Measurement of the neutron lifetime using a magneto-gravitational trap

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For the UCNτ Experiment

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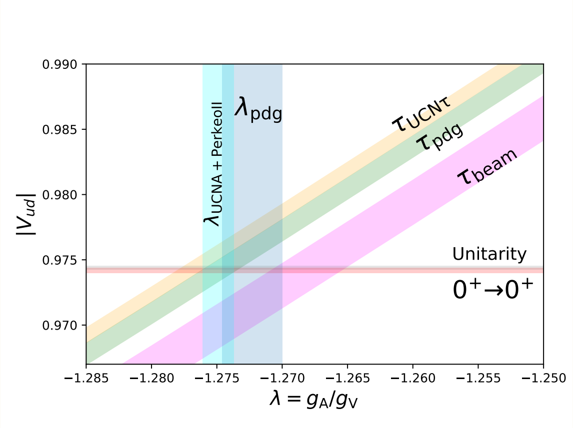
Neutron Lifetime and CKM Unitarity (Using *n* Decay)

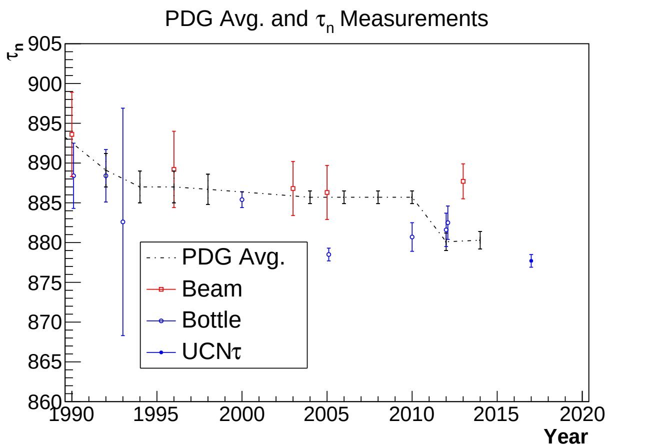
- Measure τ_n and λ to measure V_{ud}
- Want τ_n <0.1 s and λ <0.025% (A <0.1%)



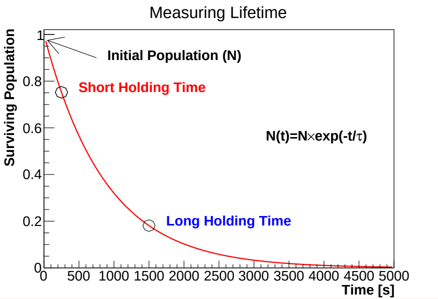
$$\tau_n = \frac{4908.7 \pm 1.9s}{|V_{ud}|^2\,(1 + 3\lambda^2)}$$

Recent history of τ_n measurements

- Beam/Bottle Discrepancy: $\sim 3\sigma$
- Beam - Absolute Counting of Neutrons and Protons
- Bottle - Non β-decay Losses



Measuring τ with Neutron Traps



$$\tau_{\text{trap}} = \frac{\Delta t}{\log(N_{\text{short}}/N_{\text{long}})}$$

$$\frac{1}{\tau_{\text{trap}}} = \frac{1}{\tau_{\text{n}}} + \frac{1}{\tau_{\text{escape}}} + \frac{1}{\tau_{\text{depol}}} + \frac{1}{\tau_{\text{material}}} + \dots$$

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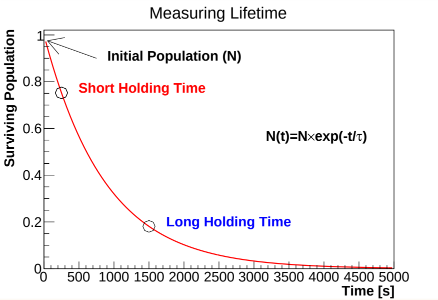

