A New (old) Approach

- 3-D Confinement
- Superthermal production
- In-situ detection
- Experimentally determine/limit systematics
- Uniform population of phase space
Ioffe Superconducting Magnetic Trap

3.1 T trap depth
V ~ 9 L

Radial Confinment

Axial Confinment

~2 m
Operation of the Experiment
Operation of the Experiment

Turn on neutron beam
Operation of the Experiment

Turn on neutron beam

Accumulate neutrons in trap
Turn off neutron beam

Neutrons remain in trap until they decay
Operation of the Experiment

Neutrons remain in trap until they decay

Detect pulse of light from each decay event

Turn off neutron beam

Neutrons remain in trap until they decay
Historical Timeline

1995
Initial Proposal

2000
First Demonstration of Magnetic Trapping

$\tau = (750 \pm 330/-200) \text{ s}

480 trapped neutrons
(no field ramping)

2004
Incorporation of New Magnet
Initial Lifetime Measurement

$\tau = (844 \pm 53/-47) \text{ s}

1,650 trapped neutrons

2009
KEK Magnet Incorporated
(fully operational Summer 2010)

$\Delta \tau = \text{few s, (statistically limited)}$

40,000 trapped neutrons
• Recoiling charged particle creates an ionization track in the helium.

• Helium ions form excited $\text{He}_2^*$ molecules (ns time scale) in both singlet and triplet states.

• $\text{He}_2^*$ singlet molecules decay, producing a large prompt ($< 20$ ns) emission of extreme ultraviolet (EUV) light.

• EUV light (80 nm) converted to blue using the organic fluor (d)TPB (tetraphenyl butadiene).
- Recoiling charged particle creates an ionization track in the helium.
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Both **active** and **passive** shielding surround dewar & cell, however backgrounds are still significant

**Sources of the background:**
- **Gammas** (Compton scattering)
- Fast / epithermal neutrons
- Cosmic rays
- Natural radioactivity
- Neutron-induced radioactivity
- Neutron-induced luminescence

**Constant**

**Time-dependent**
Trapping runs:
Quad on during entire run
\( T(t) = n(t) + b(t) \)

Background runs:
Quad off during load period
\( B(t) = b(t) \)

Signal: \( S(t) = T(t) - B(t) = n(t) \sim A \exp(-t/\tau) \)

\[
\epsilon = \frac{\sigma_T}{\tau} \approx \frac{\sigma_S}{S} = \frac{\sqrt{\sigma_T^2 + \sigma_B^2}}{S} \approx \frac{\sqrt{2b}}{n}
\]
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**Constant**

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There are neutron orbits where

\[ E_{tot} = E_{kin} + \mu \cdot B > E_{trap} \]

Briefly ramping the magnetic field down to 0.3 \( B_0 \) eliminates most neutrons on these orbits, but also reduces the number of trapped neutrons by about 50%.
Apparatus as it Looks on NG-6 at NIST
Mark III Timeline

1. Fully cold summer 2010

2. Production data from Jan. 2011 - April 2011 (2 reactor cycles of 6 weeks)
   - Split beam time ~ 50% with aCORN, so roughly 1 cycle of data.
   - roughly half is systematics checks.

3. Original plan: more data once reactor started up in April 2012.
   (experiment shutdown for NCNR upgrade/expansion)
   - experiment damaged during warm-up.... decision was made to hold off until analysis complete

4. Analysis in progress.
A typical event

- 2 ns / index
- 12 bit GaGe cards

Single photo-electron
A good run shown

Approximately 3% gain drift

- 100 Hz LED pulser (main detectors)
Deadtime Correction

Average per-bin live-time for 20 run-pairs

~ 500 Hz raw rate $\rightarrow$ 15% average dead time

Graph showing live time fraction over bin number with two lines:
- Live Time Nontrapping
- Live Time Trapping
Initial data rate > 300 Hz - trending to 130 Hz
- substantial time dependence
Pulse shape discrimination:
- most effective seems to be 'kurtosis' (4th moment of histogrammed trace, NOT time ordered)
Limitations of DAQ (that impact analysis)

- Large and/or fast pulses
  - Max out electronics or digitizer, alter change pulse shape

- NIM linear fan maxes out

- Digitizer maxes out (changes kurtosis)
Cuts Optimization (lower threshold)

Monte Carlo estimate of fractional uncertainty
Scan over a range of lower PE # cuts.

