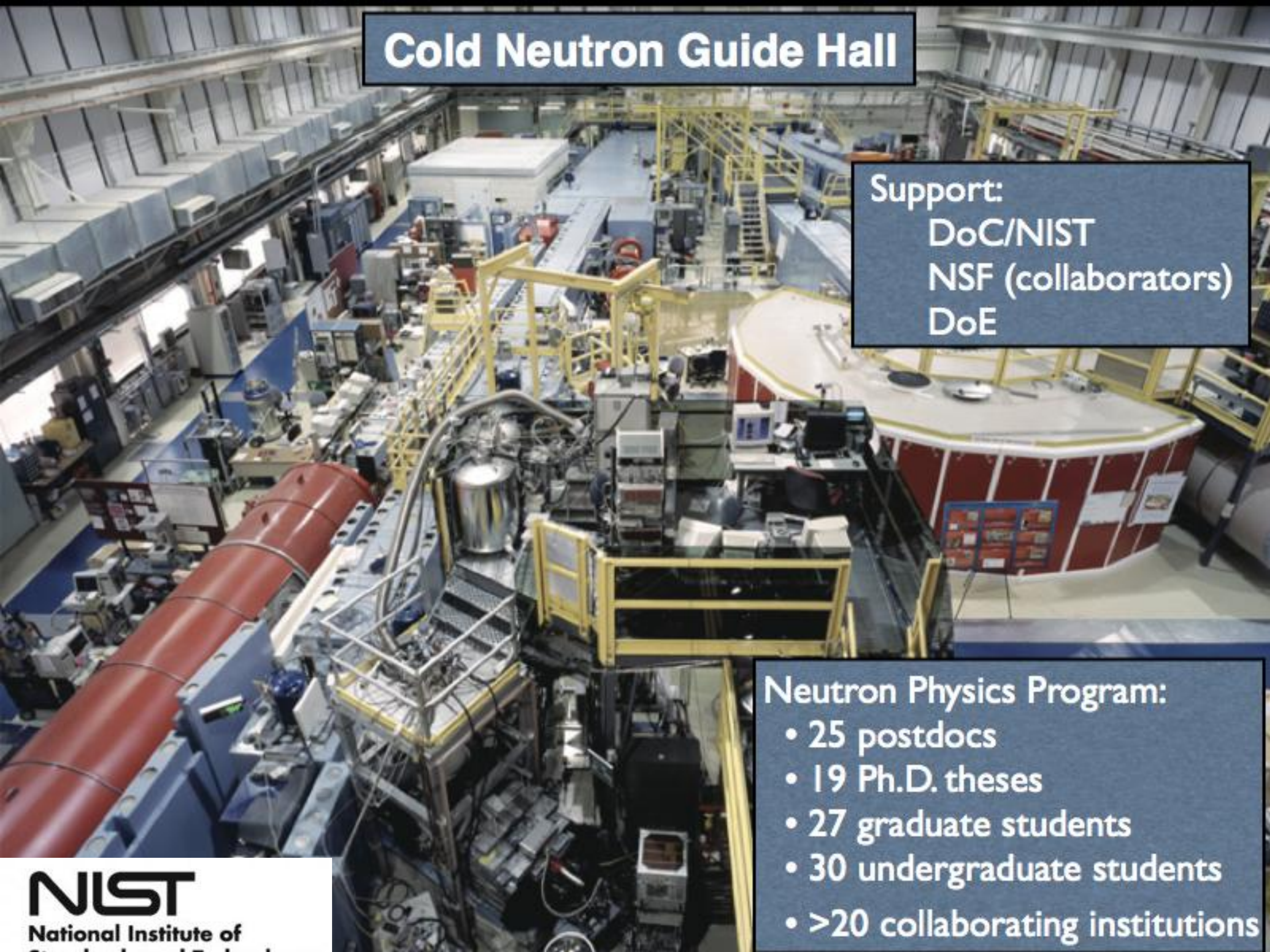
The ends of the trap are not precisely characterized, but their effects can be extrapolated out, assuming the L_{end} is the same for all trap lengths.

National Institute for Standards and Technology Center for Neutron Research

20 MW dedicated research reactor
Cold and Thermal Neutrons
Serves both academia and industry
New guide hall expansion was recently opened with NGC—our future home



Cold Neutron Guide Hall



Support:
- DoC/NIST
- NSF (collaborators)
- DoE

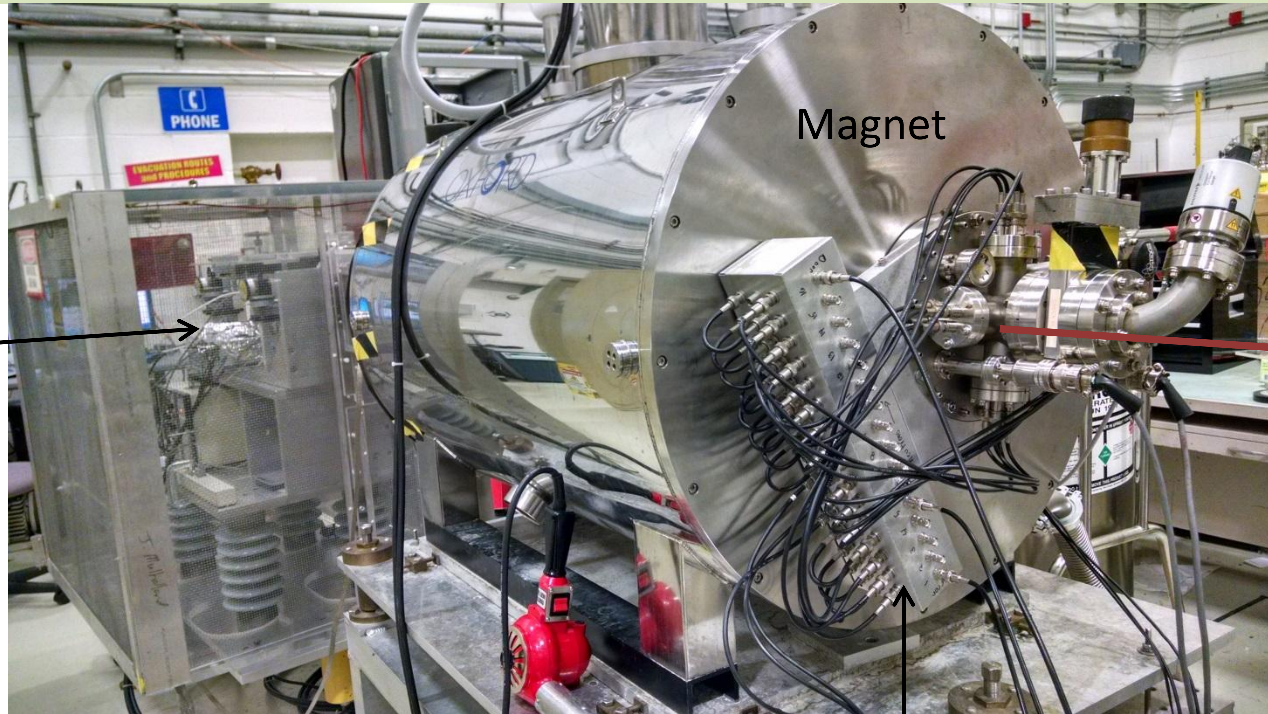
Neutron Physics Program:
- 25 postdocs
- 19 Ph.D. theses
- 27 graduate students
- 30 undergraduate students
- >20 collaborating institutions

NIST
National Institute of

NIST Beam Lifetime 2

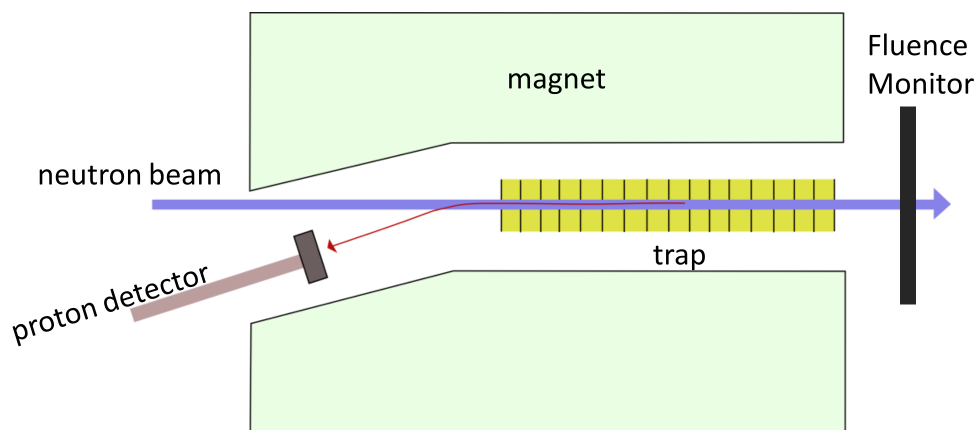
neutron upstream

proton detector electronics and control arm (floated at -30kV)



Downstream of neutron beamline

trap HV connections



NIST 2005 Result Error Budget

Source of correction	Correction (s)	Uncertainty (s)
^{6}LiF deposit areal density		2.2
^{6}Li cross section		1.2
Neutron detector solid angle		1.0
Absorption of neutrons by ^{6}Li	+5.2	0.8
Neutron beam profile and detector solid angle	+1.3	0.1
Neutron beam profile and ^{6}Li deposit shape	−1.7	0.1
Neutron beam halo	−1.0	1.0
Absorption of neutrons by Si substrate	+1.2	0.1
Scattering of neutrons by Si substrate	−0.2	0.5
Trap nonlinearity	−5.3	0.8
Proton backscatter calculation		0.4
Neutron counting dead time	+0.1	0.1
Proton counting statistics		1.2
Neutron counting statistics		0.1
Total	−0.4	3.4

Nico et al Phys. Rev. C **71** 055502 (2005)

