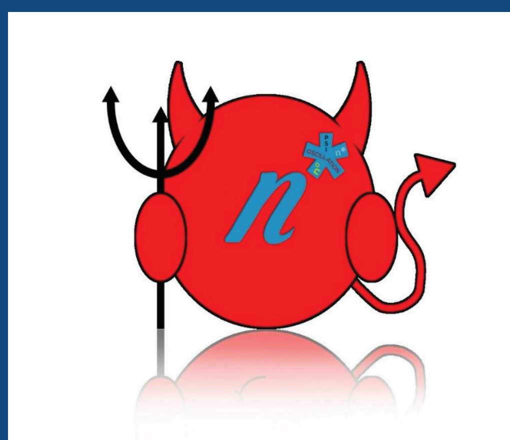
Search for Mirror Neutron Oscillations



Prajwal T. Mohan Murthy
MIT
For NStar Collaboration

Overview

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Bit of History

1

2

with B′ = 0

with Finite B′

3

4

NStar

Summary

5

① Motivation

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Strong CP Problem

?

① Motivation

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Strong CP Problem

Absence of CPV in Strong Sector

① Motivation

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Traditional Answer:
New CP Violating Term – θ
to cancel CPV in strong sector

Parity violation in weak sector? ✓

Strong CP Problem

$$L_\theta = \frac{\alpha_s \theta}{8\pi} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

$d_n < 2.9 \times 10^{-26}$ e.cm (90%C.L.)
$\theta < 10^{-10}$

?

Solution in strong sector:
Promote the "Theta" term to a QCD field. This field undergoes symmetry breaking to give rise to QCD Axions.

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But Wait…

① Motivation

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We can continue to live in the world where the QCD axion exists

But what if I told there need not be any global PV?

Morpheus: "This is your last chance. After this, there is no turning back. You take the blue pill—the story ends... You take the red pill—you stay in Wonderland, and I show you how deep the rabbit hole goes. Remember: all I'm offering is the truth. Nothing more."

① Motivation

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Enter Mirror Realm…

① Motivation

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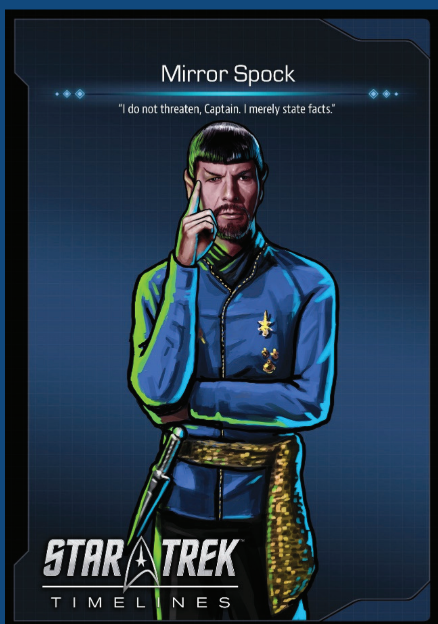
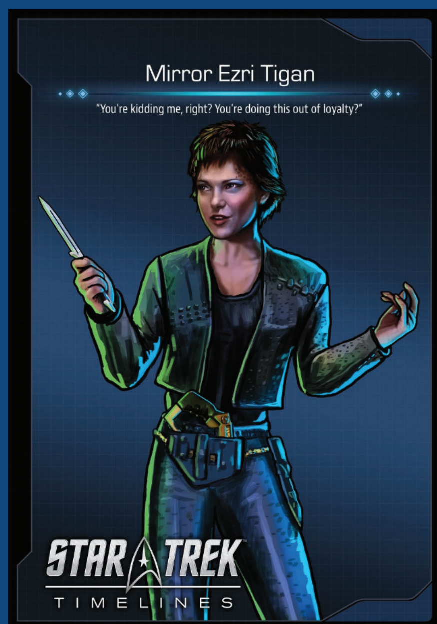
No! No! Not This...





PS: But kudos if you did...

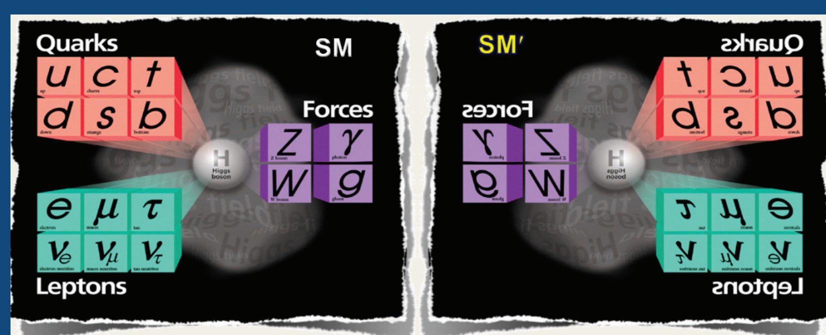
① Motivation

Non Traditional Answer:
Introduce a mirror realm

No PV even in weak sector

Mirror Universe

$$\mathcal{L}_{total} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{Mixing}$$



① Motivation

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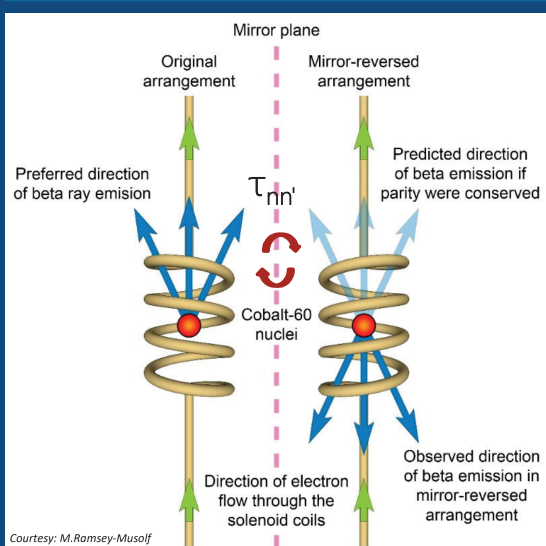
<u>"Non" Traditional Answer?</u>:
Introduce a mirror realm

No PV even in weak sector



$$\mathcal{L}_{total} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{Mixing}$$

Don't talk to each other

① Motivation

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"Non" Traditional Answer?:
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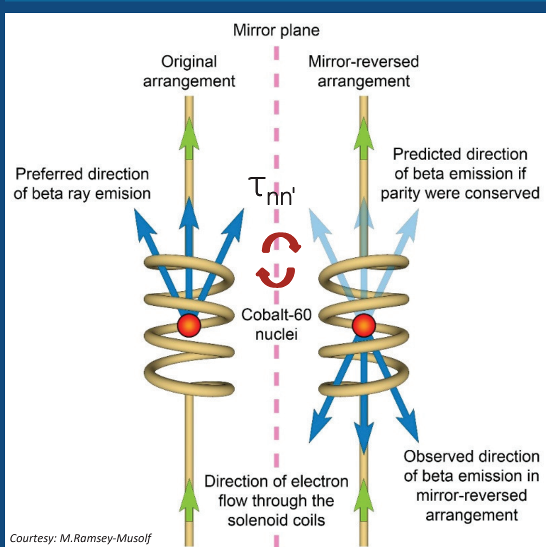


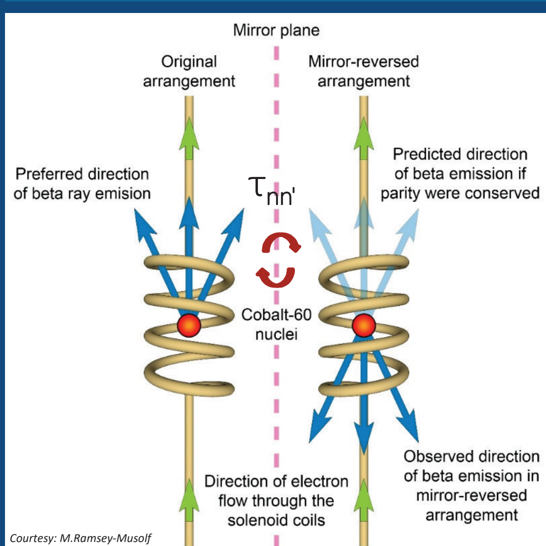
$$\mathcal{L}_{total} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{Mixing}$$

Except via the mixing term

① Motivation

"Non" Traditional Answer?:
Introduce a mirror realm

No PV even in weak sector



$$\mathcal{L}_{total} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{Mixing}$$

Except via the mixing term

The idea is actually not a new idea!
Already noted in:
Lee & Yang's PRL 104, 254 (1956):

For Mirror Matter Review:
L. B. Okun, Phys. Usp. **50** 380-389 (2007)

① Motivation

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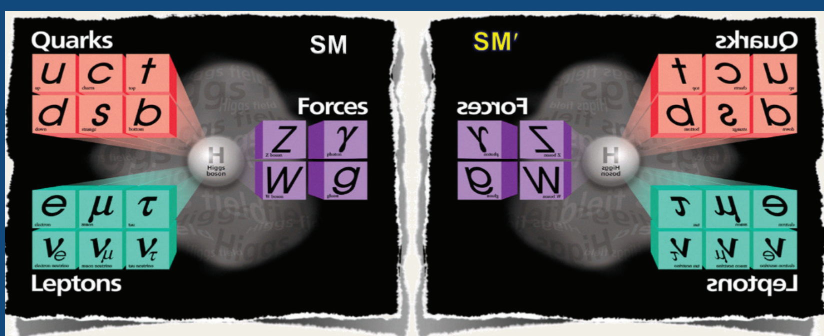


- B, L: Not conserved properties: Neutral baryon oscillation possible.
- Tune the mixing coupling and mirror matter could be DM.

These oscillations may be coupled to magnetic field: *Z. Berezhiani, Eur. Phys. J. C* **64**, *421-431 (2009).*

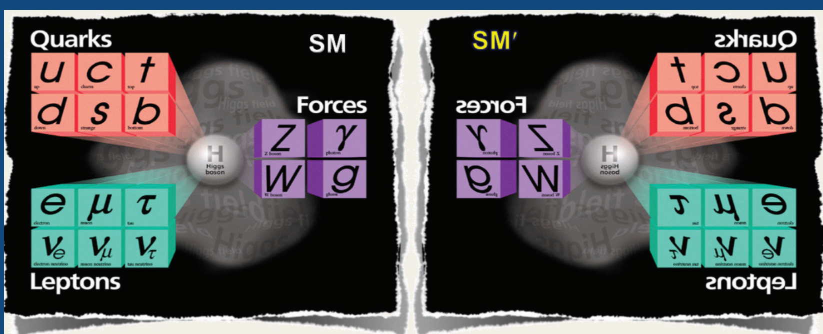
So which abundant long lived neutral particle could we test this on?

n^0(880s), ν, Δ^0 (0.26ns), Ξ^0 (0.29ns), Λ^0 (1.4ps), Ω^0 (?) ~~k^0 (512μs), ρ^0 (450ys),π^0 (840fs)~~ (not by spin coupling)

Neutrons are probably the best to start with for spin coupled searches + to probe B-L violation…

$$\mathcal{H} = \begin{bmatrix} \mu(\vec{\sigma}.\vec{B}) & 1/\tau \\ 1/\tau & \mu(\vec{\sigma}.\overrightarrow{B'}) \end{bmatrix}$$

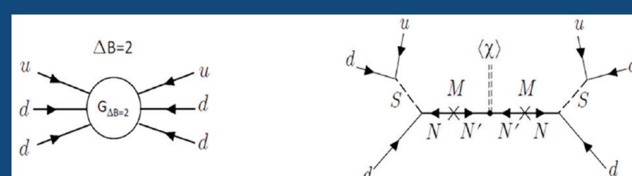
① Motivation



- B′=0, possibly.
- B′~10μT (fields in HD molecular clouds) near Earth may be well motivated: Z. Berezhiani, A.D. Dolgov, Astropart. Phys. 21, 59 (2004).
- UCN losses in Earth's magnetic field sets upper limit on B′, B′<300 μT (could be improved by a factor of 2 with strict analysis): A. Serebrov et al., Phys. Lett. A 335, 327 (2005).

