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

\[ \tau_n = \frac{G_F^2}{G_V^2 + 3G_A^2} \times 4908.7(1.9) \text{s} \]

Jonathan Mulholland
University of Tennessee
03/17/2015 UVA Nuc Seminar
Charlottesville, VA
First, a neutron history lesson
(courtesy of G. L. Greene)
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
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.

\[ \alpha + ^9\text{Be} \rightarrow ^{12}\text{C} + n \]
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:

\[ M_n = 1.15 \pm 10\% \text{ u} \]

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.”

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

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

\[ h \nu + D^1_1 > H^1_1 + n^1_0 \]

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

\[ M_n = 1.0080 \pm 0.0005 \text{ u} \]
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

\[ M_n > M_p + M_e \]

“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

Beta decay is mediated by the Weak Interaction

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

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

The ratio \( \lambda \) is related to the strong interaction within the parton, connecting weak physics to parton structure.

\[ \lambda = \frac{G_A}{G_V} \]

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

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?

\[
\frac{d\Gamma}{dE_e d\Omega_e d\Omega_\nu} \propto p_e E_e \left(E_0 - E_e\right)^2 \\
\times \left[ 1 + b \frac{m_e}{E_e} + a \frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + \left\langle \vec{\sigma}_n \right\rangle \left( A \frac{\vec{p}_e}{E_e} + B \frac{\vec{p}_\nu}{E_\nu} + D \frac{\vec{p}_e \times \vec{p}_\nu}{E_e E_\nu} \right) \right]
\]

To leading order all those correlations are given by lambda:

\[
\lambda \equiv \frac{g_A}{g_V} \quad a = \frac{1 - \lambda^2}{1 + 3\lambda^2} \quad A = -2 \frac{\lambda(\lambda + 1)}{1 + 3\lambda^2} \quad B = 2 \frac{\lambda(\lambda - 1)}{1 + 3\lambda^2}
\]
Hundredth of a Percent Level $\tau_n$ and $V_{ud}$

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

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

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

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

Measurements of $\tau_n$ and $\beta$-decay angular correlation coefficients:

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

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

## The Early Universe

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<tr>
<th>Time</th>
<th>Temperature</th>
<th>Event Description</th>
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<tbody>
<tr>
<td>$t = 0$</td>
<td>$T = \text{A LOT}$</td>
<td>The Beginning</td>
</tr>
<tr>
<td>$t = 10^{-43}s$</td>
<td>$T = 10^{32}K$</td>
<td>2 forces: gravity and GUT</td>
</tr>
<tr>
<td>$t = 10^{-35}s$</td>
<td>$T = 10^{27}K$</td>
<td>Inflation</td>
</tr>
<tr>
<td>$t = 10^{-12}s$</td>
<td>$T = 10^{15}K$</td>
<td>4 forces – no more unification</td>
</tr>
<tr>
<td>$t = 10^{-7}s$</td>
<td>$T = 10^{12}K$</td>
<td>We have protons, neutrons, positrons, and electrons</td>
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</table>
The Early Universe

Big Bang Nucleosynthesis

After the quark-gluon phase transition around $t \sim 3 \times 10^{-5} \text{s}$, while $t < 1 \text{s}$ protons and neutrons were held in thermal equilibrium by these reactions:

\[ n + e^+ \leftrightarrow p + \bar{\nu}_e \quad n + \nu_e \leftrightarrow p + e^- \]

\[ n \rightarrow e^- + p + \bar{\nu}_e \]

\[ \frac{n}{p} = e^{-\Delta m/kT} \quad \Delta m = 1.293 \text{MeV}/c^2 \]
The Early Universe

Big Bang Nucleosynthesis

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

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

The Early Universe

Early Element Abundance: Big Bang Nucleosynthesis

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

The early $^4\text{He}$ abundance, $Y_p$ can be calculated with just three parameters:

- $N_\nu$: number of neutrino species
  \[ \frac{\Delta Y_p}{Y_p} = +0.17 \frac{\Delta N_\nu}{N_\nu} \]
- $\eta = n_b/n_\gamma$: ratio of baryon density to photon density (WMAP)
  \[ \frac{\Delta Y_p}{Y_p} = +0.039 \frac{\Delta \eta}{\eta} \]
- $\tau_n$: neutron lifetime
  \[ \frac{\Delta Y_p}{Y_p} = +0.72 \frac{\Delta \tau_n}{\tau_n} \]

Uncertainty in the lifetime dominates the predictions of $Y_p$ by BBN.