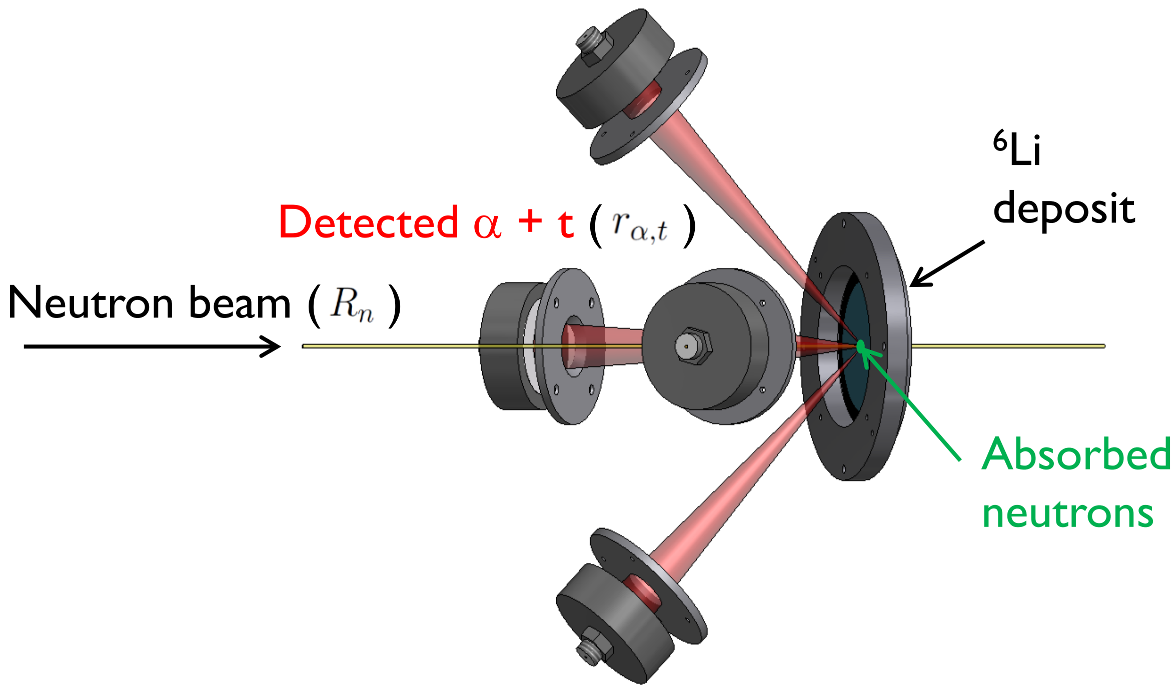
NIST 2005 Error Budget

Source of correction	Correction (s)	Uncertainty (s)
^{6}LiF deposit areal density		2.2
^{6}Li cross section		1.2
Neutron detector solid angle		1.0
Absorption of neutrons by ^{6}Li	+5.2	0.8
Neutron beam profile and detector solid angle	+1.3	0.1
Neutron beam profile and ^{6}Li deposit shape	−1.7	0.1
Neutron beam halo	−1.0	1.0
Absorption of neutrons by Si substrate	+1.2	0.1
Scattering of neutrons by Si substrate	−0.2	0.5
Trap nonlinearity	−5.3	0.8
Proton backscatter calculation		0.4
Neutron counting dead time	+0.1	0.1
Proton counting statistics		1.2
Neutron counting statistics		0.1
Total	−0.4	3.4

Neutron Counting

Nico et al Phys. Rev. C **71** 055502 (2005)

Neutron Counting and the Alpha Gamma Device



A downstream fluence (n/s) monitor measures the neutron rate:

≈1% of the beam is absorbed in this reaction

$$n + {}^{6}\mathrm{Li} \rightarrow \alpha(2.07\mathrm{MeV}) + {}^{3}\mathrm{H}(2.72\mathrm{MeV})$$

Four PIPS detectors detect alpha and triton rates. The efficiency of the detector must measured or calculated.

image courtesy A Yue

CALCULATED from *measured* detector solid angle ($\Omega_{\rm FM}$), *measured* foil areal density (ρ), and *evaluated* thermal neutron cross section (σ_0) of target material:

$$\epsilon_0 = \left[\frac{N_A}{A}\rho\,(0,0)\,\sigma_0\right] \times [2 \cdot \Omega_{\rm FM}\,(0,0)]$$

-Method used for (2005) published lifetime, achieved 0.3% uncertainty

OR

MEASURED with a second, totally absorbing neutron detector used on a monochromatic beamline

$$\epsilon_0 = \frac{r_{\alpha,t}}{R_n}\frac{\lambda_0}{\lambda_{\rm mono}}$$

-Alpha-Gamma (AG) device (completed, achieved 0.06% uncertainty)

-^{3}He gas scintillation chamber (device under construction)

-Liquid ^{3}He target radiometer (device under construction)

Improved Fluence Measurement

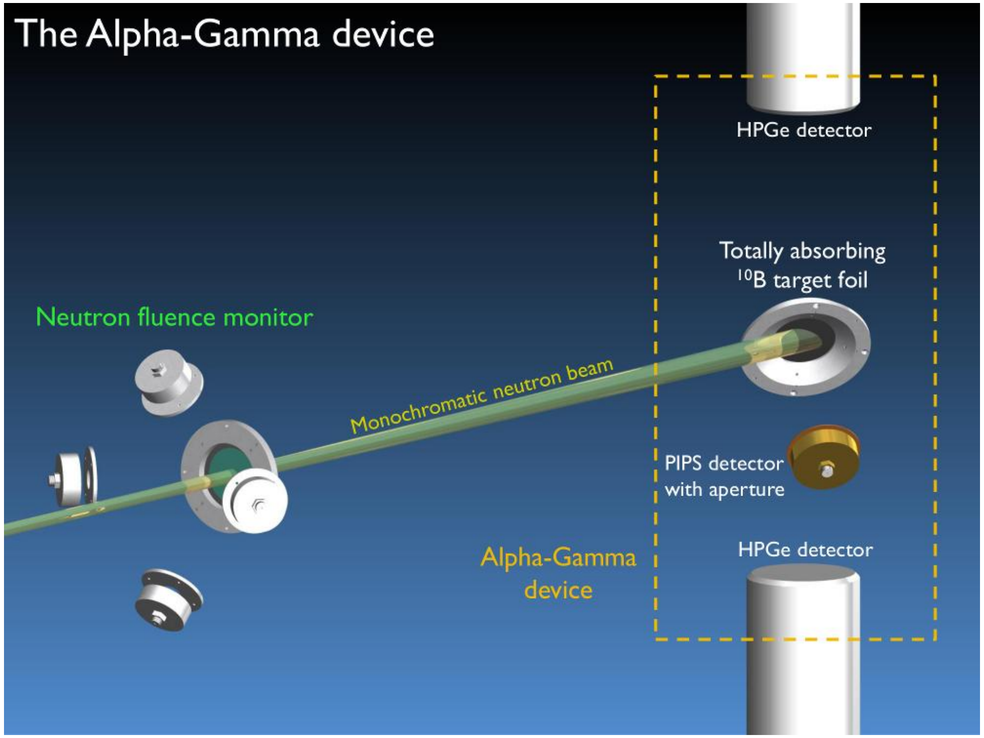
Multiple Avenues to High Precision

Operational:

- ^{10}B alpha-gamma device now working at NIST: Calibrates neutron fluence monitor to **0.06% precision**

In Development:

- He gas scintillation chamber (Tulane, NIST) – in construction/testing. Project goal is <0.05% precision
- Neutron radiometer (Michigan)



A. T. Yue , *Ph. D. thesis, University of Tennessee (2011)*
Gilliam, D. M., Greene, G. L., and Lamaze, G. P. (1989) NIM A, 284:220-222

Fluence monitor advances enabled the 2013 improved determination : 887.7 ± 2.3 s

Sussex-ILL-NIST Measurement Campaign

2003 Experimental Run

Long Paper : Nico et al Phys. Rev. C **71** 055502 (2005)

Improved determination: Yue et al Phys. Rev. Lett. 111, 222501 (2013)

Final Result: 887.7 s ± 1.2 [stat] ± 1.9 [syst]

2015 Run (**BL2**)

Same Apparatus

Improved Neutron and Proton Counting

Longer Run Time Available

Anticipated Uncertainty: ± 1.0 s (combined stat and sys)

2017 Design and Construction for 0.01% Measurement (**BL3**)

Re-Designed Apparatus

Massive Increase in Statistics

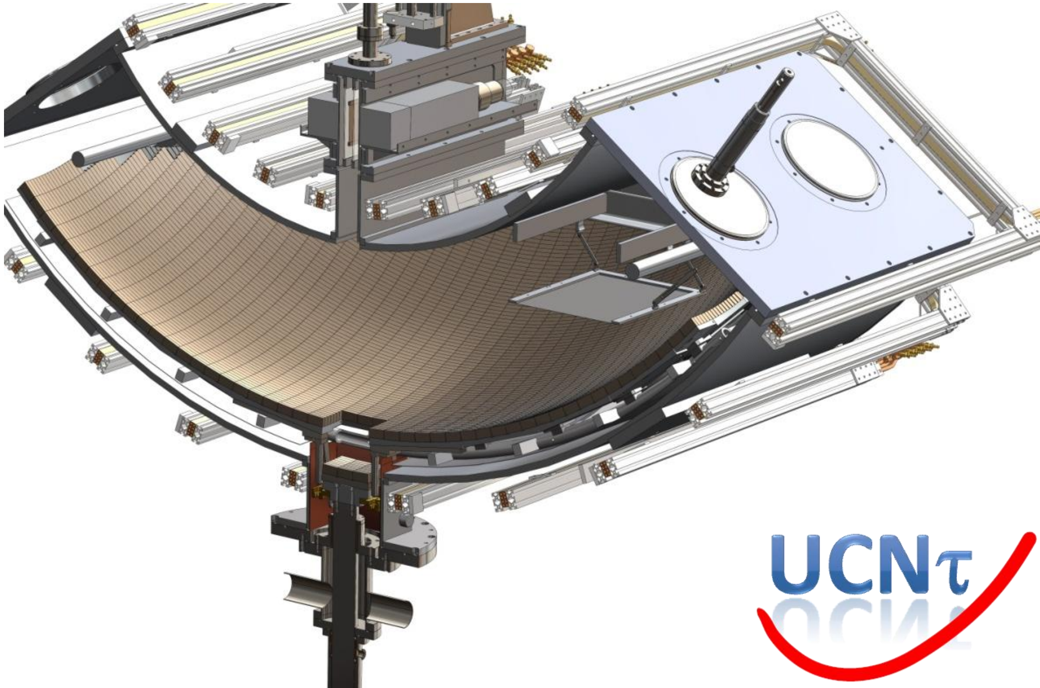
New Proton Detection System

Anticipated Uncertainty: <± 0.2s

UCNτ Overview

- UCN trap with very low intrinsic losses
  - Magneto-gravitational trap
  - Superposed holding field to eliminate B-field zeros (no depolarization losses)
  - Fast removal of quasi-bound UCNs possible through trap asymmetry and field ripple
- High statistics are achievable
  - Large volume
  - *In situ* UCN detector
    - High overall efficiency
    - Also: Less sensitive to phase-space evolution than draining

Based on original concept: P.L. Walstrom, J.D. Bowman, S.I. Penttila, C. Morris, A. Saunders, NIMA 599 (2009) 82-92



slide courtesy A. Saunders

Velocity Dependent Corrections

Source of correction	Correction (s)	Uncertainty (s)
^{6}LiF deposit areal density		2.2
^{6}Li cross section		1.2
Neutron detector solid angle		1.0
Absorption of neutrons by ^{6}Li	+5.2	0.8
Neutron beam profile and detector solid angle	+1.3	0.1
Neutron beam profile and ^{6}Li deposit shape	−1.7	0.1
Neutron beam halo	−1.0	1.0
Absorption of neutrons by Si substrate	+1.2	0.1
Scattering of neutrons by Si substrate	−0.2	0.5
Trap nonlinearity	−5.3	0.8
Proton backscatter calculation		0.4
Neutron counting dead time	+0.1	0.1
Proton counting statistics		1.2
Neutron counting statistics		0.1
Total	−0.4	3.4

Nico et al Phys. Rev. C **71** 055502 (2005)

Velocity Dependent Corrections

Source of correction	Correction (s)	Uncertainty (s)
^{6}LiF deposit areal density		2.2
^{6}Li cross section		1.2
Neutron detector solid angle		1.0
Absorption of neutrons by ^{6}Li	+5.2	0.8
Neutron beam profile and detector solid angle	+1.3	0.1
Neutron beam profile and ^{6}Li deposit shape	−1.7	0.1
Neutron beam halo	−1.0	1.0
Absorption of neutrons by Si substrate	+1.2	0.1
Scattering of neutrons by Si substrate	−0.2	0.5
Trap nonlinearity	−5.3	0.8
Proton backscatter calculation		0.4
Neutron counting dead time	+0.1	0.1
Proton counting statistics		1.2
Neutron counting statistics		0.1
Total	−0.4	3.4

Measure the velocity profile !