What does that mean for Neutron Sector?

- Fast oscillation between mirror neutrons and neutrons: Z. Berezhiani and L. Bento, Phys. Rev. Lett. 96, 081801 (2006).
- Time scales of {oscillation into mirror world (~1s) << anti-neutron oscillation (which may be 2nd order)}: A. Addazi, Z. Berezhiani & Y. Kamyshkov, Eur. Phys. J. C (2017) 77: 301.



① Motivation

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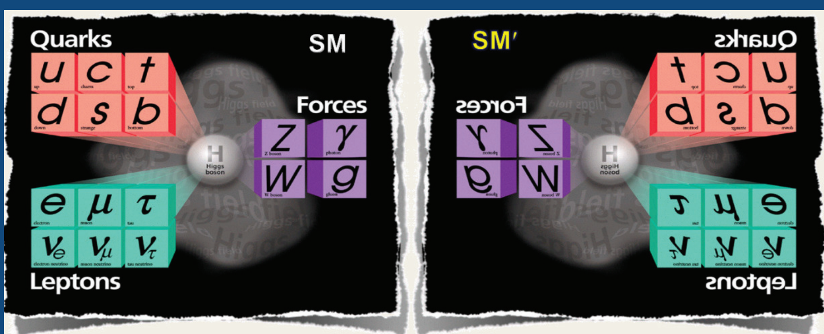

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$$\mathcal{H} = \begin{bmatrix} \mu(\vec{\sigma}.\vec{B}) & 1/\tau \\ 1/\tau & \mu(\vec{\sigma}.\overrightarrow{B'}) \end{bmatrix}$$

$$P_{n\rightarrow n'}(t) = \frac{Sin^2\left(\frac{\mu B-\mu B\prime}{2}\right)t}{2\tau^2\left(\frac{\mu B-\mu B\prime}{2}\right)^2}[1 + Cos(\beta)] + \frac{Sin^2\left(\frac{\mu B+\mu B\prime}{2}\right)t}{2\tau^2\left(\frac{\mu B+\mu B\prime}{2}\right)^2}[1 - Cos(\beta)]$$

Where β is the angle between **B** and **B’**

① General Techniques

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UCN Storage Experiment:

Store UCNs, apply 0 and >0 magnetic fields, check if some neutrons vanished (into mirror realm)?

Regeneration Experiment ("Particle Through a Wall" kind of experiment):

Shoot cold neutrons through a magnetic field onto a wall, check if neutrons can be detected on the other side of the wall under magnetic field?

① Prior Experiments

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$B'=0$ | $B'\neq0$

UCN Storage Experiments

$B'=0$:

- G. Ban et al., Phys. Rev. Lett. **99**, 161603 (2007): $\tau_{nn'}>103$s (95 % C.L.), $B'=0$ [PSI-ILL]
- A. P. Serebrov et al. Phys. Lett. B **663**, 3, 181-185 (2008): $\tau_{nn'}>414$s (90 % C.L.), $B'=0$ [PNPI-ILL]

$B'\neq0$:

- I. Altarev et al., Phys. Rev. D **80**, 032003 (2009): $\tau_{nn'}>12$s (95 % C.L.), $B'\neq0$ [PSI-ILL]

Regeneration Experiments

$B'=0$:

- U. Schmidt, Proceedings of 2007 BLNV Workshop: $\tau_{nn'}>2.7$s (90 % C.L.), $B'=0$ [FRM-II]

$B'\neq0$:

- L. Broussard et. al. (planning phase), Proceedings of 2017 DPF Meeting: $\tau_{nn'}>15$s (90 % C.L.), $B'\neq0$ [ORNL(HFIR)]

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2 0 B′

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Looked for variations in decay time constant after UCN storage time-t_s, with and without magnetic field.

$$p_{nn^*}(t) = \frac{Sin^2[\frac{t}{\tau_{nn^*}}\sqrt{(1+(\omega\tau_{nn^*})^2}]}{(1+(\omega\tau_{nn^*})^2)}$$

The experiments assumed a 0-mirror magnetic field.

oILL-$t_f \sim \frac{4(\mathrm{v}=.021m^3)}{(\mathrm{a}=.54m^2)(\mathrm{V}=3\mathrm{m}s^{-1})} = .052\ s$

At finite B_0 magnetic fields ($\omega_{\uparrow\downarrow} t_f > 1 \rightarrow B_0 > 420nT$): $R_{\uparrow\downarrow} = \frac{1}{\overline{t_f}}\frac{1}{2(\omega_{\uparrow\downarrow}\tau_{nn^*})^2}$

At 'zero' B_0 magnetic fields ($\omega_0 t_f < 1 \rightarrow B_0 < 420nT$): $R_0 = \frac{1}{\overline{t_f}}\frac{\overline{t_f^2}}{\tau_{nn^*}^2}$

Refer to A. Knecht's thesis for a full oscillation treatment P. 113-124.

② $0\ B'$

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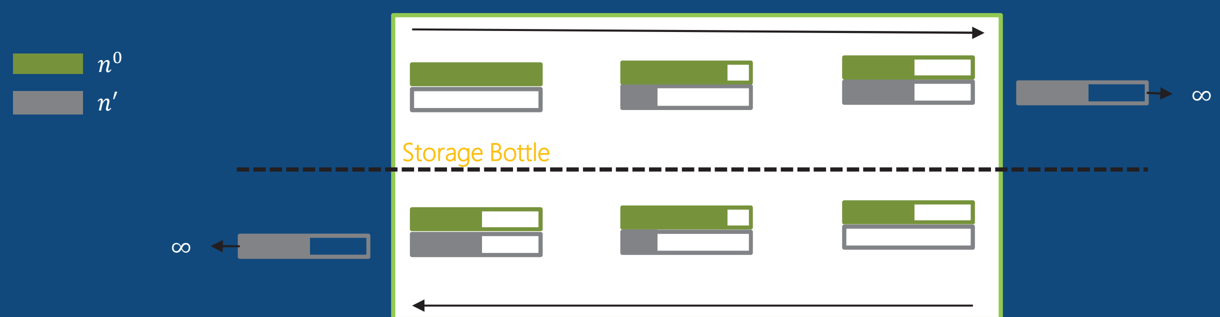
The experiments assumed a 0-mirror magnetic field.

oILL-$t_f \sim \frac{4(v=.021m^3)}{(a=.54m^2)(V=3ms^{-1})} = .052$ s

t_f is the time scale of oscillation because:



1. **We start with purely neutrons.**
2. **As the particle moves inside the chamber, it acquires some probability that it is n'.**
3. **But when the particle reaches the wall, the n' part of the wave-function cannot be trapped by the walls of the bottle so it escapes out. #1 starts again.**

2 0 B′

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At 'zero' B_0 magnetic fields ($\omega_0 t_f < 1 \rightarrow B_0 < 420nT$): $R_0 = \frac{1}{t_f}\frac{\overline{t_f^2}}{\tau_{nn^*}^2}$

If neutron count $\mathrm{N}(t_s) = e^{-[(\sum \lambda_i + R)t_s]}$

where 'R' is the possible contribution from mirror neutron oscillations

$$N_{0/\uparrow\downarrow} = \frac{N_0(t_s)}{N_{\uparrow\downarrow}(t_s)} = e^{-[(R_{\uparrow\downarrow} - R_0)t_s]}$$

2 0 B′

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$$N_{0/\uparrow\downarrow} = \frac{N_0(t_s)}{N_{\uparrow\downarrow}(t_s)} = e^{-[(R_{\uparrow\downarrow} - R_0)t_s]}$$

In case of a null result for $N_{0/\uparrow\downarrow} - 1$:

$$N_{0/\uparrow\downarrow} > 1 - \frac{t_f^2}{\tau_{nn^*}^2}\frac{t_s}{t_f} \rightarrow \tau_{nn^*} > \sqrt{\frac{t_s t_f}{1 - N_{0/\uparrow\downarrow}}}$$

Notice: $\tau_{nn^*} \propto \sqrt[4]{N}$ $\tau_{nn^*} \propto \sqrt{t_s t_f}$

② 0 B′: What can be accessed with oILL?

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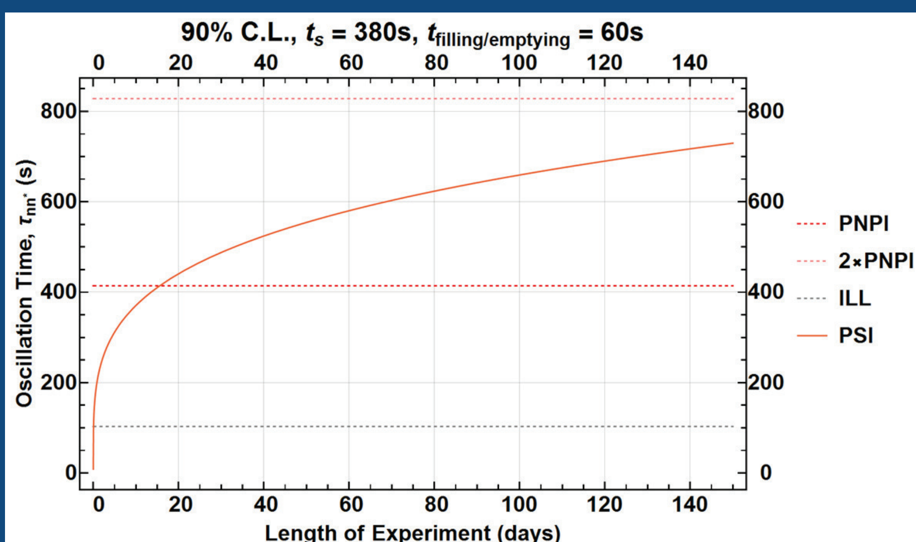
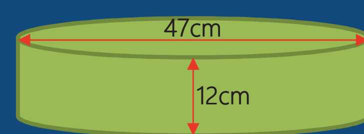
In current oILL (PSI-ILL) chamber:

$_{ILL}\tau_{nn^*} > 109\ s$ (90% C.L.)