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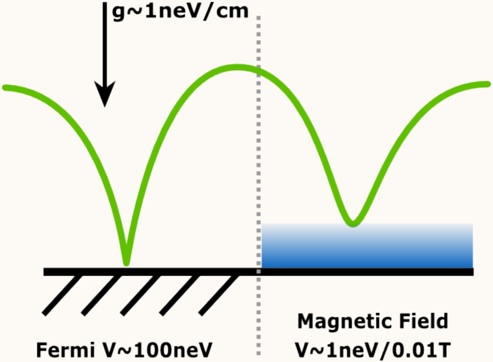
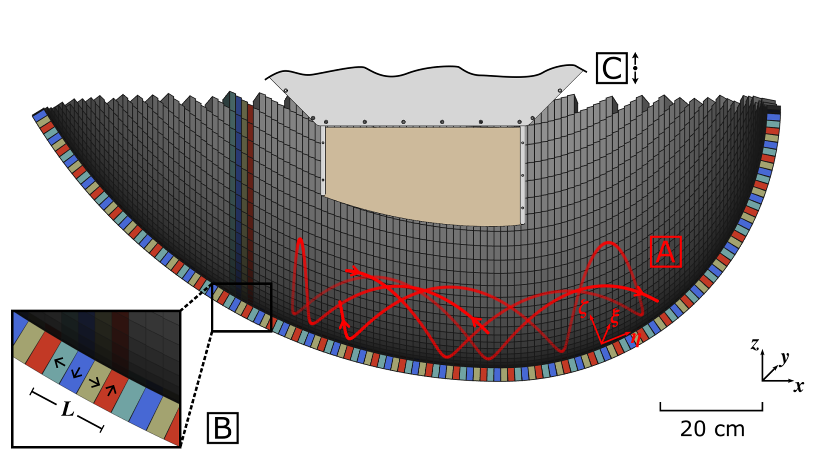
How can you even trap a neutron?



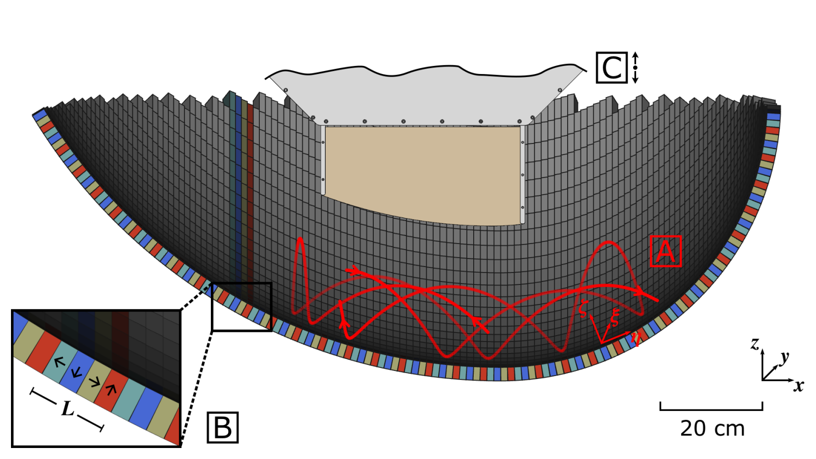
- Material - $V_f \sim \mathcal{O}(100 \text{ neV}) \rightarrow$ Loss of UCN during Storage
- Magnetic Field - $V_B \sim$ 1neV/1000 Gauss $\rightarrow$ Lossless
- Gravity - $V_g \sim 1$ neV/cm
- $\sim$1 Bounce per Second