→ $0.1s$

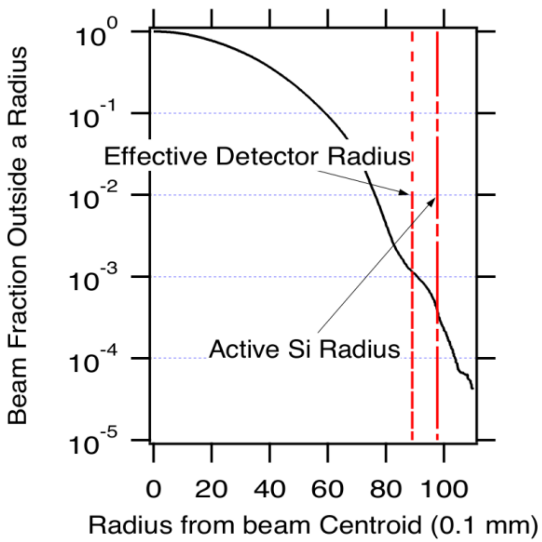
Nico et al Phys. Rev. C **71** 055502 (2005)

Proton Counting Corrections

Source of correction	Correction (s)	Uncertainty (s)
^{6}LiF deposit areal density		2.2
^{6}Li cross section		1.2
Neutron detector solid angle		1.0
Absorption of neutrons by ^{6}Li	+5.2	0.8
Neutron beam profile and detector solid angle	+1.3	0.1
Neutron beam profile and ^{6}Li deposit shape	−1.7	0.1
Neutron beam halo	−1.0	1.0
Absorption of neutrons by Si substrate	+1.2	0.1
Scattering of neutrons by Si substrate	−0.2	0.5
Trap nonlinearity	−5.3	0.8
Proton backscatter calculation		0.4
Neutron counting dead time	+0.1	0.1
Proton counting statistics		1.2
Neutron counting statistics		0.1
Total	−0.4	3.4

Nico et al Phys. Rev. C **71** 055502 (2005)

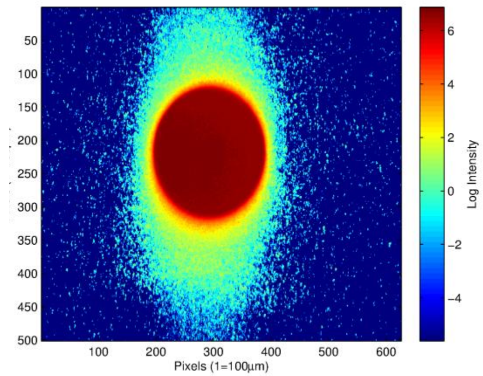
Beam Halo



Nico et al Phys Rev C 71 055502 (2005)

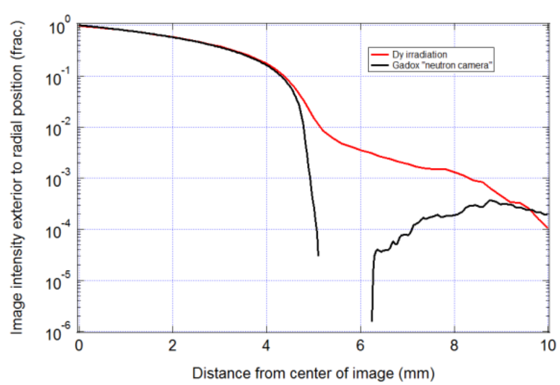
“Blooming”

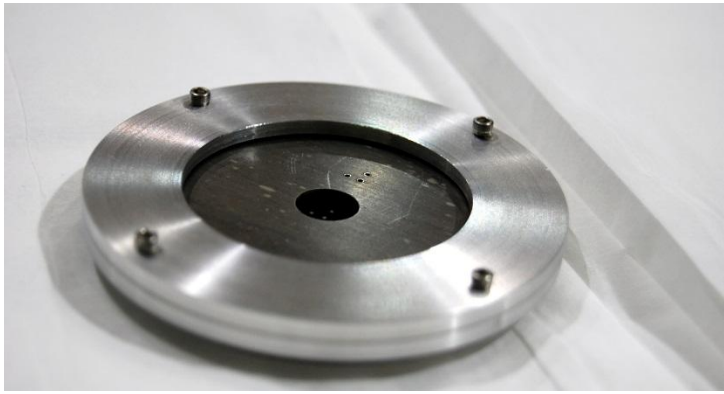
Images were taken using Cd masks to obtain sharp edges



We are re-examining the imaging process. We suspect the halo might have been over estimated. If not, we will be using larger detectors. Either way the uncertainty in halo loss for this run will be around 0.1s instead of 1s.

Dysprosium imaging techniques were used to measure the neutron beam profile. 10^{-3} beam fraction were found outside the active detector radius.





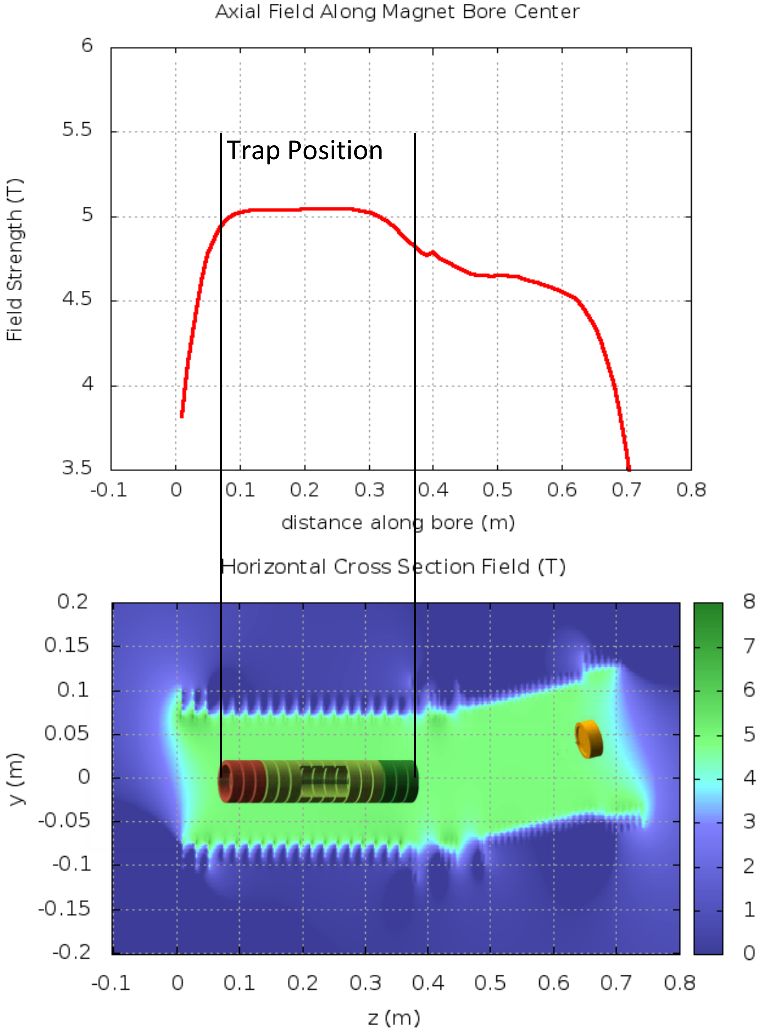
Precision machined Cadmium mask for Dy foil in collimator mount.

Proton Counting Corrections

Source of correction	Correction (s)	Uncertainty (s)
^{6}LiF deposit areal density		2.2
^{6}Li cross section		1.2
Neutron detector solid angle		1.0
Absorption of neutrons by ^{6}Li	+5.2	0.8
Neutron beam profile and detector solid angle	+1.3	0.1
Neutron beam profile and ^{6}Li deposit shape	−1.7	0.1
Neutron beam halo	−1.0	1.0
Absorption of neutrons by Si substrate	+1.2	0.1
Scattering of neutrons by Si substrate	−0.2	0.5
Trap nonlinearity	−5.3	0.8
Proton backscatter calculation		0.4
Neutron counting dead time	+0.1	0.1
Proton counting statistics		1.2
Neutron counting statistics		0.1
Total	−0.4	3.4

Nico et al Phys. Rev. C **71** 055502 (2005)

Trap Non-Linearity



$$\frac{R_p}{R_n} = \tau^{-1}\left(\frac{\varepsilon_p}{\varepsilon_{th}\nu_{th}}\right)(nl + L_{end})$$

L_{end} varies with the trap length due to difference in the electrostatic potential at different radial positions and with the changing magnetic fields near the trap ends.