*Burles et al. 1999*
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

\[ Y_p = 0.2516 \pm 0.0011 \quad \text{Izotov, Thuan, & Stasinska 2007} \]

\[ Y_p = 0.2561 \pm 0.0108 \quad \text{Porter Hel emissivities} \]

\[ Y_p = 0.2565 \pm 0.005 \quad \text{Aver, Olive, Skillman 2010} \]

\[ Y_p = 0.2561 \pm 0.0108 \quad \text{extragalactic H II regions} \]

\[ Y_p = 0.2565 \pm 0.005 \quad \text{Izotov & Thuan 2010} \]

\[ Y_p = 0.2565 \pm 0.005 \quad \text{low-Z extragalactic HII regions} \]

Measurement of lifetime to 1 s gives

\[ 0.72 \Delta \tau_n / \tau_n = 0.08\% \]

But do we know \( \tau_n \) to 1s?

references at http://www.pas.rochester.edu/~emamajek/memo_Yp.html
How to Measure $\tau_n \ldots N(t) = N_0 e^{-t/\tau_n}$

Direct Observation of Exponential Decay:

Observe the decay rate of $N_0$ neutrons and the slope of

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

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

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

“Bottle” Experiments:

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 \( \tau_n = 880.3 \pm 1.1 \text{s} \)

see PDG for references
The State of the Neutron Lifetime

Beam Average
\[ \tau_n = 888.0 \pm 2.1 \text{s} \]

Storage Average
\[ \tau_n = 879.6 \pm 0.8 \text{s} \]

see PDG for references
Measurement of the neutron lifetime by counting trapped protons in a cold neutron beam

J. S. Nico, M. S. Dewey, and D. M. Gilliam
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Tulane University, New Orleans, Louisiana 70118, USA

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

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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 $\tau_n$ 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 $\tau_n = (886.3 \pm 1.2_{\text{stat}} \pm 2.3_{\text{sys}})$ 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 $^6\text{Li}(n,n')\pi^0$ 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 $\tau_n$ in a Beam

Cold Neutrons

Velocity profile: $\phi(v)$

Decay Volume

Thin 1/$v$ neutron counter

Proton Counter

Velocity profile: $\phi(v)$

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

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

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

FM absorbs neutrons as 1/$v$
So it’s calibrated at thermal velocity
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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.

Galileo and Extrapolating Away End Effects

$$V_{\text{light}} = \frac{d_{\text{light}}}{t_{\text{light}}}$$

but...

$$t_{\text{measured}} = (t_{\text{light}} + t_{\text{open}})$$

$$d(t_{\text{meas}}) = V_{\text{light}} \times (t_{\text{light}} + t_{\text{open}})$$
Sussex-ILL-NIST Beam Experiments

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

where:

\( R_p \): decay proton rate
\( R_n \): neutron rate
\( \varepsilon_p \): proton detection efficiency
\( \varepsilon_{th} \): thermal neutron detection efficiency
\( nl \): number of electrodes times electrode and spacer length
\( L_{end} \): the trap end lengths

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.

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 Beam Lifetime 2

- Neutron upstream
- Proton detector electronics and control arm (floated at -30kV)
- Magnet trap HV connections
- Fluence Monitor

Downstream of neutron beamline

Diagram:
- Neutron beam
- Magnet
- Trap
- Proton detector

Legend:
- Fluence Monitor
## NIST 2005 Result Error Budget

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

\[ n^+{}^6\text{Li} \rightarrow \alpha(2.07\text{MeV}) + {}^3\text{H}(2.72\text{MeV}) \]

\approx 1\% of the beam is absorbed in this reaction.

Four PIPS detectors detect alpha and triton rates. The efficiency of the detector must be measured or calculated.
**CALCULATED** from *measured* detector solid angle ($\Omega_{FM}$), *measured* foil areal density ($\rho$), and *evaluated* thermal neutron cross section ($\sigma_0$) of target material:

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

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

**OR**

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

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

-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)


Fluence monitor advances enabled the 2013 improved determination: $887.7 \pm 2.3 \text{ s}$
Sussex-ILL-NIST Measurement Campaign

2003 Experimental Run
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
UCN$\tau$ 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

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<td>0.8</td>
</tr>
<tr>
<td>Neutron beam profile and detector solid angle</td>
<td>$+1.3$</td>
<td>0.1</td>
</tr>
<tr>
<td>Neutron beam profile and $^6\text{Li}$ deposit shape</td>
<td>$-1.7$</td>
<td>0.1</td>
</tr>
<tr>
<td>Neutron beam halo</td>
<td>$-1.0$</td>
<td>1.0</td>
</tr>
<tr>
<td>Absorption of neutrons by Si substrate</td>
<td>$+1.2$</td>
<td>0.1</td>
</tr>
<tr>
<td>Scattering of neutrons by Si substrate</td>
<td>$-0.2$</td>
<td>0.5</td>
</tr>
<tr>
<td>Trap nonlinearity</td>
<td>$-5.3$</td>
<td>0.8</td>
</tr>
<tr>
<td>Proton backscatter calculation</td>
<td></td>
<td>0.4</td>
</tr>
<tr>
<td>Neutron counting dead time</td>
<td>$+0.1$</td>
<td>0.1</td>
</tr>
<tr>
<td>Proton counting statistics</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Neutron counting statistics</td>
<td>0.1</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>$-0.4$</td>
<td>3.4</td>
</tr>
</tbody>
</table>