$_{PNPI}\tau_{nn^*} > 414\ s$ (90% C.L.)

VALUE (s)	CL%	DOCUMENT ID		TECN	COMMENT
>414	90	SEREBROV	08	CNTR	UCN, B field on & off
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 12	95	[29] ALTAREV	09A	CNTR	UCN, scan $0 \le B \le 12.5\ \mu$T
>103	95	BAN	07	CNTR	UCN, B field on & off





4V/A → t_f (s)

oILL: *This = .053 : .053

0	0	↑	↑	↓	↓	0	0	B_0
16	16	16	16	16	16	16	16	#

3 Finite B′

Looked for variations in decay time constant after UCN storage time-t_s, with and without magnetic field by scanning B_0.

$$\mathcal{H} = \begin{pmatrix} 2\omega\sigma & \varepsilon \\ \varepsilon & 2\omega'\sigma \end{pmatrix} = \begin{pmatrix} (\langle 0,0,b\rangle - \langle a_x, 0, a_z\rangle)\sigma & \varepsilon \\ \varepsilon & (\langle 0,0,b\rangle + \langle a_x, 0, a_z\rangle)\sigma \end{pmatrix}$$

Refer to EPJ C 64: 421-431 (2009) by Z. Bereziani for a full oscillation treatment.

3 Finite B′

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$$p_B(t) = Sin^2(2\theta)[Cos^2(\phi - \phi')Sin^2(\Omega^- t) + Sin^2(\phi - \phi')Sin^2(\Omega^+ t)]$$

where $\Omega^\pm = \omega \pm \omega'$, $Tan(2\theta) = \frac{\varepsilon}{a_z}$ and $Tan\left(2\phi^{(\prime)}\right) = \frac{a_x}{b -^{(+)} \sqrt{a_z^2 + \varepsilon^2}}$

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At ‘zero’ B_0 magnetic fields ($\omega_0 t_f < 1 \rightarrow B_0 < 420nT$): $p_0 = \frac{1}{2}\frac{\varepsilon^2}{\omega'^2}$

At finite B_0 magnetic fields ($\omega_{\uparrow\downarrow} t_f > 1 \rightarrow B_0 > 420nT$): $p_B(t) = p_0 \frac{1+\eta^2+2\eta Cos(\beta)}{(1-\eta^2)^2}$

where $\eta = {}^{\omega'}/_{\omega} = {}^{B'}/_{B_0}$ and β is the angle between B' and $B0$

Refer to EPJ C 64: 421-431 (2009) by Z. Bereziani for a full oscillation treatment.

3 Finite B′: Previous Experiments

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B′=0 | B′≠0

UCN Storage Experi…

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- A. P. Serebrov et al. Phys. Lett. B **663**, … 185 (2008): $\tau_{nn'}$>414s (90 % C.L.) … ILL]

- … Phys. Rev. D **80**, 032003 … $\tau_{nn'}$>12s (95 % C.L.), B′≠0 [PSI-ILL]

Since $\tau_{nn'}$ is excluded up to 414s, why do we want to do more of this?

…ation Experiments

- U. Schmidt, P… of 2007 BLNV Workshop: $\tau_{nn'}$… (90 % C.L.), B′=0 [FRM-II]

- L. Broussard et. al. (planning phase), Proceedings of 2017 DPF Meeting: $\tau_{nn'}$>15s (90 % C.L.), B′≠0 [ORNL(HFIR)]

- *Z. Bereziani, EPJ C 64: 421-431 (2009):* Reanalysis of PRL 99 161603; PRD 80, 032003; and PLB 663, 3, 181-195: shows that there are signals of oscillations (B ≠0) in these data sets!
- It makes sense to extend the sensitivity of $\tau_{nn'}$ to neutron half life (890s). If $\tau_{nn'}$ is less than neutron half-life, then these dedicated mirror neutron search experiments would be vital to test such theories.

3 Finite B′: Reanalysis of old experiments

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Looked for variations in decay time constant after UCN storage time-t_s, with and without magnetic field by scanning B_0.

At 'zero' B_0 magnetic fields ($\omega_0 t_f < 1 \rightarrow B_0 < 420nT$): $p_0 = \frac{1}{2}\frac{\varepsilon^2}{\omega'^2}$

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where $\eta = {\omega'}/{\omega} = {B'}/{B_0}$ and β is the angle between B' and B_0

t_s	73 s	73 s †	123 s	198 s
$N_{B\uparrow}(t_s)$	44197 ± 53	44443 ± 53	28671 ± 30	17047 ± 31
$N_{B\downarrow}(t_s)$	44128 ± 53	44316 ± 46	28596 ± 30	16974 ± 31
$N_0(t_s)$	44317 ± 40	44363 ± 53	28635 ± 21	17015 ± 22
$E(t_s) \times 10^3$	3.50 ± 1.24	-0.37 ± 1.43	0.05 ± 1.04	0.27 ± 1.83
$A(t_s) \times 10^3$	0.78 ± 0.85	1.43 ± 0.79	1.31 ± 0.74	2.15 ± 1.28

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$$A(t_s) = \frac{N_B(t_s) - N_{-B}(t_s)}{N_B(t_s) + N_{-B}(t_s)} = \frac{e^{-n_s p_B} - e^{-n_s p_{-B}}}{e^{-n_s p_B} + e^{-n_s p_{-B}}} \approx -n_s D_B Cos(\beta)$$

$$E(t_s) = 1 - \frac{N_0(t_s)}{N_B(t_s)} = \frac{2e^{-n_s p_0}}{e^{-n_s p_B} + e^{-n_s p_{-B}}} \approx -n_s \Delta_B$$

where $n_s = {}^{t_s}/_{t_f}$; $p_B - p_{-B} = 2D_B Cos(\beta)$ and $2\Delta_B = (p_B + p_{-B}) - 2p_0$

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$p_B - p_{-B} = 2D_B Cos(\beta)$ and $2\Delta_B = (p_B + p_{-B}) - 2p_0$

PNPI

$$D_{B=20\mu T} Cos(\beta) = (9.5 \pm 3.0) \times 10^{-7}$$
$$\Delta_{B=20\mu T} = (3.5 \pm 2.5) \times 10^{-7}$$

oILL (Knecht)

$$D_{B=6\mu T} Cos(\beta) = (6.2 \pm 2.0) \times 10^{-7}$$
$$\Delta_{B=6\mu T} = (2.9 \pm 4.4) \times 10^{-7}$$

③ Finite B′: Current Status

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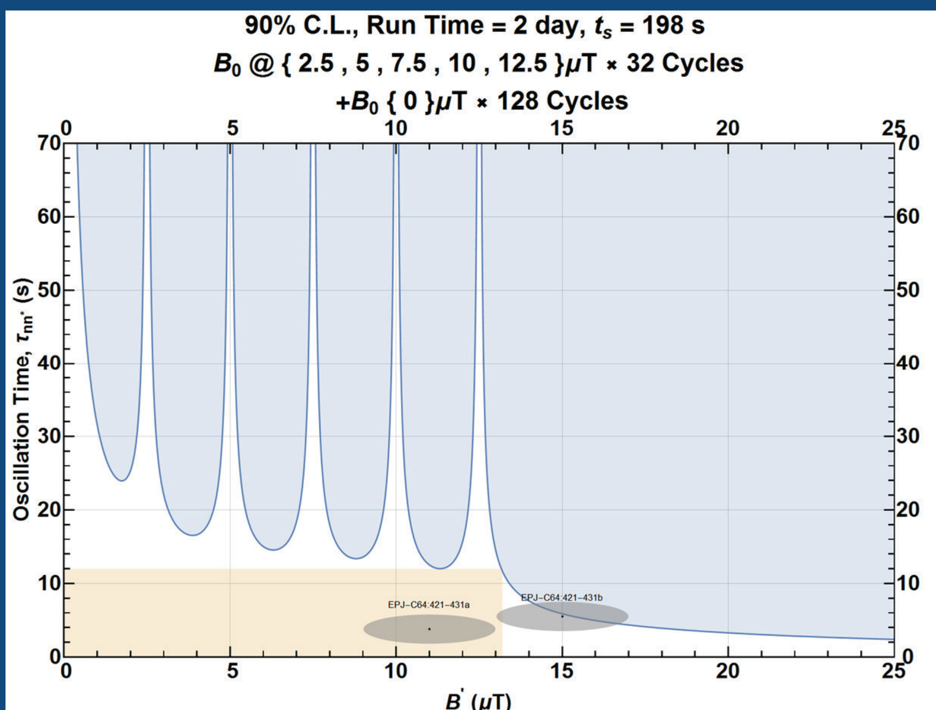


$$t_s^* = \{50, 100, 175\} s$$

$$t_s = \{73, 123, 198\} s$$

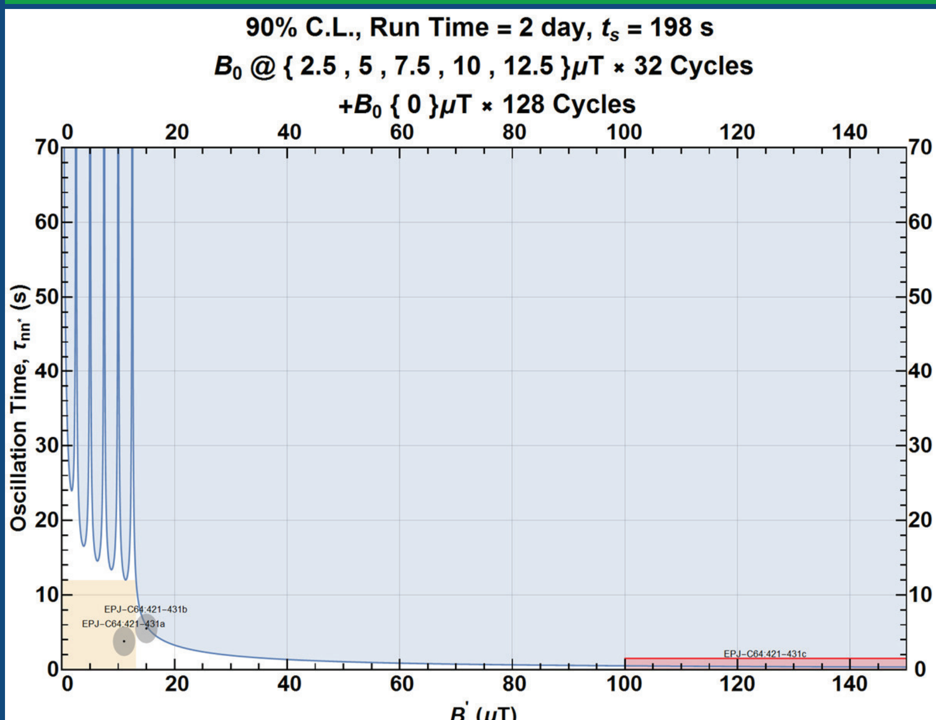
$$B_0 = \{0, 2.5, 5, 7.5, 10, 12.5\} \mu T$$

0	0	↑	↑	↓	↓	0	0	B_0
16	16	16	16	16	16	16	16	#

VALUE (s)	CL%	DOCUMENT ID		TECN	COMMENT
>414	90	SEREBROV	08	CNTR	UCN, B field on & off
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 12	95	[29] ALTAREV	09A	CNTR	UCN, scan $0 \leq B \leq 12.5$ μT
>103	95	BAN	07	CNTR	UCN, B field on & off

$${}^{B}_{ILL}\tau_{nn^*} > 12.8\ s$$ (90% C.L.)