Previously uncertainty dominated by the variation in the magnetic field for the longest trap length : $\sigma_{trap} = 0.8s$

Running with smaller trap lengths will eliminate the largest contribution to this systematic uncertainty, giving : $\sigma_{trap} \approx 0.2s$

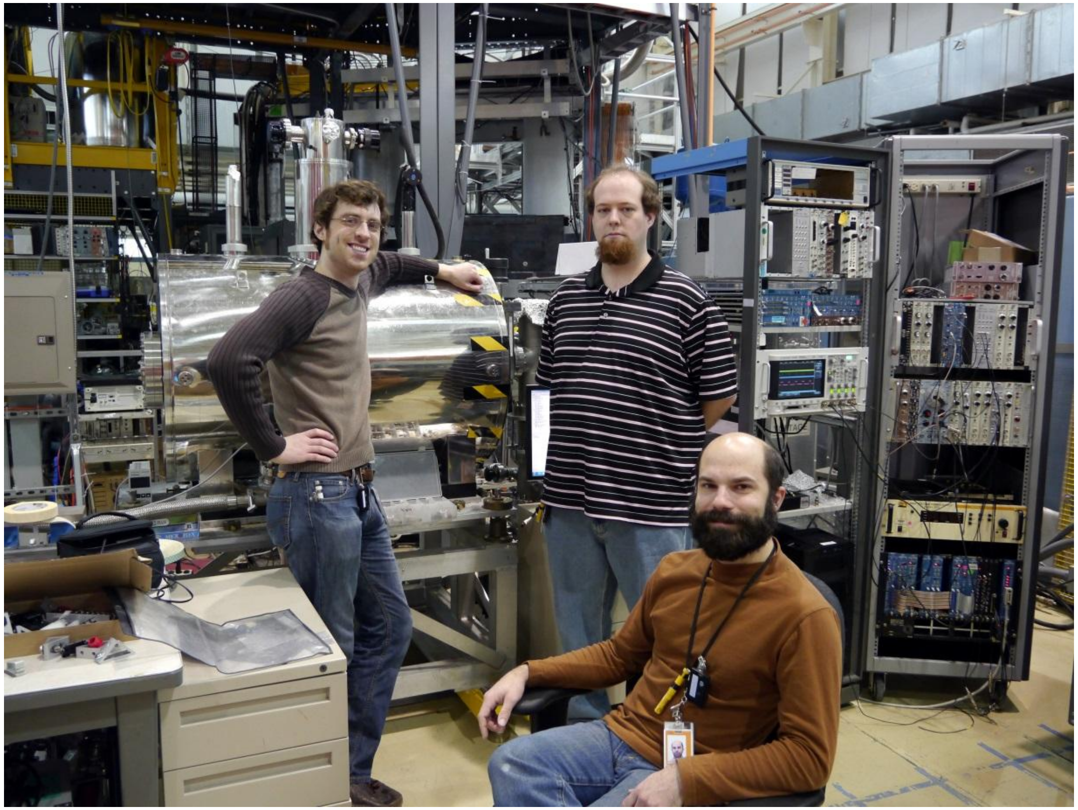
Projected BL2 Error Budget

Most significant improvement

Other major improvements

Source of correction	Correction (s)	Uncertainty (s)	
^{6}LiF deposit areal density		2.2	
^{6}Li cross section		1.2	0.5*s*
Neutron detector solid angle		1.0	
Absorption of neutrons by ^{6}Li	+5.2	0.8	0.1*s*
Neutron beam profile and detector solid angle	+1.3	0.1	
Neutron beam profile and ^{6}Li deposit shape	−1.7	0.1	
Neutron beam halo	−1.0	1.0	0.1*s*
Absorption of neutrons by Si substrate	+1.2	0.1	
Scattering of neutrons by Si substrate	−0.2	0.5	
Trap nonlinearity	−5.3	0.8	0.2*s*
Proton backscatter calculation		0.4	
Neutron counting dead time	+0.1	0.1	
Proton counting statistics		1.2	0.6*s*
Neutron counting statistics		0.1	
Total	−0.4	3.4	$\delta\tau_n \approx 1.0s$

Setting Up For BL2 Measurement



Eamon Anderson, Kyle Grammer, Jonathan Mulholland, and behind the camera, Andrew Yue

Completed:

•Found a home for the apparatus till Winter 2015
•Completed assembly of proton detection system, trap, daq, and cryogenics
•Reestablished alignment proc.
•Full data production mode sans neutrons

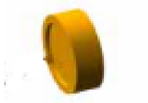
Current Work:

•Exploring high voltage stability in multiple configurations
•Building 2nd trap
•Exploring new detector technology (in communication with JPL and Caltech)

Exploring High Voltage Stability

The magnet bore is an extreme environment
-30kV
4.6T
Oscillating HV trap

There are often ion traps and unpredictable discharges in such environments, and for sensitive charged particle detectors….



Exploring High Voltage Stability

The magnet bore is an extreme environment
-30kV
4.6T
Oscillating HV trap

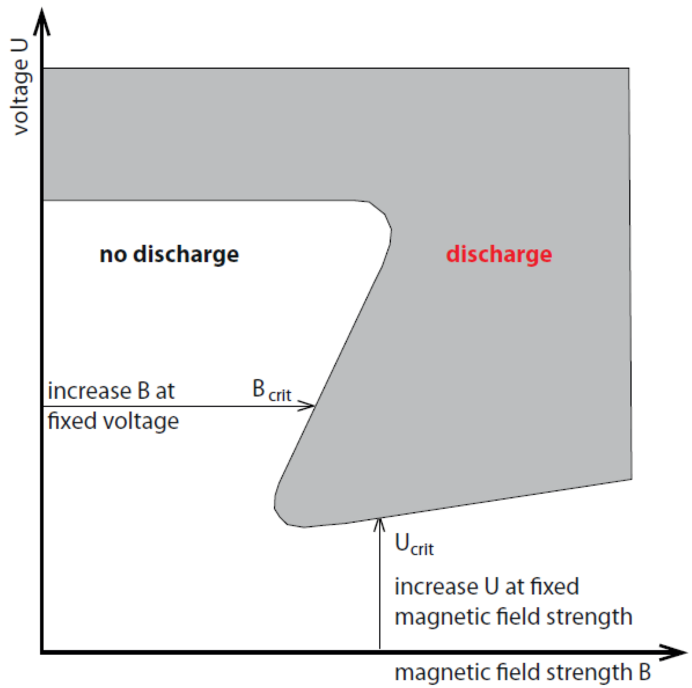
There are often ion traps and unpredictable discharges in such environments, and for sensitive charged particle detectors there is no guarantee of survival…

Exploring High Voltage Stability

Electromagnetic instabilities are not uncommon in apparatuses with high strength crossed E and B fields.

The Katrin collaboration spent a lot of time trying to understand instabilities and unplanned Penning traps in their spectrometer.

Log-Log scale



from F. M. Frankle et al. Jinst **9** P07028
adapted from Hara et al. Cryogenics **29** (1989) 448

The instability of these systems depends on the magnetron orbits of ions and critical ionization energy of the residual gasses. It is not well studied and geometry dependent.

The shape in V-B space one follows during ramp up may take one through a “dangerous” zone.

Running at low voltage can avoid this problem altogether.

Response of a delta-doped charge-coupled device to low energy protons and nitrogen ions

Review of Scientific Instruments **77**, 053301 (2006);

Efficient low energy charged particle detection is also necessary for space astronomy. In particular, the detection of interplanetary coronal mass ejections rely on detecting signatures from many different particles. This drove the development of "delta-doped" detectors at JPL.

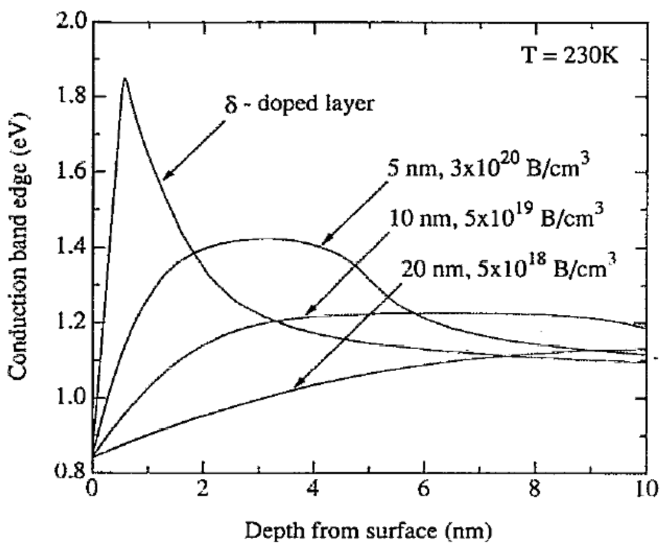


FIG. 2. Calculated spatial dependence of the conduction band edge near the backside of a CCD for various p^+ doping levels and profiles. The two lower curves represent dopant concentrations accessible by ion implantation. The curve for 5 nm of 3×10^{20} B/cm^3 represents a typical dopant level for standard MBE growth. Finally, the curve for δ-doping corresponds to the layer grown on a CCD in this experiment. Thin, highly doped layers produce a narrow backside potential well, and a high potential gradient which optimize the UV quantum efficiency of a CCD.

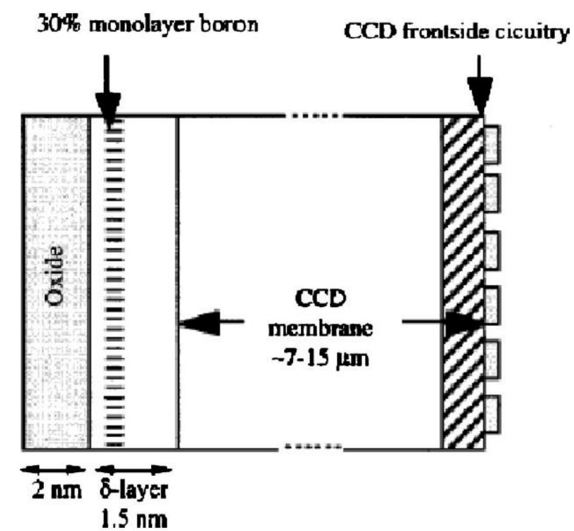


FIG. 5. Schematic of delta-doped CCD structure (not to scale) showing boron atoms 0.5 nm below the silicon epilayer surface and protected by an oxide overlayer. Delta-doped CCDs are back-illuminated devices, meaning that particles are incident on the back surface. [Adapted from Nikzad *et al.* (Ref. 13).]

Applied Physics Letters **61**, 1084 (1992)

The use of "delta doped" detectors offer an order of magnitude improvement in the detection of low energy particles.

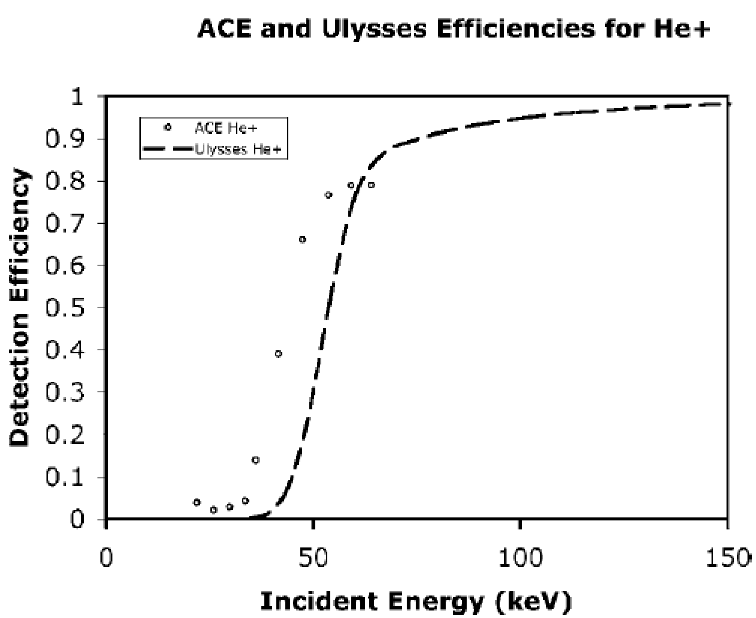


FIG. 4. Solid-state detector efficiencies for He^+ for the ACE and Ulysses spacecraft. Improved technology for the ACE mission allows He^+ to be detected at lower energies compared to the Ulysses SSD. However, ions below 25 keV still elude detection.