15% improvement in sensitivity
Summary of Cuts

Counts: Asymmetry Plot

upper PE cut: 180

lower PE cut: 18

kurtosis < 15

20 run-pairs
## Cuts Summary

<table>
<thead>
<tr>
<th>Cut Sequence</th>
<th>Cut Type</th>
<th>Value of Cut</th>
<th>Percentage of Events Removed Relative to Remaining Events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Trapping</td>
</tr>
<tr>
<td>1</td>
<td>Pulser</td>
<td>20000</td>
<td>25.96 ± 1.04%</td>
</tr>
<tr>
<td>2</td>
<td>Muon</td>
<td>dynamic</td>
<td>6.52 ± 0.32%</td>
</tr>
<tr>
<td>3</td>
<td>Low PE</td>
<td>12</td>
<td>64.03 ± 1.39%</td>
</tr>
<tr>
<td>4</td>
<td>Kurtosis</td>
<td>15</td>
<td>20.11 ± 0.32%</td>
</tr>
<tr>
<td>5</td>
<td>High PE</td>
<td>200</td>
<td>13.37 ± 0.24%</td>
</tr>
<tr>
<td>6</td>
<td>Height</td>
<td>10%</td>
<td>4.28 ± 0.14</td>
</tr>
</tbody>
</table>
Example Trapping Data (70% – 50% – 70% flushing)

20 data pairs
Example Trapping Data (70% – 50% – 70% flushing)

Lifetime: $682 \pm 32$ s

chisq = 192.696; pnts = 169
P-value: 0.10

$y_0 = 0.0052743 \pm 0.108$
$A = 9.1812 \pm 0.163$
$\tau = 682.5 \pm 31.6$

Approx: 9000 trapped neutrons/fill
Warm Data, $T \sim 910$ mK

- Trapping - Non trapping data (all cuts).
  - long time constant term evident: $640 \pm 90$ s (cooper, Ti?...)
Warm Data, $T \sim 910$ mK

Data taken at $\sim 910$ mK

- Expected lifetime from thermal upscatter $\sim 134$ s
- Fit to data: $186 \pm 42$ s (offset consistent with zero)
Warm Data, T \sim 850 \text{ mK}

- Data taken at \sim 850 \text{ mK}
- Expected lifetime from thermal upscatter \sim 190 \text{ s}
- Fit to data: 186 \pm 42 \text{ s}
chisq = 150.895; npnts = 173

\[
y_0 = 75.414 \pm 21.4
\]
\[
A_1 = 160.23 \pm 2.88
\]
\[
\tau_1 = 189.69 \pm 2.03 \text{ (Aluminum)}
\]
\[
A_2 = 10.405 \pm 7.4
\]
\[
\tau_2 = 843.87 \pm 0.0743
\]

fit: 190 ± 2 s

Al: 194 ± .1 s
We are not sensitive to:
- wall interactions as a direct loss mechanism
- Marginally stable orbits (no trap dump)
- Trap filling procedures (full population of phase space)
- Spin flip (at least minimized: no zero field regions)

Known systematics:

➊ Majorana (Spin-Flip) Transitions
   - Bias Field (i.e. no zero-field regions), < 0.1 s

➋ Systematic effects such as detector gain shifts, imperfect background subtraction, < 1 s

➌ UCN depolarization by charged particles estimated to be less than 0.1 s

➍ Fitting bias due to non-linear fit with poor S/N < 1s

➎ Thermal (phonon) Upscattering
   - $T^7$ temperature dependence, at $T = 300$ mK, < 0.1 s
Dominant systematics:

1. **Above Threshold Neutrons**
   - In current a 1.1 T trap cannot be totally eliminated, introduces up to 40 s shift
   - For a 3.1 T trap, numerical simulation shows that above threshold neutrons can be completely eliminated under certain conditions.