UCNτ - A magnetic neutron bottle



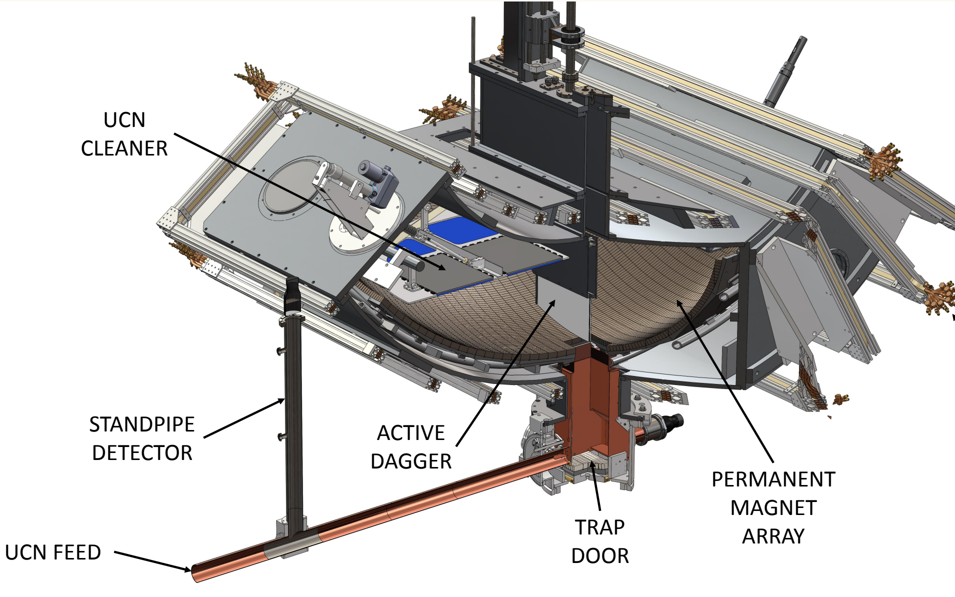
Trapped Above by **Gravity** Below by **Magnetic Field** (**A**)

UCNτ - A magnetic neutron bottle

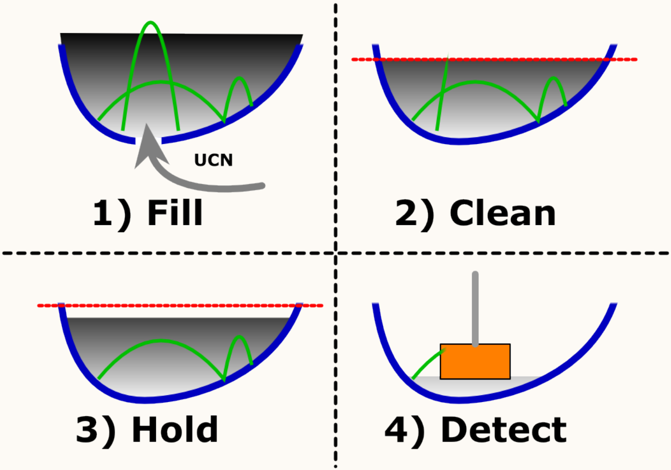


In-Situ Detector - Real Time, Fast, Efficienct, Height Sensitive (**C**)

UCNτ Apparatus



A Typical Lifetime Run



Where we are now

877.7 $\pm$0.7 $\pm$0.3(systematic)

R. W. Pattie et. al. *Science* 2018 [arXiv:1707.01817]

Effect	Upper bound [s]	Method
Depolarization	$+$ 0.07	Varied $\boldsymbol{B}_{\text{hold}}$
Microphonic heating	$+$ 0.24	Count High-E UCN
Insufficient cleaning	$+$ 0.07	Count High-E UCN
Dead time	$\pm$ 0.04	Known dead time
Phase space evolution	$\pm$ 0.10	Mean Arrival Time
Residual gas interactions	$\pm$ 0.03	Measured Pressure
Background shifts	$\pm$ $<$0.01	Measured background
Total	0.28	(uncorrelated sum)

- $\sim$7,000,000 UCN from 2 Months Data
- More Statistics to come!