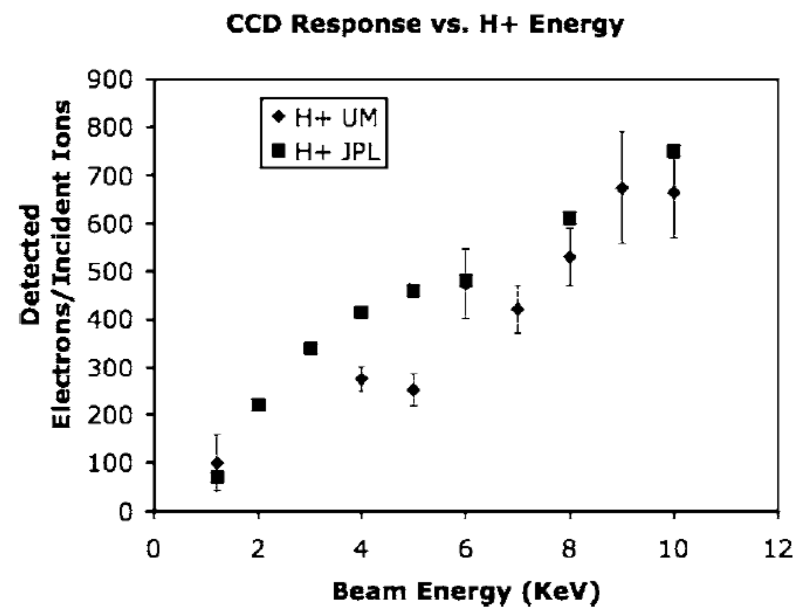


FIG. 9. The response of the delta-doped CCD to H^+ beam. The squares represent the data obtained by JPL in 1999 using the CCD in imaging mode to detect individual protons (Ref. 13). The diamonds represent our data obtained in this study using the CCD in current mode.

State of the art SSD from ACE
Detection limit: 25keV (He+)

Delta Doped Detectors
Detection limit: <2keV (H+)

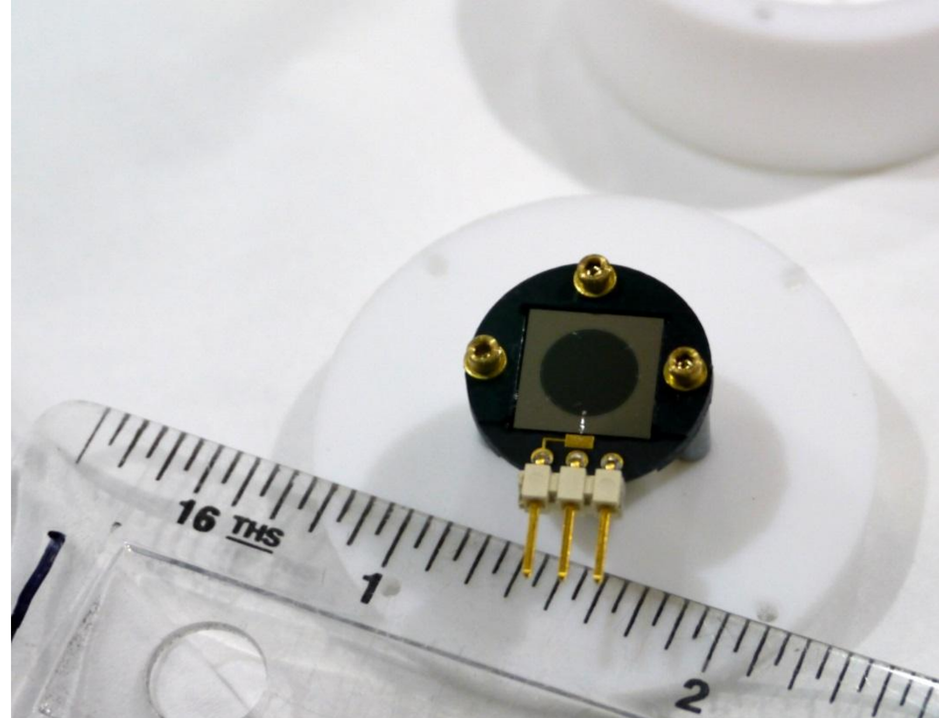
Disclaimer: I'm not sure how to compare He+ and H+ here, but the order of magnitude claim is valid for our system.

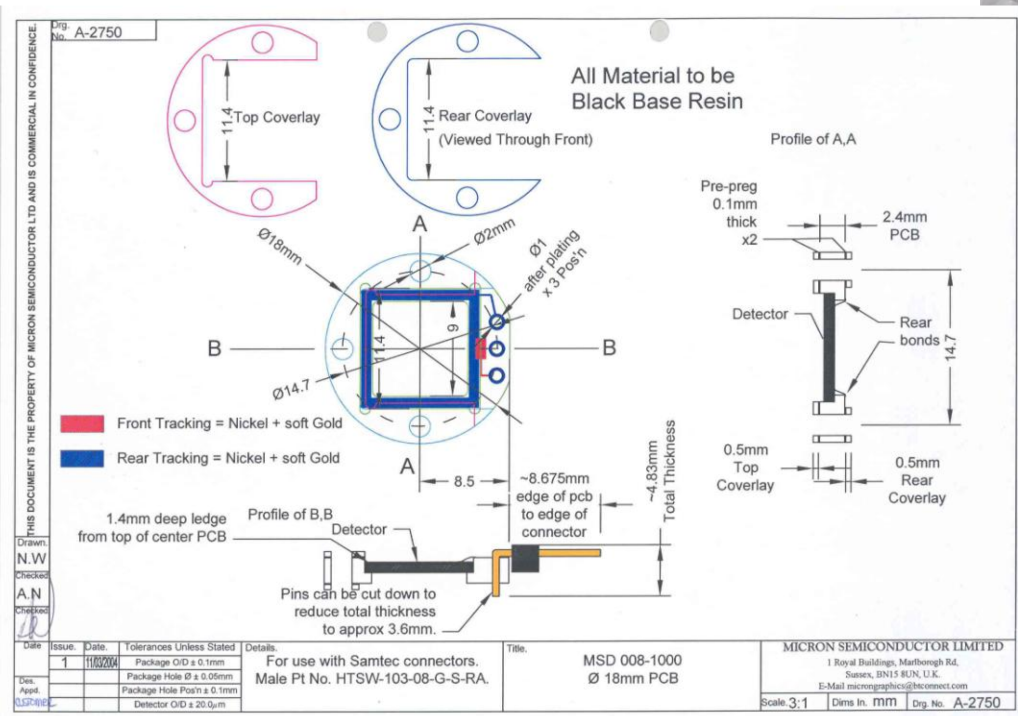
UCLA Researchers in the Experimental Space Physics Group have worked with JPL to produce a 500um thick detector based off of Micron's MSD007 detector.

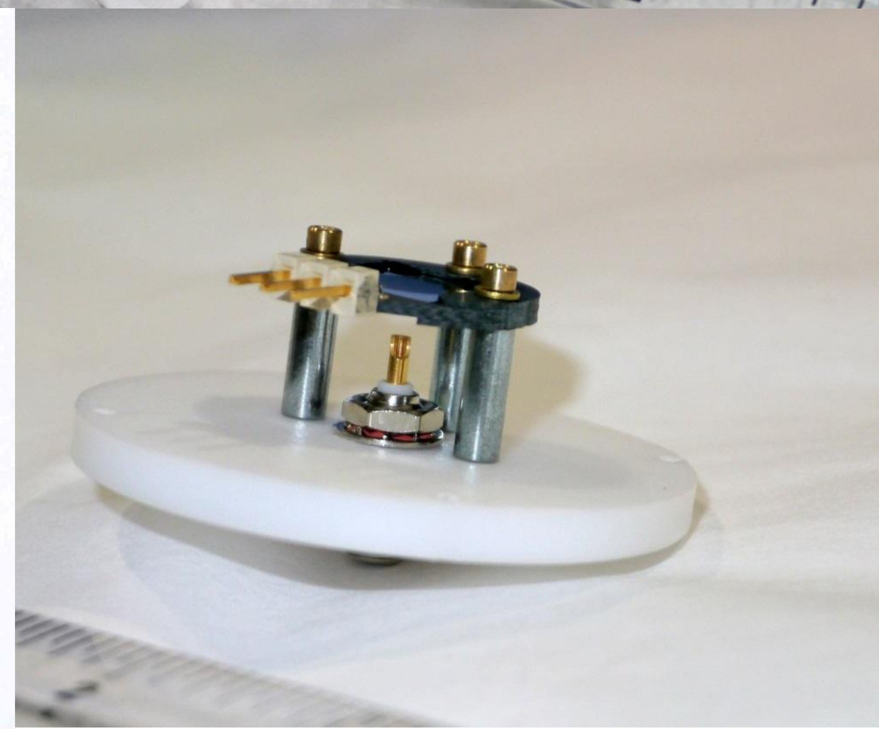
A departure from the CCDs, the MSD007 is exactly the type of SSD we use for experiments in neutron physics.