③ Finite B′: Current Status



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>103	95	BAN	07	CNTR	UCN, B field on & off

$${}^{B}_{ILL}\tau_{nn^*} > 12.8\ s$$ (90% C.L.)

3 What next?

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How can the limits be improved?

Better sources, larger storage volume:
Increase number of stored neutrons

Better storage vessels (coating):
Increase t_s

Larger storage vessel, shape (spherical):
Increase t_f

More importantly: How can we check the apparent signal of mirror neutron oscillation?

Notice: $\tau_{nn^*} \propto \sqrt[4]{N}$ $\tau_{nn^*} \propto \sqrt{t_s t_f}$

④ NStar-1a: PSI UCN Source

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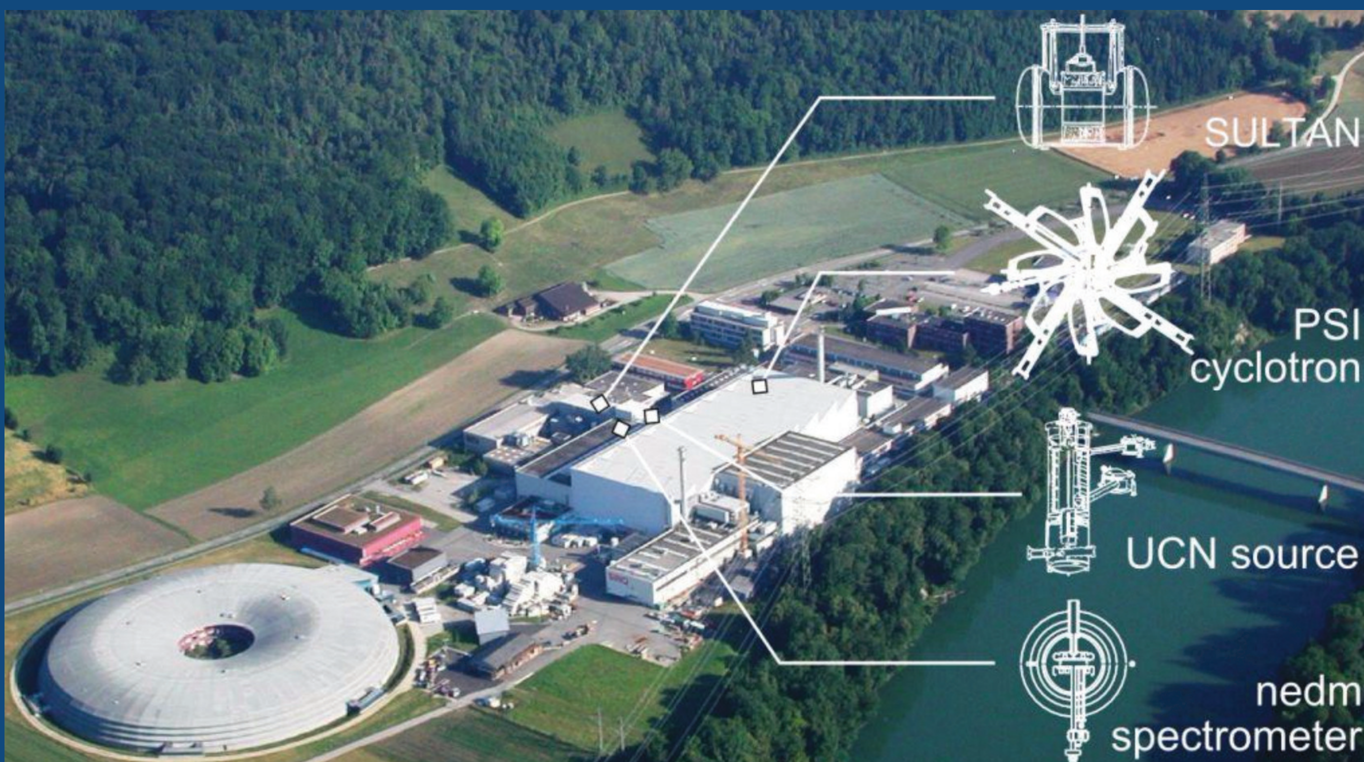

④ NStar-1a: PSI UCN Source

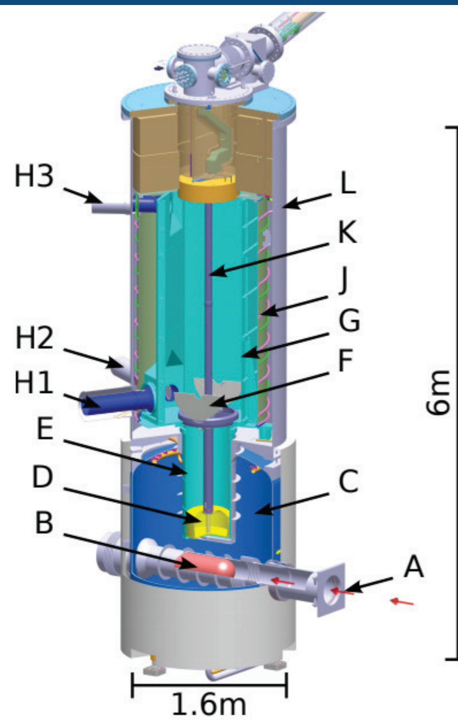

Figure 2.2: *Rendering of the central part of the UCN source from construction CAD files. A: Incoming proton beam; B: Spallation target; C: Heavy water tank; D: Solid deuterium moderator vessel; E: Vertical UCN guide; F: Central storage vessel flaps; G: Central storage vessel; H1-H3: Guides towards beamports "South", "West-1" and "West-2"; J: Thermal shield; K: Deuterium and helium supply lines; L: Vacuum vessel.*

The UCN Spallation target receives 8s/300s of 590MeV p+ beam.

H1: South Port, connected to the SC-magnet and PSI nEDM apparatus.

H2: West-1 port, usually closed. Connected to a detector. Opened for 2 kicks/day.

H3: West-2 port also connected to a detector and always counting.

④ NStar-1a: Use PSI nEDM Apparatus

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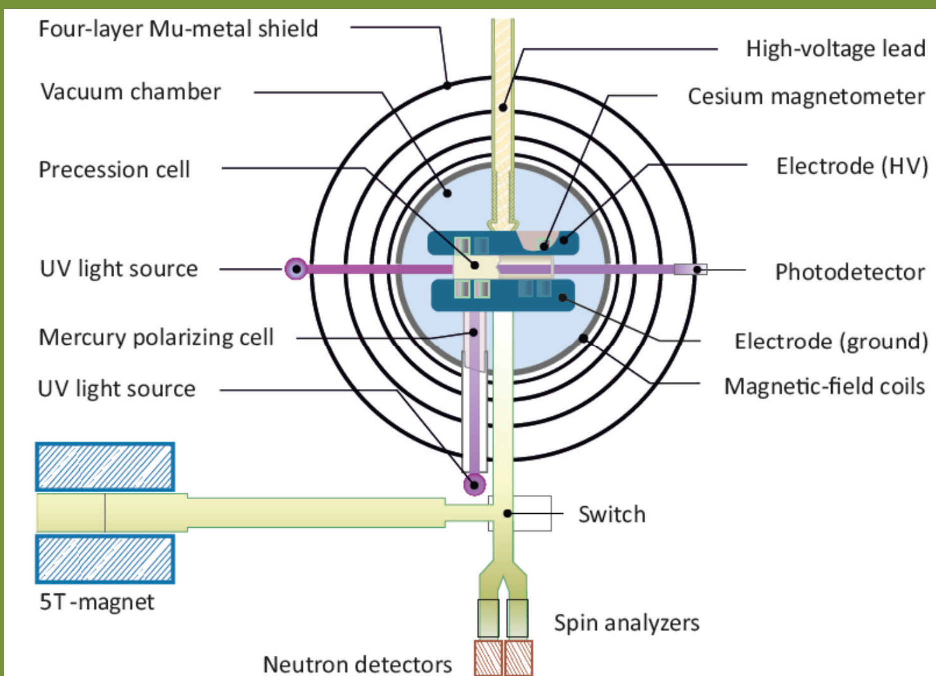
Static Field Compensation



1. S-C Magnet
   Polarizes Neutrons
2. SF1
   Spin Flipper
3. Switch
   Guides neutrons
4. Shutter
   UCN tight flap
5. SF2
   Spin Flipper
6. Analyzer Foils
   Spin Analyser
7. NANOSC
   UCN Detector

4 NStar-1a: Use Un-Polarized UCNs

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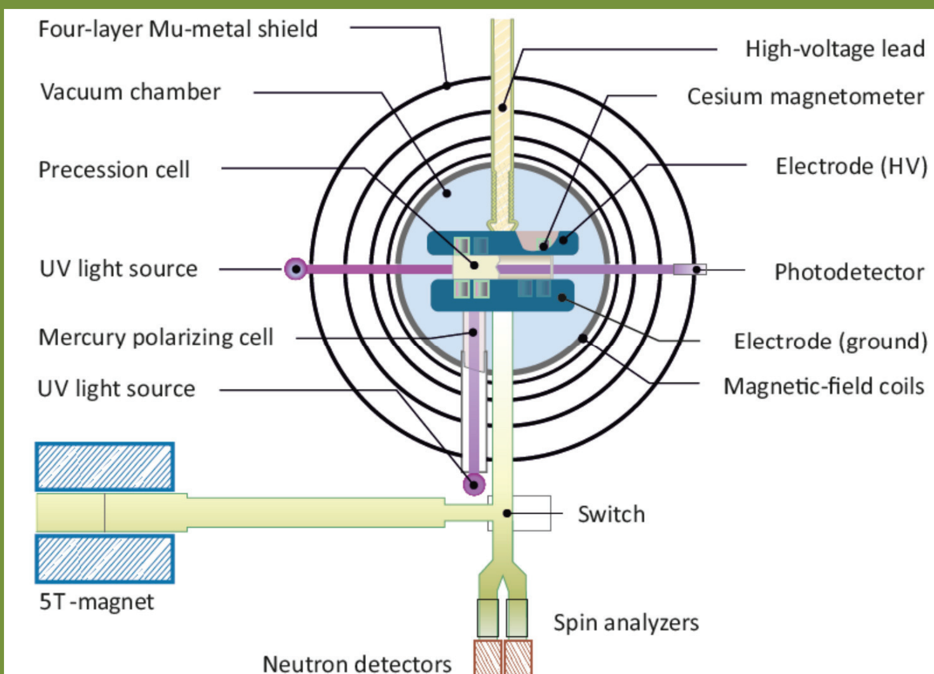
Static Field Compensation



1. ~~S-C Magnet~~
~~Polarizes Neutrons~~
~~2. SF1~~
~~Spin Flipper~~
3. Switch
Guides neutrons
4. Shutter
UCN tight flap
~~5. SF2~~
~~Spin Flipper~~
6. ~~Analyzer Foils~~
~~Spin Analyser~~
7. NANOSC
UCN Detector

④ NStar-1a: To start with…

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How can the limits be improved?