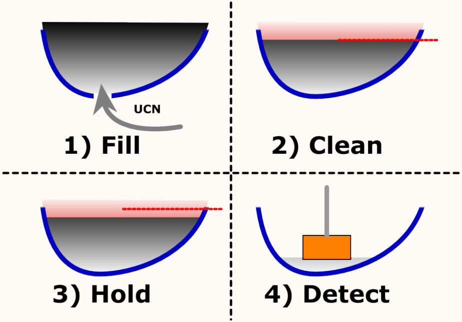
Subsequent work

Effect	Estimate [s]	Method
Depolarization	$+\ 0.07$	Measured
Microphonic heating	$<\ 0.15$	Monte Carlo
Insufficient cleaning	$<\ 0.05$	Monte Carlo
Dead time/pileup	$\pm\ 0.04$	Measured
Phase space evolution	$\pm\ 0.10$	Measured
Residual gas interactions	$\pm\ 0.03$	Measured
Background shifts	$\pm\ <0.01$	Measured

*Preliminary

Cleaning Systematic

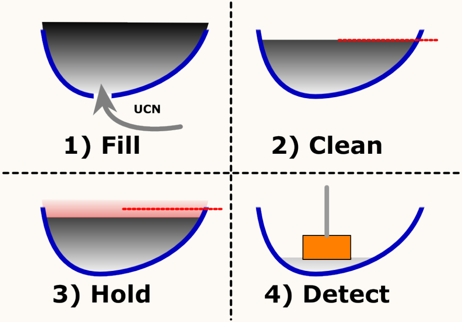
$$\frac{1}{\tau_{\text{trap}}} = \frac{1}{\tau_{\text{n}}} + \frac{1}{\tau_{\text{escape}}}$$



- Fraction of UCN uncleaned
- High E UCN eventually reach raised cleaner and escape

Heating Systematic

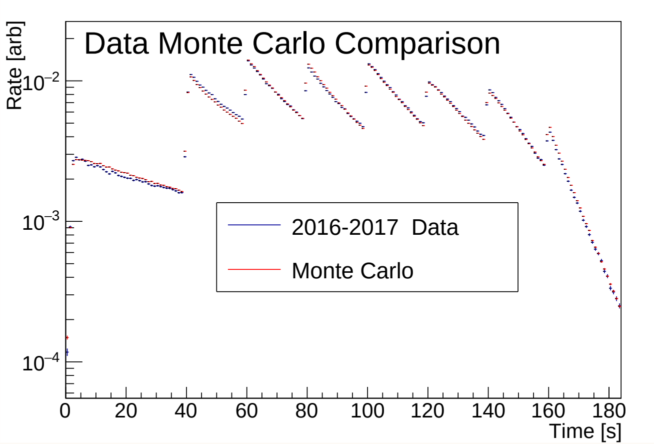
$$\frac{1}{\tau_{\text{trap}}} = \frac{1}{\tau_{\text{n}}} + \frac{1}{\tau_{\text{heating}}}$$

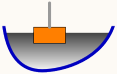


- Assume 100% Cleaning
- Small kicks of energy during storage
- Randomly walk up to raised cleaner and escape

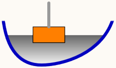
Trap Monte Carlo

- Simplified Spectral Model (3 parameters)
- Detector Model (2 parameters)