UCLA contact: Vassilis Angelopoulos http://esp.ess.ucla.edu/

JPL contact: Michael Hoenk or Shouleh Nikzad
http://scienceandtechnology.jpl.nasa.gov/people/s_nikzad/



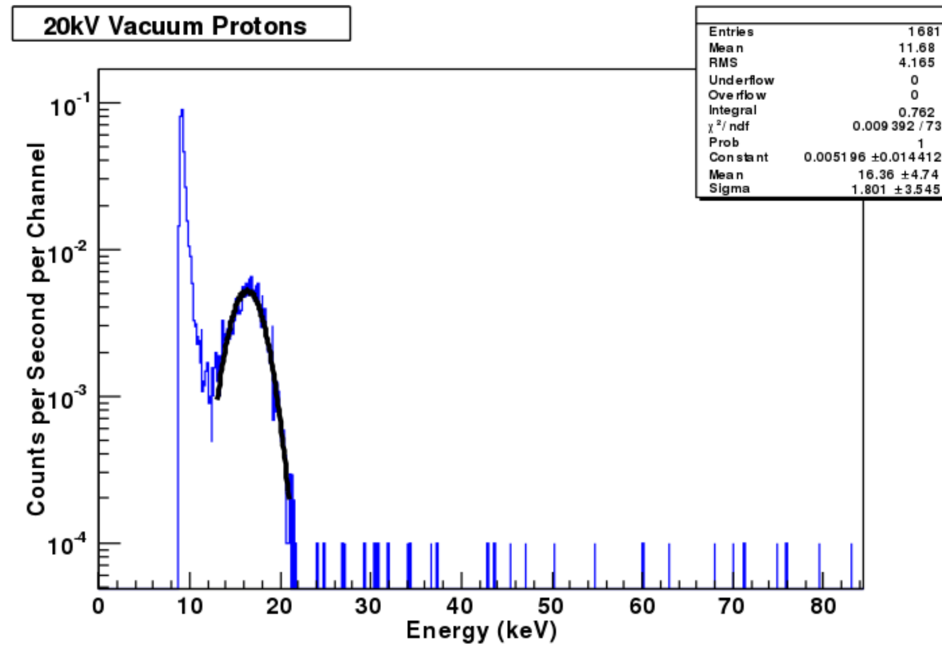


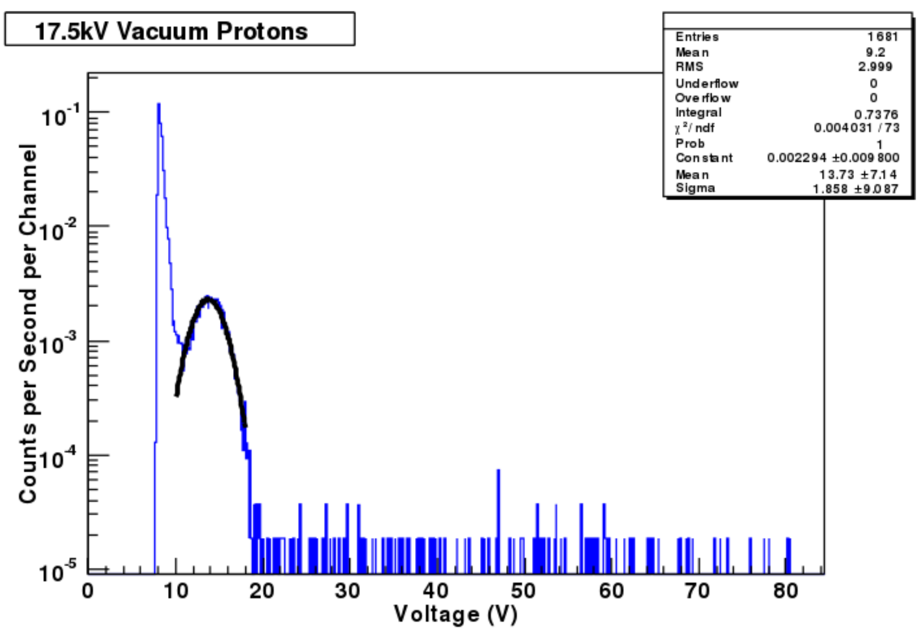


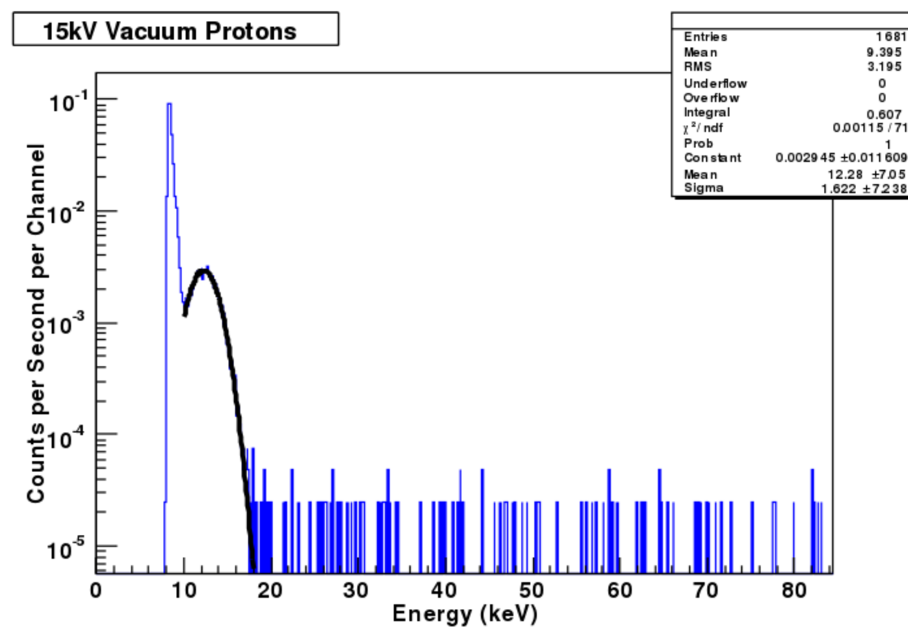
Lower noise on the JPL detectors showed use proton peaks at relatively low energy

But…

Large energy loss in dead layer
Poor resolution







Sussex-ILL-NIST Measurement Campaign

2003 Experimental Run

Long Paper : Nico et al Phys. Rev. C **71** 055502 (2005)

Improved determination: Yue et al Phys. Rev. Lett. 111, 222501 (2013)

Final Result: 887.7 s ± 1.2 [stat] ± 1.9 [syst]

2015 Run (**BL2**)

Same Apparatus

Improved Neutron and Proton Counting

Longer Run Time Available

Anticipated Uncertainty: ± 1.0 s (combined stat and sys)

2017 Design and Construction for 0.01% Measurement (**BL3**)

Re-Designed Apparatus

Massive Increase in Statistics

New Proton Detection System

Anticipated Uncertainty: <± 0.2s

NIST Beam Lifetime Collaboration

National Institute of Standards and Technology

M S Dewey
J Nico
A Yue
D Gilliam
P Mumm

University of Tennessee

G Greene
J Mulholland
N Fomin
K Grammer

Indiana University

M Snow
E Anderson
R Cooper
J Fry

Tulane University

F Wietfeldt
G Darius

University of Michigan

T Chupp
M Bales

Sussex-ILL-NIST Beam Experiments

$$\frac{R_p}{R_n} = \tau^{-1}\left(\frac{\varepsilon_p}{\varepsilon_{th} v_{th}}\right)(nl + L_{end})$$

Trap Length

R_p : decay proton rate

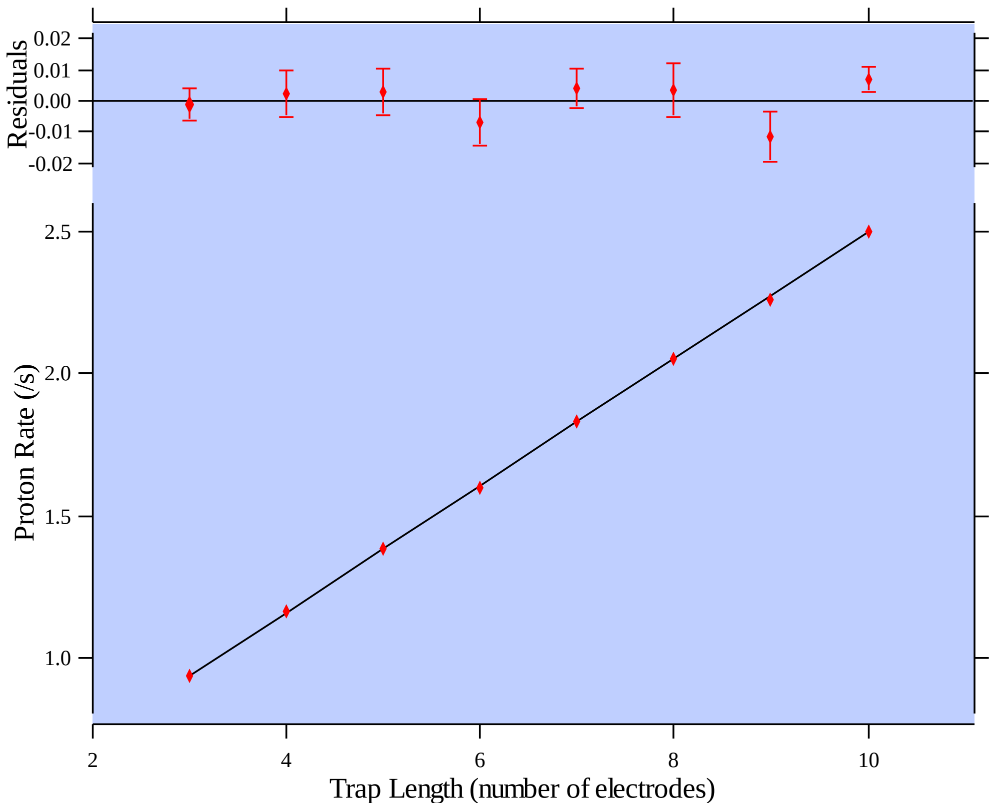
R_n : neutron rate

ε_p : proton detection efficiency

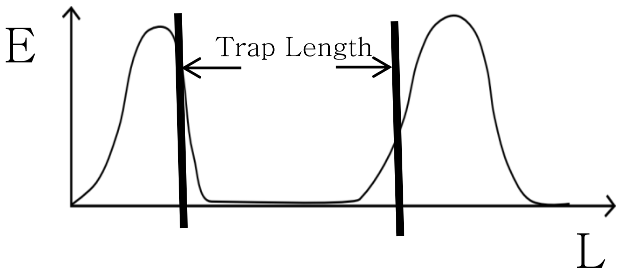
ε_{th} : thermal neutron detection efficiency