- With higher statistics, mostly coming from a longer run
- Dedicated run to scan the predicted parameter space

<u>More importantly</u>: How can we check the apparent signal of mirror neutron oscillation?

4 NStar-1a: Sample Cycle

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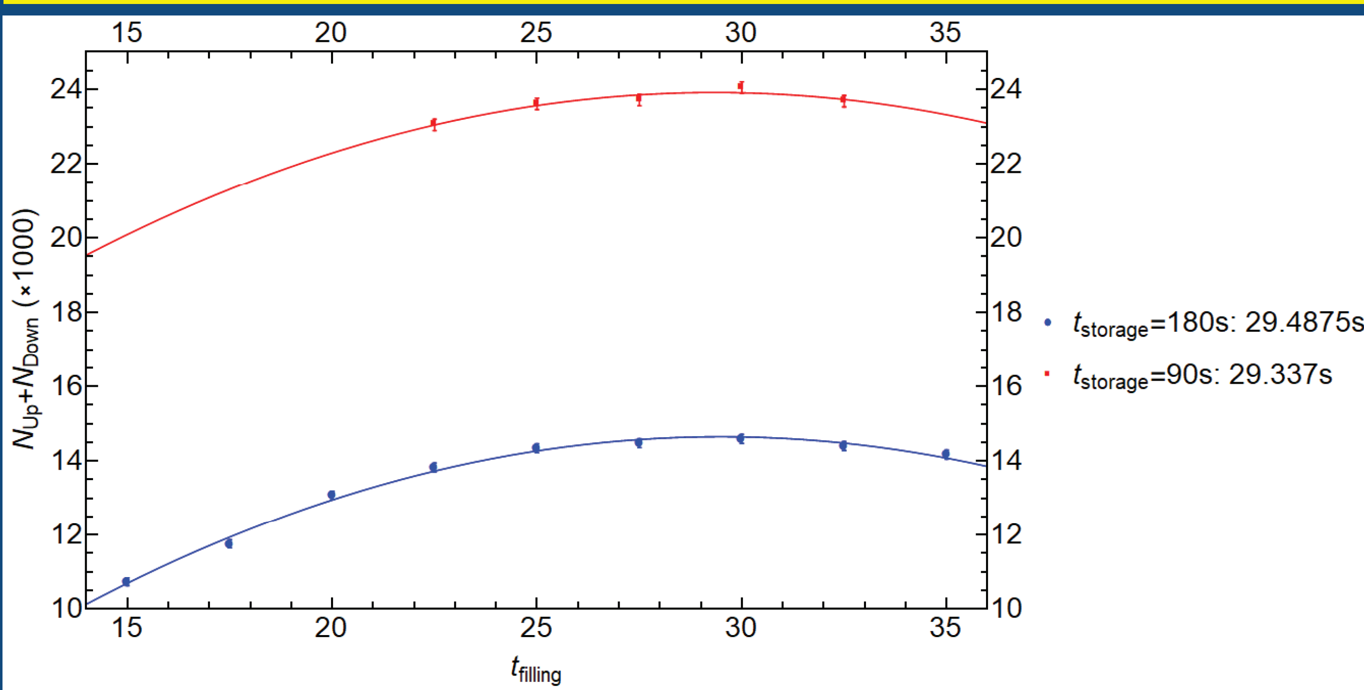
We only take 8s/300s (max.) of the p+ beam, our runs are divided into cycles.

4

Optimizing $t_{filling}$

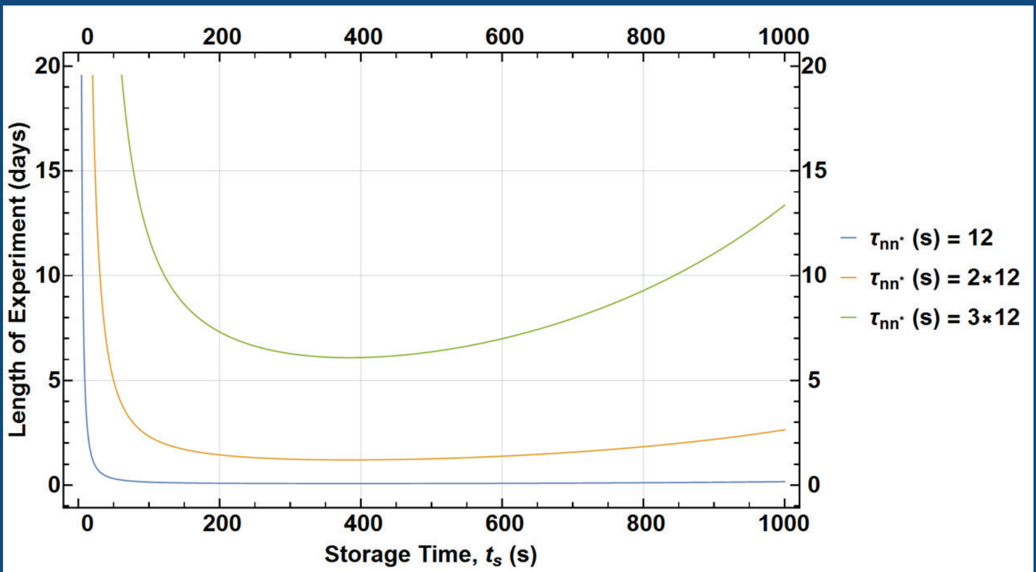
For neutrons stored for t^*_s = 180s, optimal $t_{filling}$ = 29.5s and this stays around 29.5s even after changing t_s significantly.



④ Optimizing t^*_s

But with storage time, the number of neutrons decreases exponentially.

We don't just optimize $\sqrt{t_s\sqrt{N}}$, because with increase in storage time, the time to complete a cycle increases linearly.



Remember:

$\tau_{nn^*} \propto \sqrt[4]{N}$

$\tau_{nn^*} \propto \sqrt{t_s t_f}$

Optimizing:

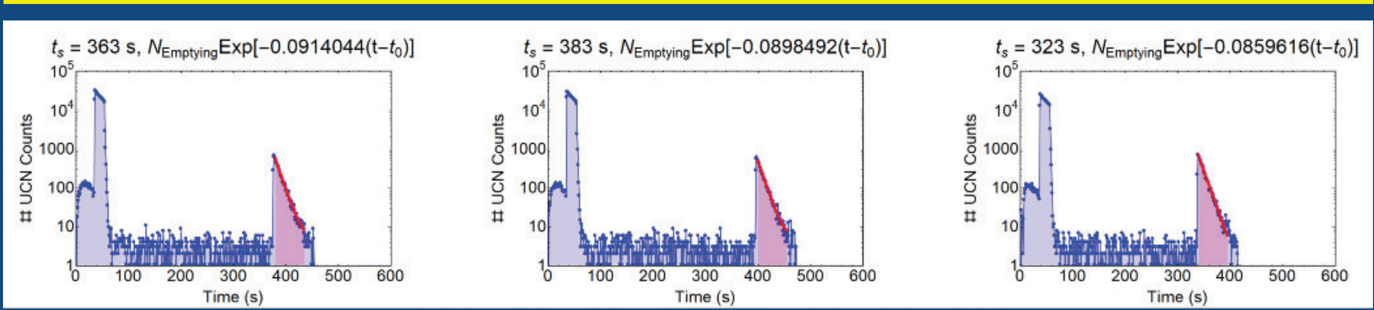
$\tau_{nn^*}(t_t \propto t_s) \propto \sqrt{t_s\sqrt{N}},$

Choose:

$t_s^* = 380s$

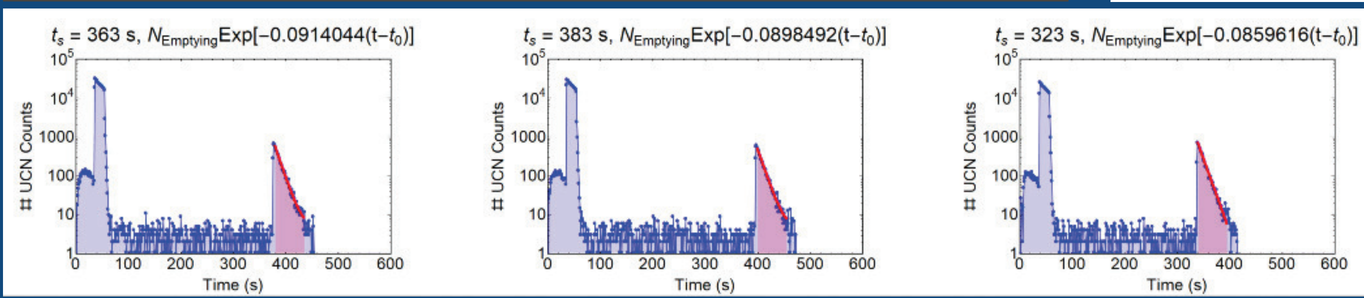
4 Optimizing $t_{emptying}$

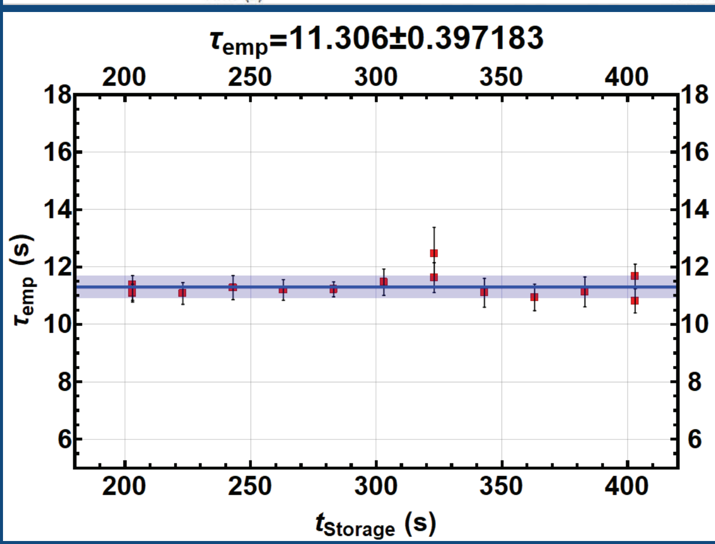
We'd want $t_{emptying}$ to be the longest time possible to amply measure all the neutrons remaining.



$t_{emptying}$=75s. They can be accommodated with t_s={180, 380}s, into cycles t_t={300,500}s long.