2. **Absorption by $^3$He**
   - Isotopically pure $^4$He produced using heat flush technique
   - Theoretically limit $< 10^{-15}$, best indirect measurement limit $< 10^{-13}$
   - Direct measurement with accelerator mass spectroscopy shows possible high concentration of $^3$He ($4 \times 10^{-12}$), (80 second shifts in lifetime)?
There are neutron orbits where

\[ E_{tot} = E_{kin} + \mu \cdot \vec{B} > E_{trap} \]

Briefly ramping the magnetic field down to 0.3 \( B_0 \) eliminates most neutrons on these orbits, but also reduces the number of trapped neutrons by about 75%.

\[ r_0 B_0^{1/3} = \text{const} \]
## Marginally Trapped Neutrons

<table>
<thead>
<tr>
<th>Ramp config.</th>
<th>Monte Carlo</th>
<th>Runs</th>
<th>Projected Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 static</td>
<td></td>
<td>17</td>
<td>46 s</td>
</tr>
<tr>
<td>0.6 static</td>
<td>49 ± 2</td>
<td>107</td>
<td>18 s</td>
</tr>
<tr>
<td>0.6-0.3-0.6</td>
<td></td>
<td>92</td>
<td>20 s</td>
</tr>
<tr>
<td>0.7-0.5-0.7</td>
<td>-17 ± 1 s</td>
<td>71</td>
<td>22 s</td>
</tr>
<tr>
<td>0.7-0.35-0.7</td>
<td>-2.3 ± 0.5 s</td>
<td>167</td>
<td>15 s</td>
</tr>
</tbody>
</table>

Simulation using 686 s as trap lifetime
Capture on $^3\text{He}$

$$\Gamma_{cap} = \int_n nR_{34}\sigma v\phi(v)dv = nR_{34}\sigma_{th}v_{th}$$

$^3\text{He}$ thermal capture cross-section: $\sim 5300$ b

$$\frac{\Gamma_{cap}}{\Gamma_\beta} = 2.3 \times 10^{10} R_{34}$$

For 0.1 s: $5 \times 10^{-16}$

Isotopically-Pure produced and purity tested using the heat flush technique.
ATLAS

Accelerator Mass Spectroscopy

RF Source

Split-Pole Spectrometer
Spectrometer

Accelerator Mass Spectroscopy

Enge Split-Pole Spectrograph

RF Source

POSSP_E Sum 2,840 Peak 104 Scale Log

Scattering chamber

PPAC + ionisation chamber

/Nitrogen (10 torr)

(39A)

(39K)

(39F)

(39O)

(39P)

(39R)

(39T)

(39U)

(39V)

(39W)

(39X)

(39Y)

(39Z)
Challenges

1. Natural Helium $R_{34} \sim 2 \times 10^{-7}$
   - HIGH backgrounds

2. Absolute Measurement
   - Source Stability
   - Accelerator Stability

3. Very weak beam

Backgrounds - new RF source design
Stability - reference beam
Cross check w/ reference samples
Helium Results

Oregon: traditional mass spec.

- Natural (same sample)
- "10e-9" sample
- "10e-12" sample

3He/4He vs. log scale (10^-7 to 10^-12)
Helium Results

- Oregon Measurements
- Calculated
- ATLAS

Natural (same sample)

"10e-9" sample

"10e-12" sample
Helium Results

1.3 x 10^{-11}

Calculated reference

Oregon Measurements
Argonne (unscaled)
Argonne (scaled)
F (Calculated reference)

3He/4He

"10e-9" sample
"10e-12" sample
Ultrapure (apparatus)
Ultrapure (unused)
3He

Ratio of $^3$He to $^4$He

Lifetime Correction (s)

- Apparatus
- $10^{-9}$ Standard
- $5 \times 10^{-12}$
- 2nd Ultrapure
Conclusions

Significant progress with background reduction

Data quality looks quite good

Expect to be able to test marginal trapping models

Significant systematic effect remains
- Completing helium work highest priority