nl : number of electrodes times electrode and spacer length

L_{end} : the trap end lengths

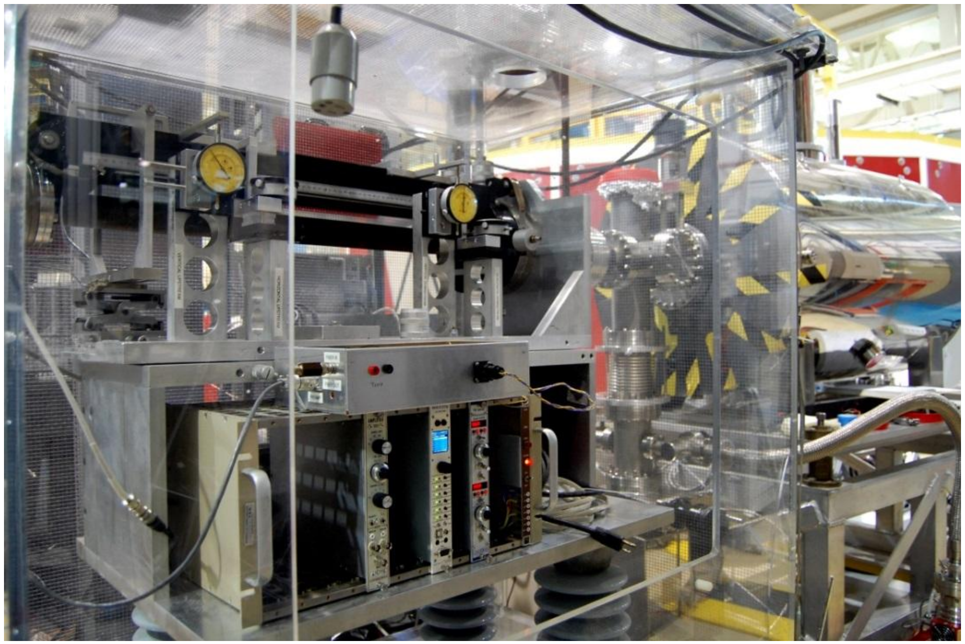


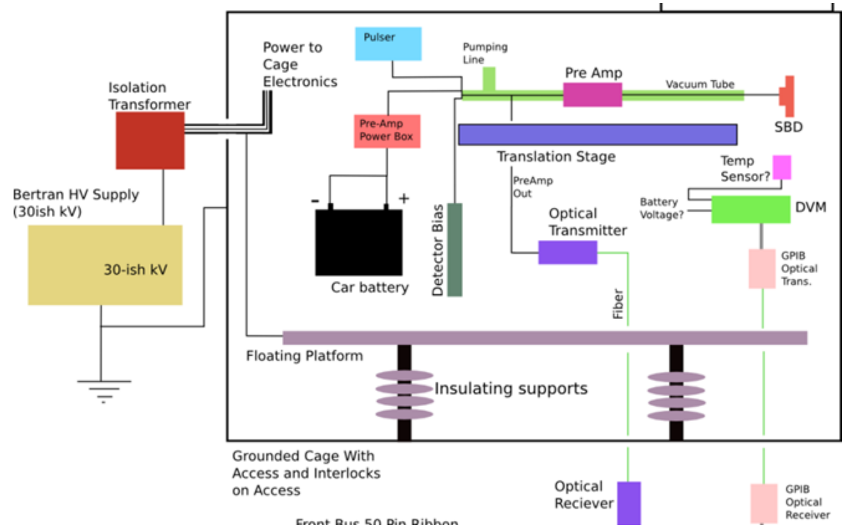
Nico et al Phys Rev C 71 055502 (2005)

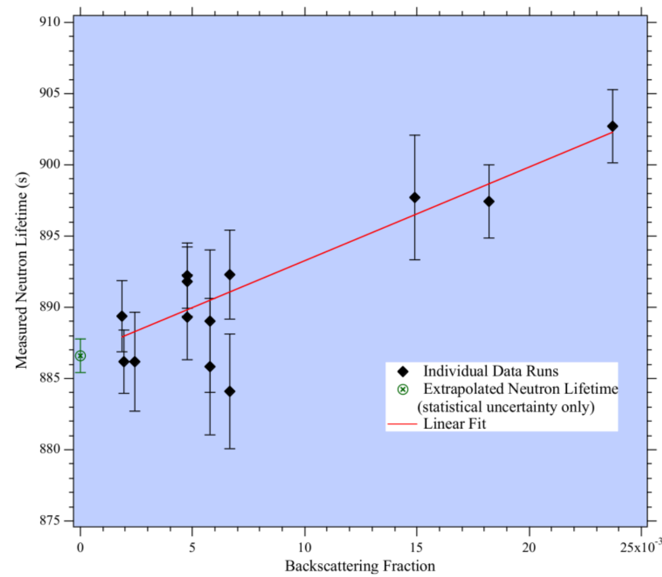


The ends of the trap are not precisely characterized, but their effects can be extrapolated out, assuming the L_{end} is the same for all trap lengths.

Proton Counting



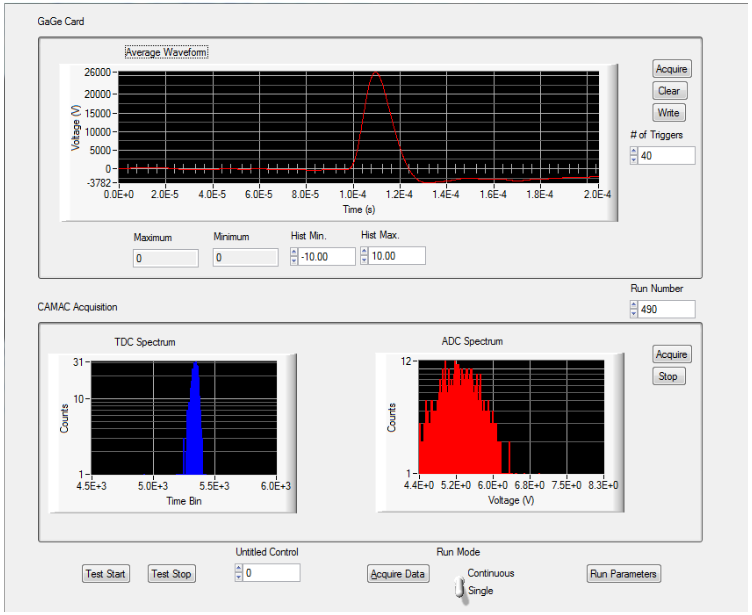




Absolute Proton counting is essential

- Final lifetime result is obtained by extrapolating to zero backscatter loss
- New delta-doped detectors are being explored
- Exploration of systematics is being extended for this run

Proton Counting and the New DAQ



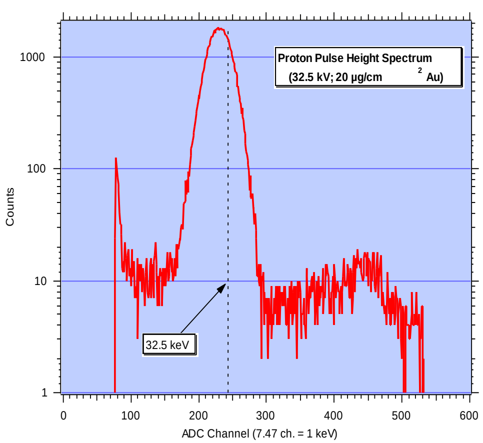
Two Parallel DAQ Systems

Old DAQ: CAMAC based, uses the TDC spectrum to count neutrons

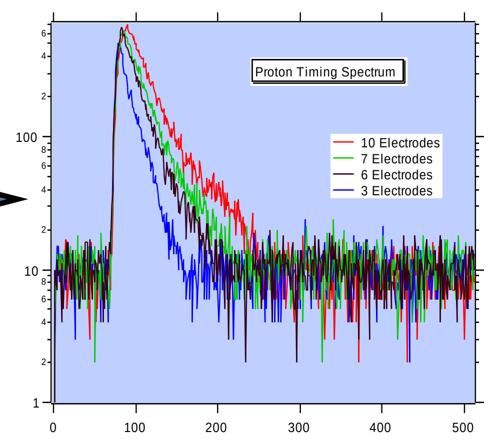
Advantage: Simple, low deadtime, well understood

New DAQ: Digitizes detector output and incorporates pulse shape analysis

Advantage: Characterizes background and multiple events; provides cross check on CAMAC based DAQ



Energy Spectrum



Timing Spectra

Calibration of Alpha-Gamma as a black detector

1. Measure the absolute activity of an alpha source

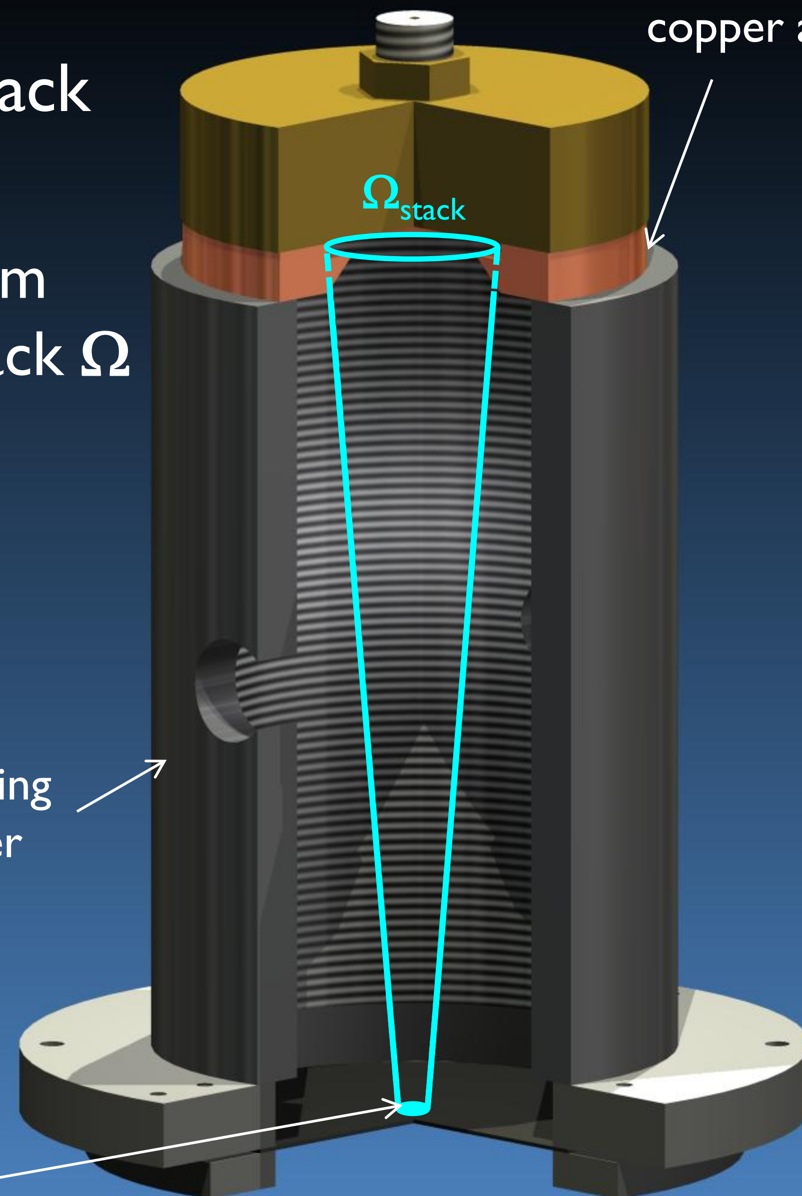
2. Use this source to determine solid angle of alpha detector