④ Effective Storage time: $t_s + 2\tau_f$





$$t_s^* = \{50, 100, 175\}s$$

$$t_s = \{72.6, 122.6, 197.6\}s$$

- Notice we made the distinction between t_s^* and t_s.
- UCNs can also oscillate during filling (11.3s) and emptying (11.3s), we add 22.6s to the scheduled storage time.
- $t_s = t_s^* + 2\tau_f = t_s^* + 22.6(4)$
- τ_f is independent of the storage time.

④ Nstar-1a: Final Cycle Plan

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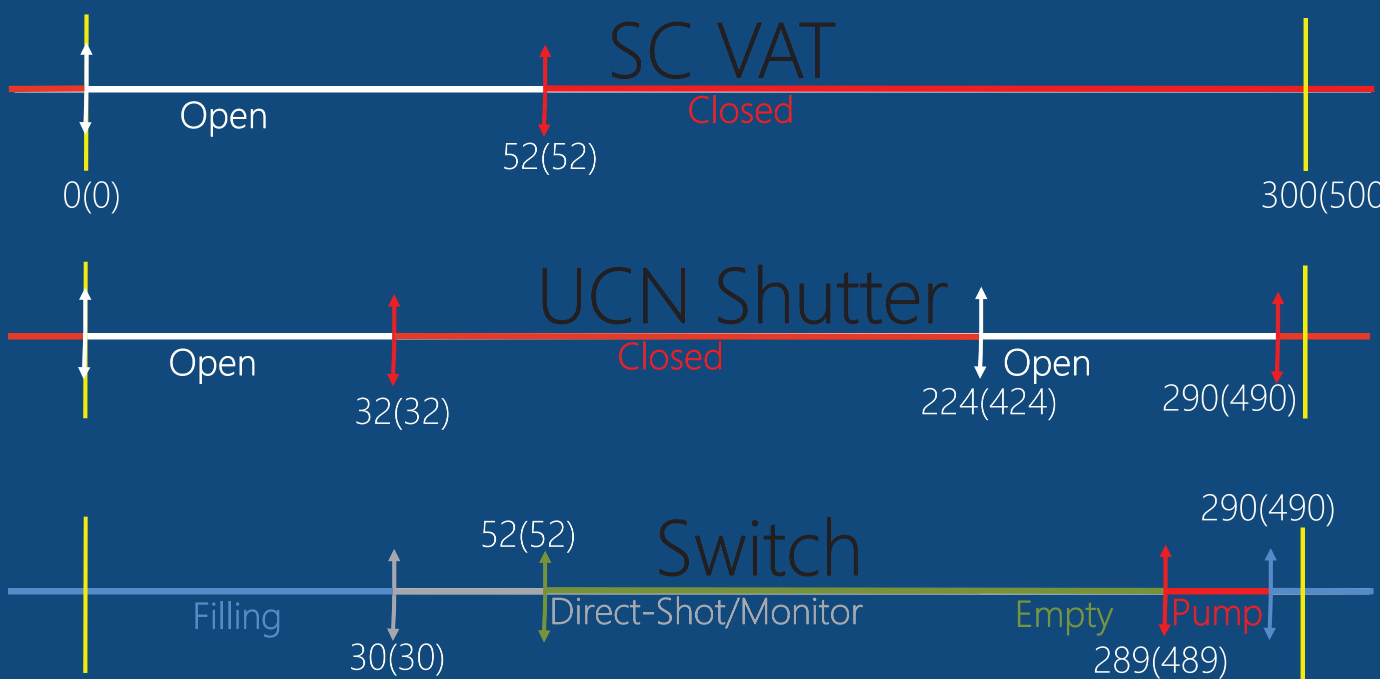
t_s=180s to replicate old experiment, t_s=380s for maximum sensitivity



④ NStar-1a: Data Collected

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Run Plan: We took data Aug-Oct 2017.

Cluster	Pattern	t^*_s (t_t) /s	B_0 /μT	# Cycles
1	0↑0↓0↓0↑0↓0↑0↑0↓0	180 (300)	10	1243
2	0↑0↓0↓0↑0↓0↑0↑0↓0	380 (500)	10	1136
3	0↑0↓0↓0↑0↓0↑0↑0↓0	180 (300)	20	864
4	0↑0↓0↓0↑0↓0↑0↑0↓0	380 (500)	20	775

- There was a break in between 10 and 20μT cycles as a part of risk management
- The data was collected such that 'a' and 'b' signal could be confirmed (or rejected) with just 10μT data and 'c' could be tested on addition of 20μT data.
- This results in approximately x2 @ 10μT.

- In addition to the main cluster of NStar runs, there were data taken for also t_s scans, mainly to extract $t_f(t_s)$

4

UCN Counting

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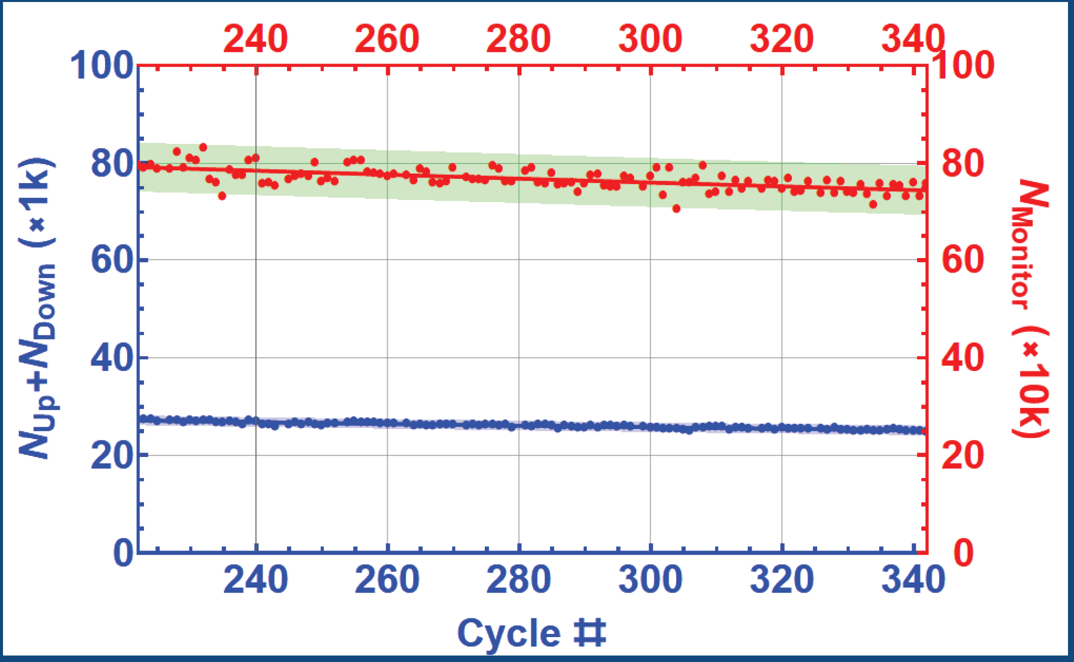
Raw Counts



④ Raw UCN Counts

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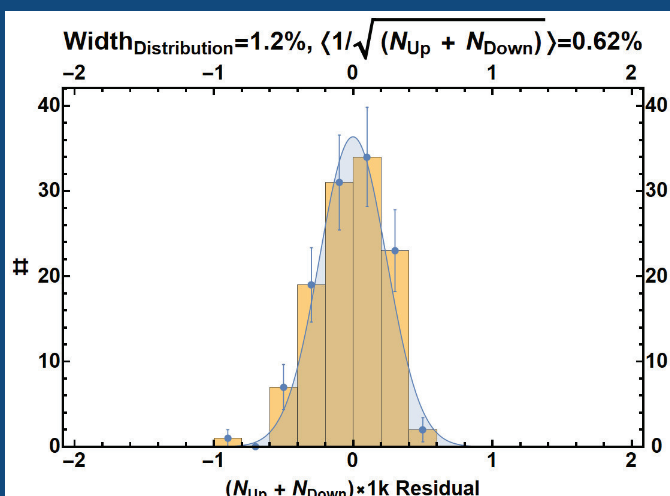
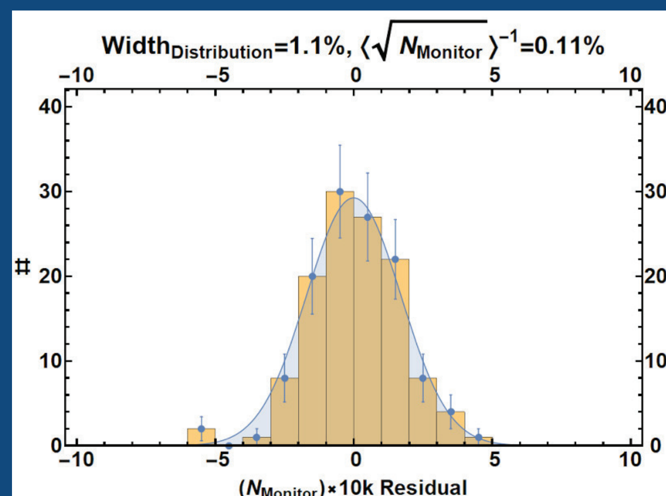
How are raw counts distributed?





- The UCN source doesn't always provide the same number of neutrons.
- The number of neutrons provided by the source varies as a function of charge on target and motion of all the flaps.

4 Normalized UCN Counts

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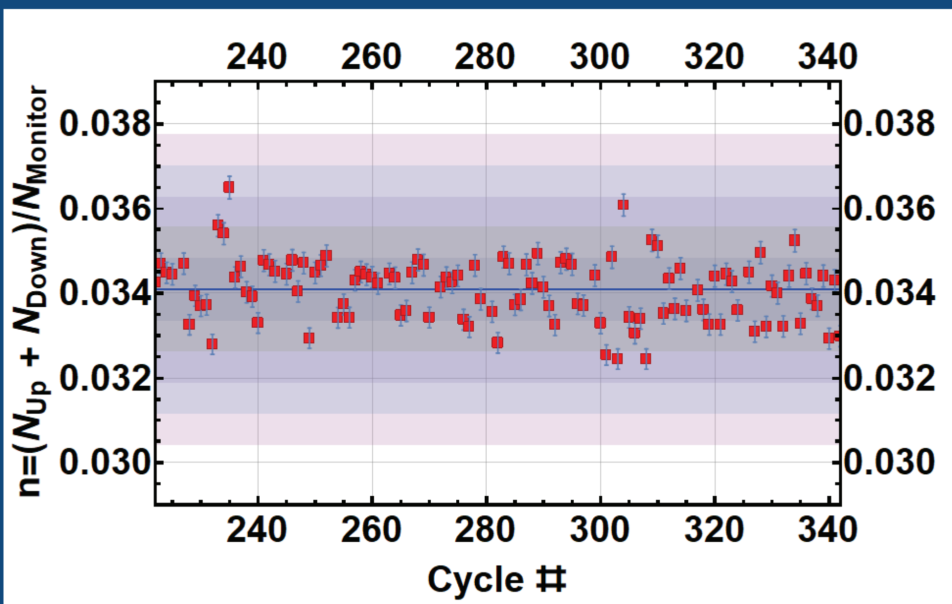
Since we are extracting storage lifetimes by counting the number of neutrons remaining after time – t_s, we have to have an independent means to normalize initial UCN counts.