## Proton Counting Corrections

<table>
<thead>
<tr>
<th>Source of correction</th>
<th>Correction (s)</th>
<th>Uncertainty (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^6$LiF deposit areal density</td>
<td>2.2</td>
<td></td>
</tr>
<tr>
<td>$^6$Li cross section</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Neutron detector solid angle</td>
<td>1.0</td>
<td></td>
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</tr>
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<td><strong>Total</strong></td>
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<td><strong>3.4</strong></td>
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Dysprosium imaging techniques were used to measure the neutron beam profile. $10^{-3}$ beam fraction were found outside the active detector radius.

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.

"Blooming" Images were taken using Cd masks to obtain sharp edges.

Precision machined Cadmium mask for Dy foil in collimator mount.
# Proton Counting Corrections

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</tr>
<tr>
<td>$^6$Li cross section</td>
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</table>

Trap Non-Linearity

\[
\frac{R_p}{R_n} = \tau^{-1} \left( \frac{\mathcal{E}_p}{\mathcal{E}_{th} V_{th}} \right) (n l + L_{\text{end}})
\]

\(L_{\text{end}}\) 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: \(\sigma_{\text{trap}} = 0.8s\)

Running with smaller trap lengths will eliminate the largest contribution to this systematic uncertainty, giving: \(\sigma_{\text{trap}} \approx 0.2s\)
## Projected BL2 Error Budget

<table>
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<tr>
<th>Source of correction</th>
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</tr>
</thead>
<tbody>
<tr>
<td>$^6$LiF deposit areal density</td>
<td>Most significant improvement</td>
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</tr>
<tr>
<td>$^6$Li cross section</td>
<td>1.2</td>
<td></td>
</tr>
<tr>
<td>Neutron detector solid angle</td>
<td>1.0</td>
<td></td>
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<tr>
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<td>0.1</td>
</tr>
<tr>
<td>Proton counting statistics</td>
<td></td>
<td>0.6s</td>
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<td>Neutron counting statistics</td>
<td></td>
<td>0.6</td>
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<td>Total</td>
<td>−0.4</td>
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</table>

$\delta \tau_n \approx 1.0s$
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 2\textsuperscript{nd} trap
• Exploring new detector technology (in communication with JPL and Caltech)

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

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.

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

![Graph of conduction band edge vs depth from surface](image1)

**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 $3 \times 10^{20}$ 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.

![Diagram of delta-doped CCD structure](image2)

**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).]

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

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/](http://esp.ess.ucla.edu/)

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
   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

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

- \(R_p\): decay proton rate
- \(R_n\): neutron rate
- \(\varepsilon_p\): proton detection efficiency
- \(\varepsilon_{th}\): thermal neutron detection efficiency
- \(nl\): number of electrodes times electrode and spacer length
- \(L_{end}\): the trap end lengths

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.

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
Calibrate the $\alpha$-source

$^{239}$Pu $\alpha$-source measured in stack of known solid angle

- source activity determined from measured $\alpha$-rate and known stack $\Omega$

PIPS detector

Diamond-turned copper aperture

Scatter-suppressing precision spacer

Pu source spot
2 Calibrate the $\alpha$-detector with $\alpha$-source

Source loaded into AG vacuum chamber and counted
- known source activity gives detector $\Omega$
3 Calibrate the $\gamma$-detectors

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

- $n + ^{10}\text{B} \rightarrow ^{7}\text{Li} + \alpha + \gamma$ ($b_{\gamma} = 93.70(1)\%$)
- 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...

\[ \epsilon_0 = \frac{r_{\alpha,t} \lambda_0}{R_n \lambda_{mono}} = \frac{r_{\alpha,t}}{r_\gamma(\text{thick})} \cdot \frac{r_\gamma(\text{thin})}{r_\alpha(\text{thin})} \cdot \frac{r_\alpha(\text{Pu})}{R_\alpha(\text{Pu})} \cdot \frac{\lambda_0}{\lambda_{mono}} \]

**Thick target**
- \(1/\text{“\(\gamma/\text{FM}\”}\)}

**Thin target**
- \(1/\text{“\(\alpha/\gamma\”}\)}

**\(^{239}\text{Pu counting}**
- \(\text{“\(R_{\text{Pu}}\)}\)

**Wavelength**
- \(\text{“\(R_\lambda\)}\)

In practice, \(\lambda\) and \(\text{Pu}\) are measured infrequently.

Every efficiency measurement has its own measurements of \(\gamma/\text{FM}\) and \(\alpha/\gamma\).