3. Use an (n,$\alpha\gamma$) reaction to transfer the calibration to the gamma detectors

1 Calibrate the α-source

^{239}Pu α-source measured in stack of known solid angle

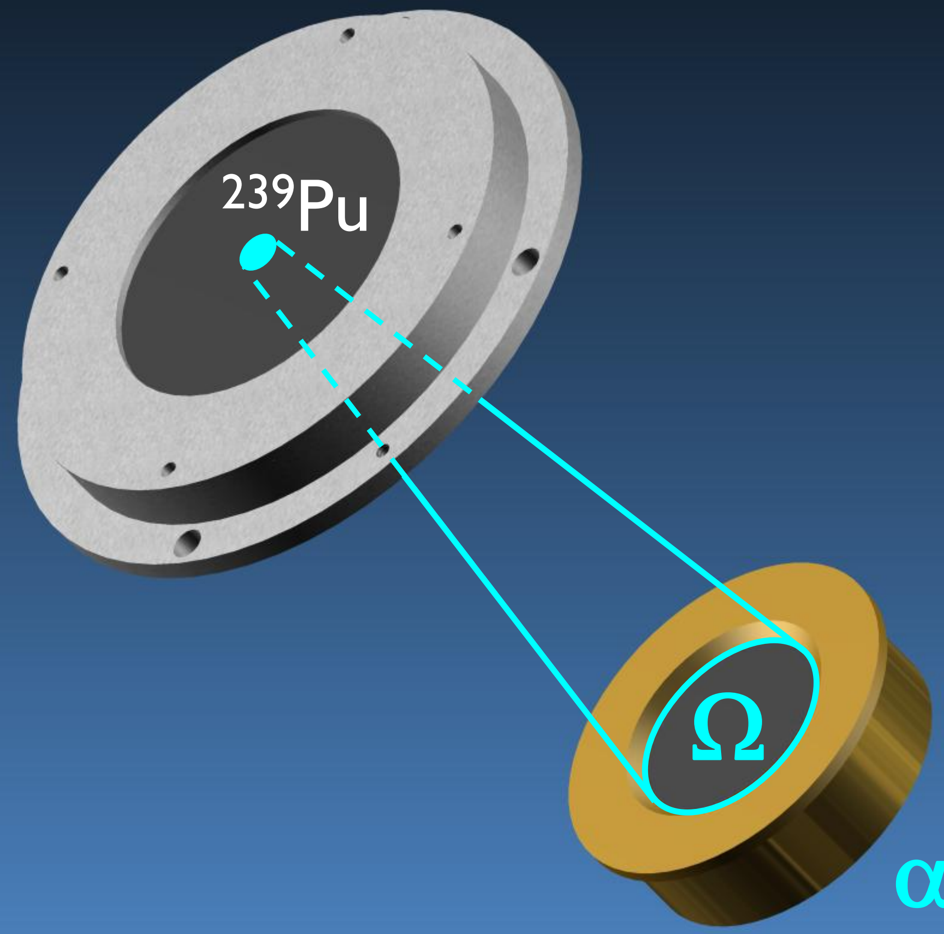
- source activity determined from measured α-rate and known stack Ω



2 Calibrate the α-detector with α-source

Source loaded into AG vacuum chamber and counted

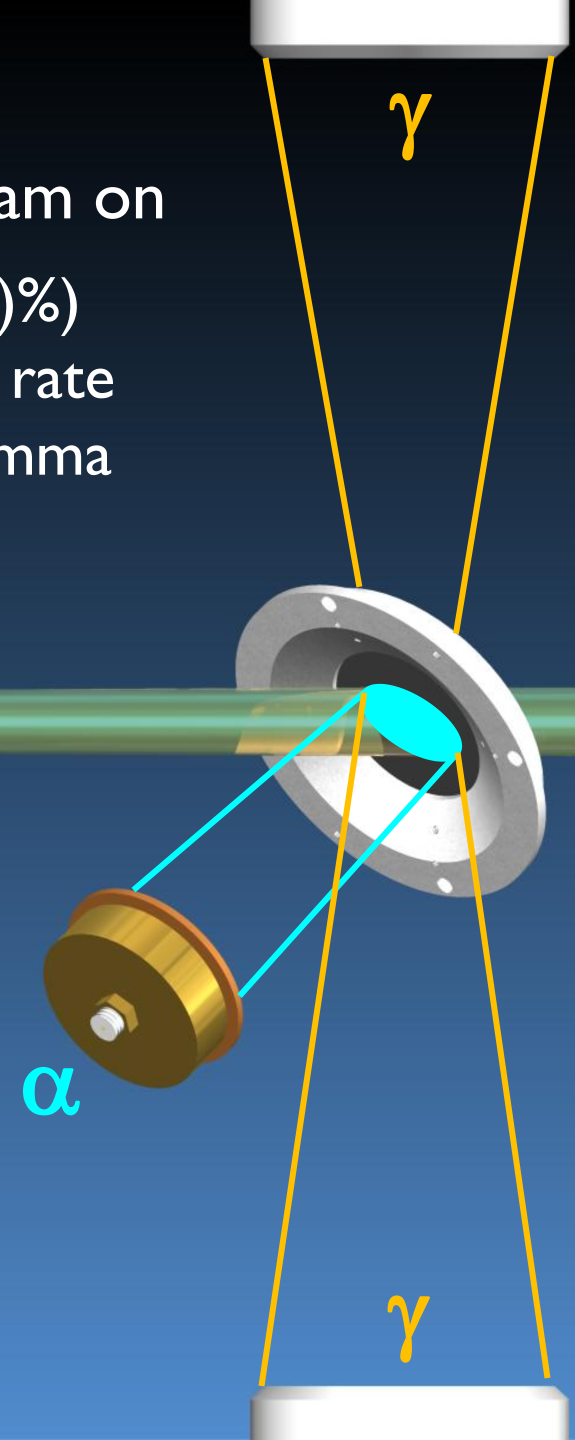
- known source activity gives detector Ω



3 Calibrate the γ-detectors

^{239}Pu replaced with thin ^{10}B foil, beam on

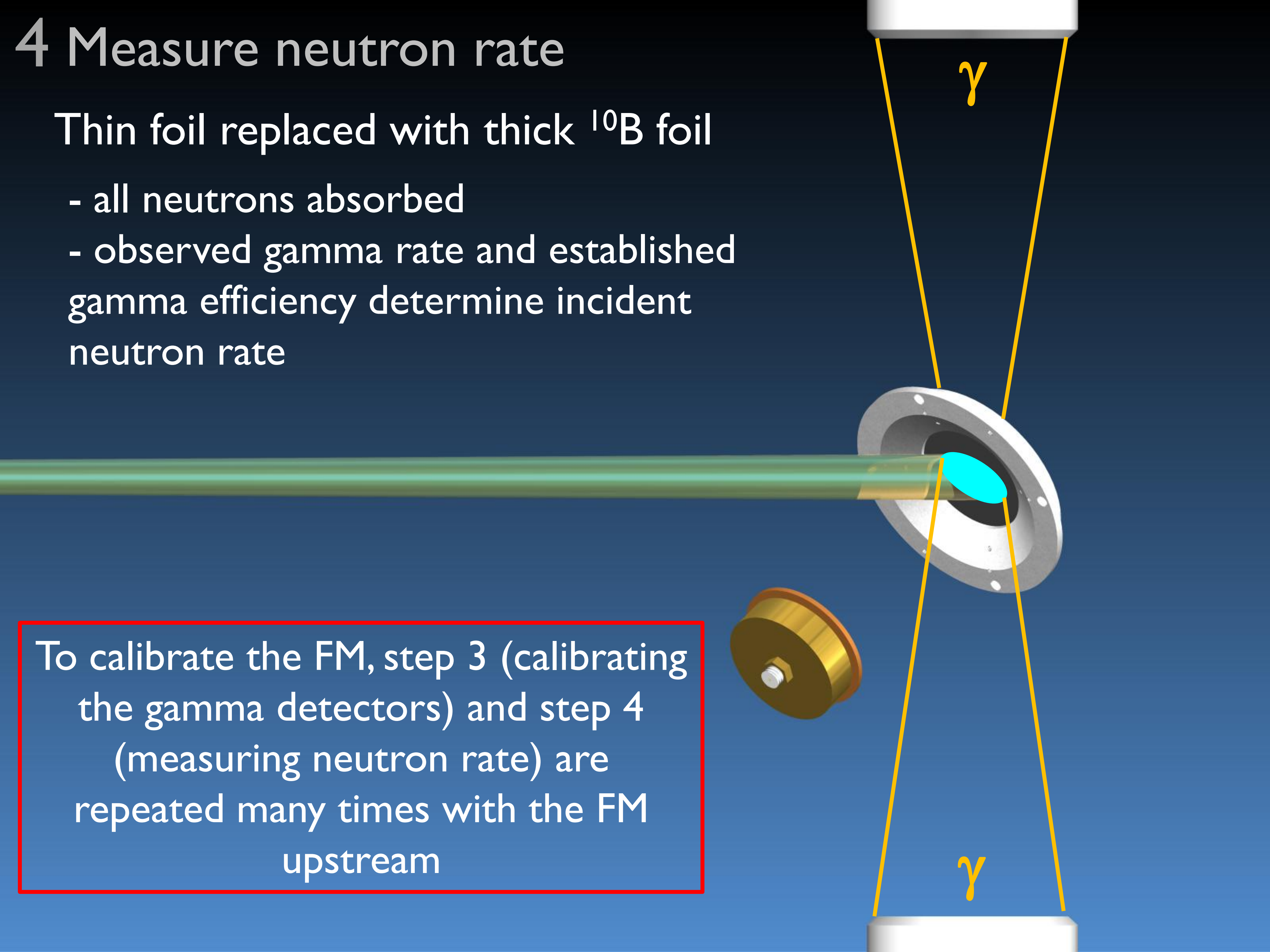
- $n + {}^{10}B \rightarrow {}^{7}Li + \alpha + \gamma$ ($b_\gamma = 93.70(1)\%$)
- Observed gamma rate and neutron rate (determined from alpha rate) give gamma efficiency



4 Measure neutron rate

Thin foil replaced with thick ^{10}B foil

- all neutrons absorbed
- observed gamma rate and established gamma efficiency determine incident neutron rate



To calibrate the FM, step 3 (calibrating the gamma detectors) and step 4 (measuring neutron rate) are repeated many times with the FM upstream

Or, more rigorously…

$$\epsilon_0 = \frac{r_{\alpha,t}}{R_n}\frac{\lambda_0}{\lambda_{\rm mono}} = \overbrace{\frac{r_{\alpha,t}}{r_\gamma(\rm thick)}}^{\text{Thick target: } 1/\text{“}\gamma/\text{FM”}} \frac{r_\gamma(\rm thin)}{\underbrace{r_\alpha(\rm thin)}_{\text{Thin target: } 1/\text{“}\alpha/\gamma\text{”}}} \frac{\overbrace{r_\alpha(\rm Pu)}^{{}^{239}\text{Pu counting: “}R_{\rm Pu}\text{”}}}{R_\alpha(\rm Pu)} \frac{\lambda_0}{\underbrace{\lambda_{\rm mono}}_{\text{Wavelength: “}R_\lambda\text{”}}}$$

In practice, λ and Pu are measured infrequently

Every efficiency measurement has its own measurements of γ/FM and α/γ