- West-2 has about ~15% scatter.
- West-1 doesn't count regularly.
- Monitor [counts ~ 10^6] normalization has a maximum scatter of <1%, as expected from statistics.

④ Normalized UCN Counts

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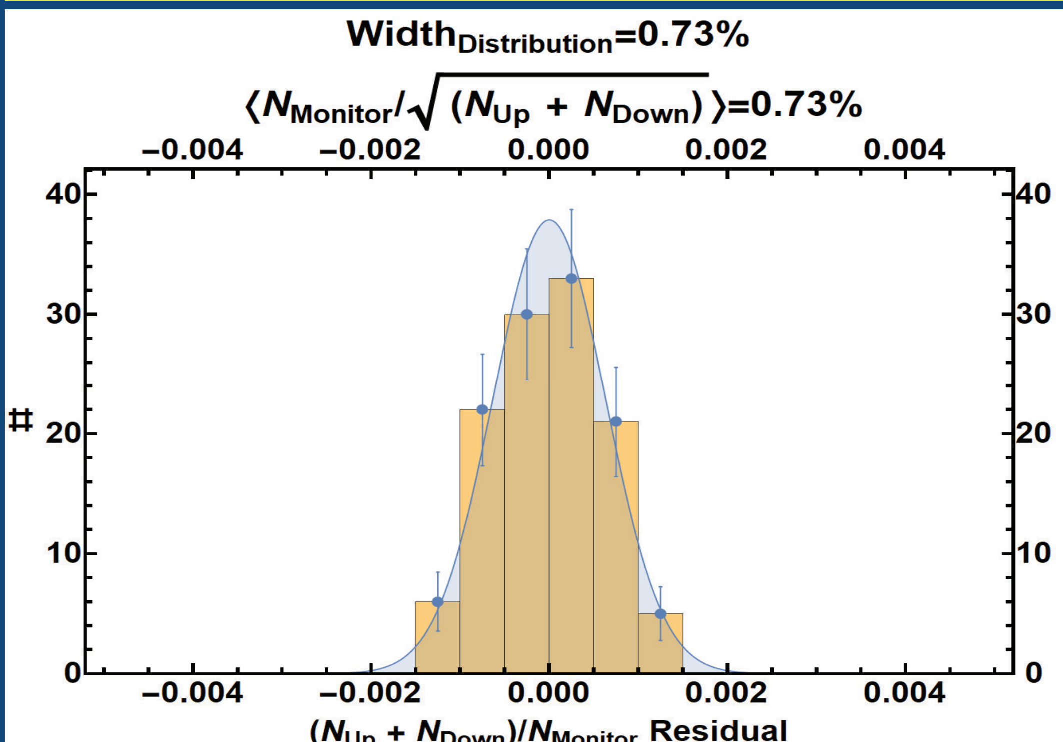
How are normalized counts distributed?



④ Estimating t_f

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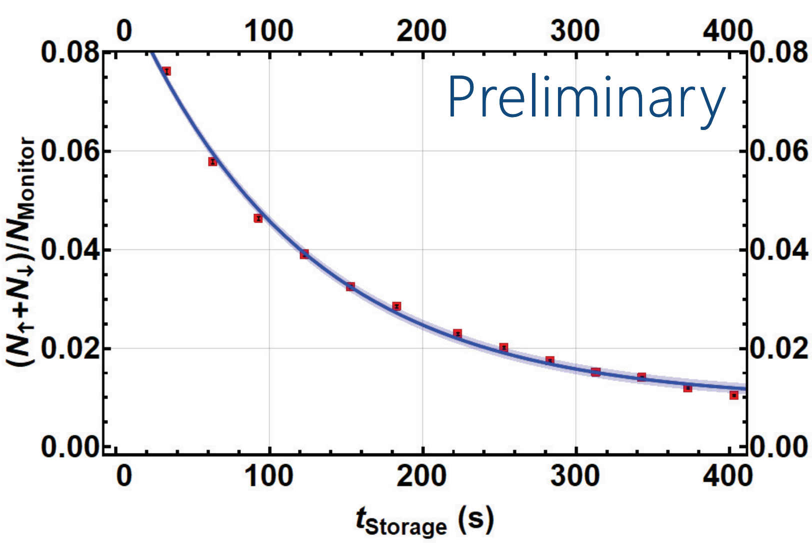
t_f may change with t_s due to softening of the UCN energy spectra



- $N(t_s) \longrightarrow t_f(t_s)$
- $N(t_s)$ depends not only on neutron decay half life but mainly on loss (per bounce) parameter η(E) which is energy dependent.
- $N(t_s)$ gives us the energy distribution of the neutrons.

④ Estimating t_f

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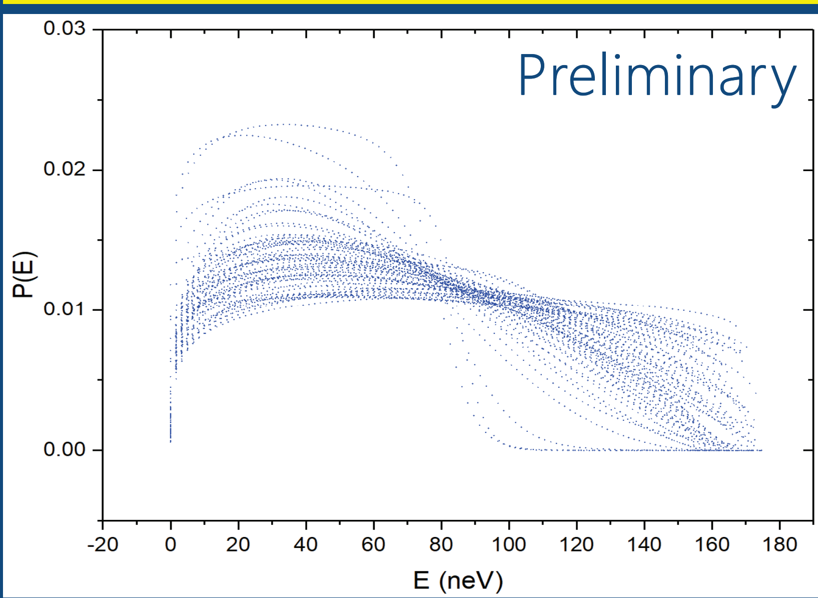
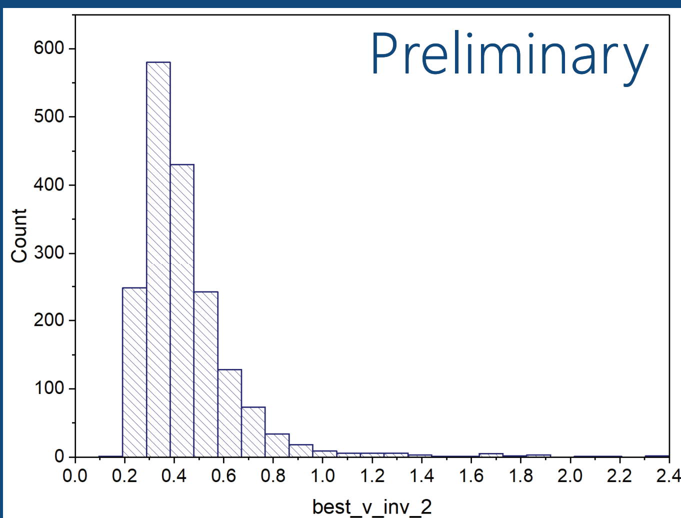
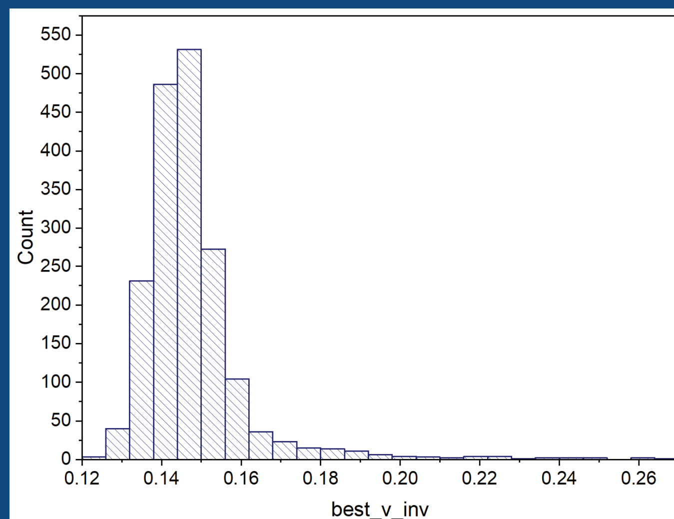
t_f may change with t_s due to softening of the UCN energy spectra



- $N(t_s) \rightarrow t_f(t_s)$
- $N(t_s)$ depends not only on neutron decay half life but mainly on loss (per bounce) parameter $\eta(E)$ which is energy dependent.
- $N(t_s)$ gives us the energy distribution of the neutrons.

④ Estimating t_f





$t_f(t_s=202.6s)$

$$t_f \sim \frac{4(\mathrm{v} = .021m^3)}{(\mathrm{a} = .54m^2)} \left(\frac{1}{\mathrm{V}}\right)$$

Attribute (Units)	<1/v> ($m^{-1}s$)	<1/v²> ($m^{-2}s^2$)	t_f (s)	t_f^2 (s^2)
Value	0.145	0.315	0.023	0.008

④ What is the Magnetic Field Inside?

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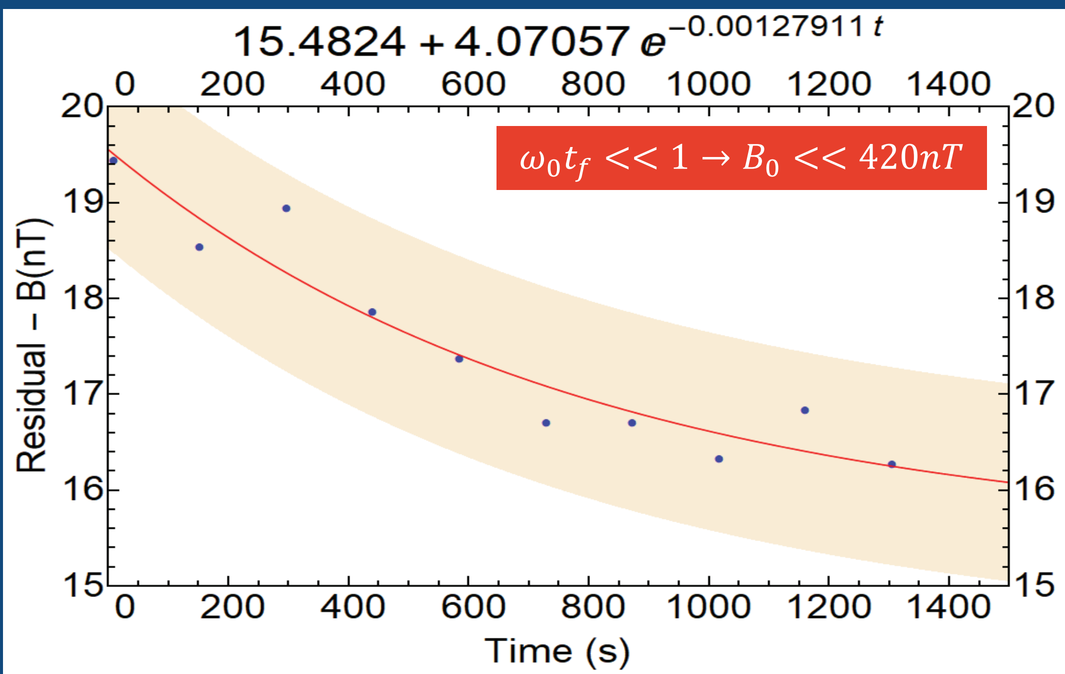
Once we ramp to ±20μT (max) and down to 0μT, do we any residual field? This residual field must be <420nT. Using Hg co-magnetometer...:



We are interested in the average <B(I$_0$)> during storage.