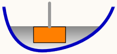




Peak 2



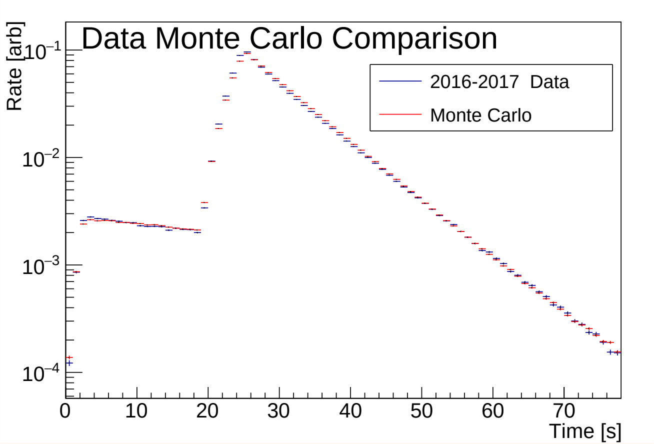
Peak 4

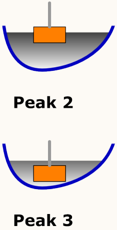


Peak 9

Monte Carlo Validation

- Use χ^2 minimized parameters on separate dataset

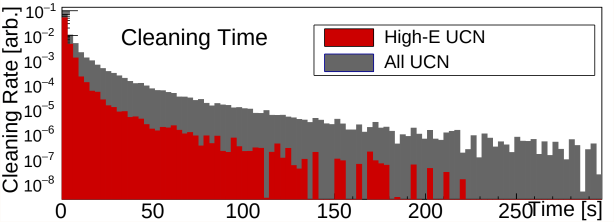




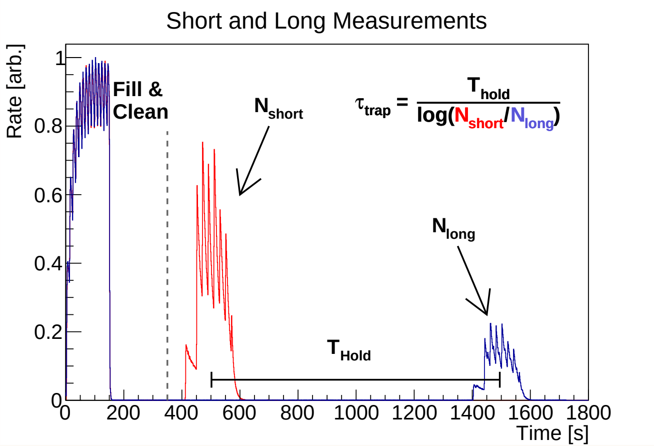
Systematics Simulation

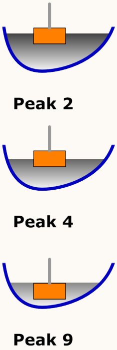
- Simulate **Cleaning** and **Storage** (optionally **Heating**)
- Count losses from **Uncleaned** or **Heated** UCN $\rightarrow \Delta\tau$

Condition	$\Delta\tau$ [s]	Statistical Uncertainty
Cleaning 100% Absorption	0.034	± 0.0006
Cleaning 50% Absorption	0.050	± 0.0007
Accelerometer Vibrations (1 μm)	0.031	± 0.005
Simulated 40 μm Vibrations	0.151	± 0.009



Phase Space Evolution

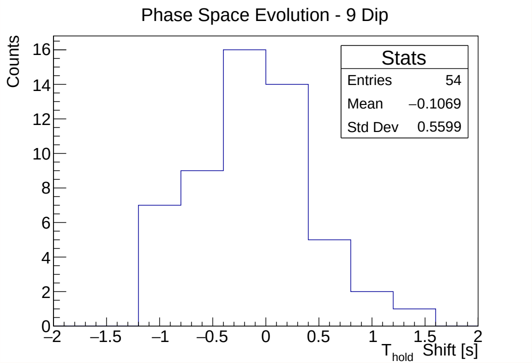




- Phase space evolution can change **Draining Efficiency**
- Use mean arrival time to measure T_{hold}

Phase Space Evolution

- Shift $= T_{\text{program}} - \bar{T} = \Delta T_{\text{hold}}$
- Systematic ΔT_{hold} shift $\rightarrow \boldsymbol{\delta\tau_n < 0.1}$ **s**



Data Set	ΔT_{hold}
200/1	-0.005(14)
200/9	-0.107(76)
300/9	-0.038(68)
50/3	+0.009(16)
50/3′	-0.016(18)

Key: $\boldsymbol{T_{\text{clean}}}$/**#Dips**

Conclusion

- Measure neutron lifetime with trapped UCN
- 0.7 s Statistical Uncertainty
- Need to investigate loss mechanisms (heating, cleaning, etc)
- Monte Carlo estimates small effects from Heating and Cleaning ($<$0.15 s)
- *In-Situ* detector allows for **Spectral Monitoring**
- Phase Space Evolution is small ($<$0.1 s)

The UCNτ Collaboration

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Students are shown in blue

Questions