4 NStar: What was accessed with oILL?

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Cluster	Pattern	t^*_s (t_t) /s	B_0/μT	# Cycles
1	0↑0↓0↓0↑0↓0↑0↑0↓0	180 (300)	10	1243
2	0↑0↓0↓0↑0↓0↑0↑0↓0	380 (500)	10	1136
3	0↑0↓0↓0↑0↓0↑0↑0↓0	180 (300)	20	864
4	0↑0↓0↓0↑0↓0↑0↑0↓0	380 (500)	20	775

We find no finite asymmetries

$$\frac{n_0}{n_{\uparrow\downarrow}} = 1 - \frac{t_f t_s}{\tau^2_{nn'}} \xrightarrow{B'=0} \tau_{nn^*} > 426\ s \text{ (90\% C.L.)}$$

$$\frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow} = -\frac{t_s}{t_f} \frac{\eta^3 Cos\beta}{\omega^2 \tau^2_{nn'} (1-\eta^2)^2} \xrightarrow{B'\neq 0} \tau_{nn^*} > 36\ s \text{ (90\% C.L., } B_0=[0,20]\mu T)$$

$$\eta = B'/B$$

Very Preliminary...

4 NStar 0 B′: What was accessed with oILL?

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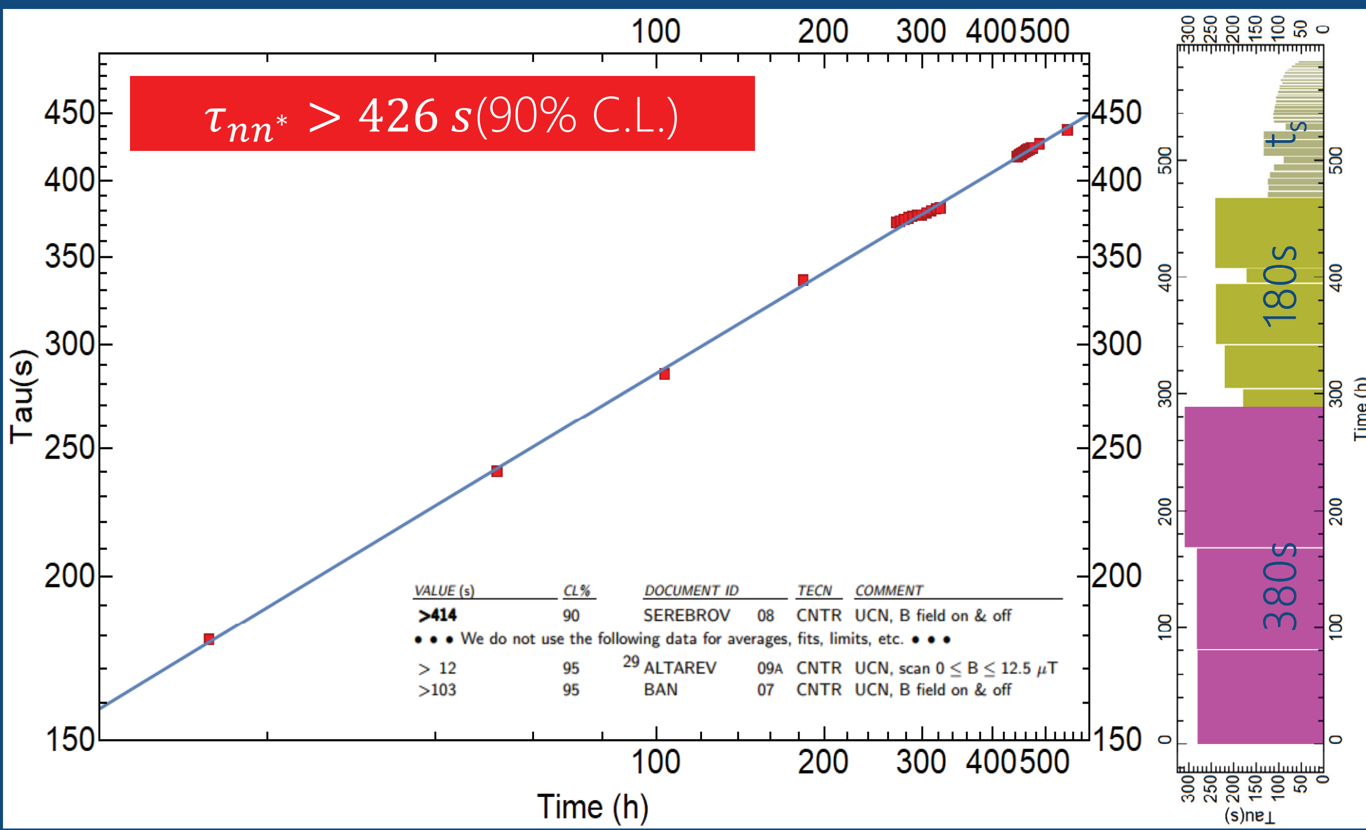

VALUE (s)	CL%	DOCUMENT ID		TECN	COMMENT
>414	90	SEREBROV	08	CNTR	UCN, B field on & off
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 12	95	[29] ALTAREV	09A	CNTR	UCN, scan $0 \le B \le 12.5\ \mu T$
>103	95	BAN	07	CNTR	UCN, B field on & off

4 NStar Finite B′: What was accessed with oILL?

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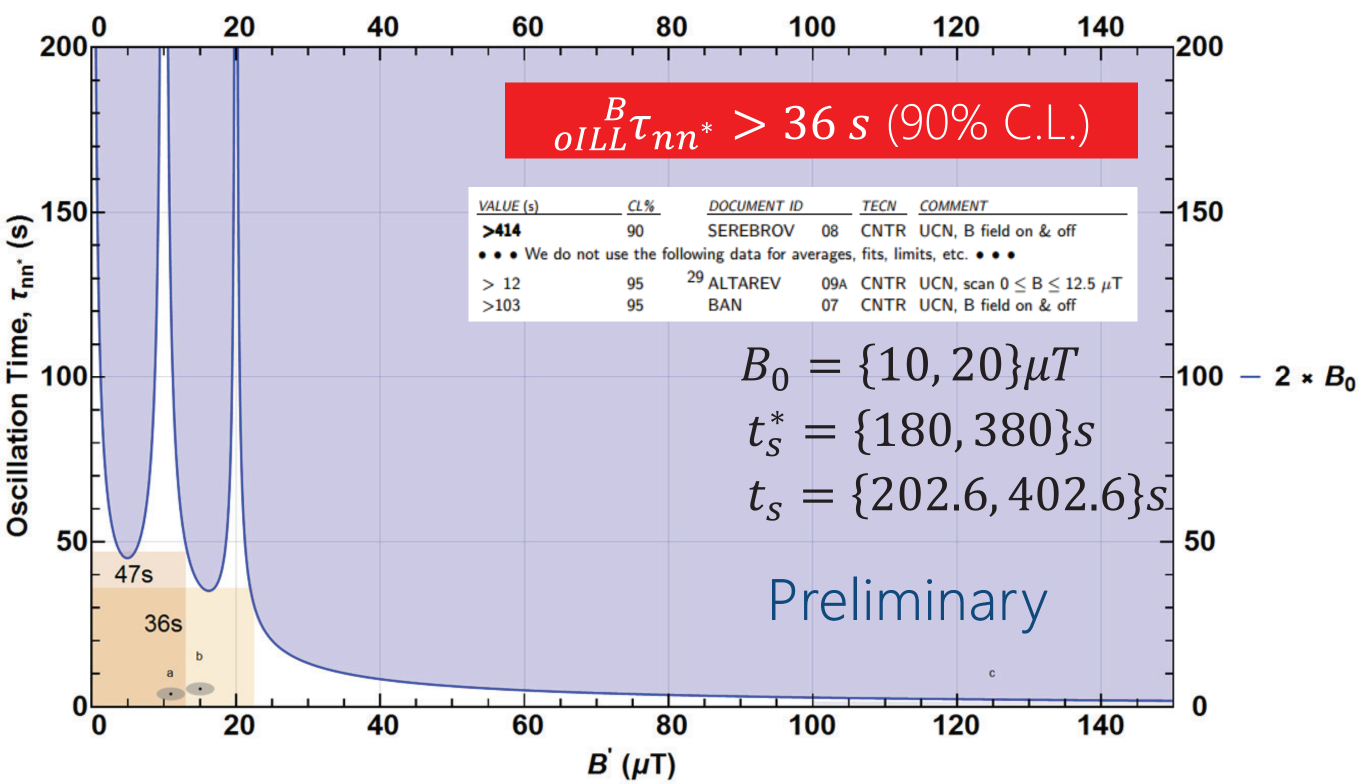

5

Summary

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Resolved (?) the crisis

$$\frac{n_0}{n_{\uparrow\downarrow}} = 1 - \frac{t_f t_s}{\tau^2_{nn'}} \xrightarrow{B'=0} \tau_{nn^*} > 426\ s \text{(90\% C.L.)}$$

$$\frac{n_\uparrow - n_\downarrow}{n_\uparrow + n_\downarrow} = -\frac{t_s}{t_f}\frac{\eta^3 Cos\beta}{\omega^2\tau^2_{nn'}(1-\eta^2)^2} \xrightarrow{B'\neq 0} \tau_{nn^*} > 36\ s \text{ (90\% C.L., } B_0\text{=[0,20]}\mu\text{T)}$$

VALUE (s)	CL%	DOCUMENT ID		TECN	COMMENT
>414	90	SEREBROV	08	CNTR	UCN, B field on & off
• • • We do not use the following data for averages, fits, limits, etc. • • •					
> 12	95	[29] ALTAREV	09A	CNTR	UCN, scan $0 \le B \le 12.5\ \mu$T
>103	95	BAN	07	CNTR	UCN, B field on & off

Where do we go from here?

- Obviously finish a rigorous analysis (the numbers are bound to change).
- Nstar-1b: Dedicated Mirror Neutron Search (to look for modulating signal) with a sensitivity of $\tau_{nn^*} > 1000s$.