The neutron lifetime experiment τSPECT

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Precision Physics of Simple Atomic Systems 2024

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Ultracold Neutrons - UCN

Subatomic Particles at Human Velocities

$$E_{\text{kin}} \lesssim 335\,\text{neV}$$

$$\Leftrightarrow$$

$$v < 8\,\text{m}\,\text{s}^{-1} \simeq 30\,\text{km}\,\text{h}^{-1} \simeq 18.6\,\text{mph}$$

UCN Interactions

- Strong Interaction
  - Neutron Optical Potential (Fermi Potential):
  - $V_F \propto \rho b_{\text{coh}}$
  - ^{58}Ni: ∼335 neV, Stainless steel: ∼190 neV, Al: ∼54 neV

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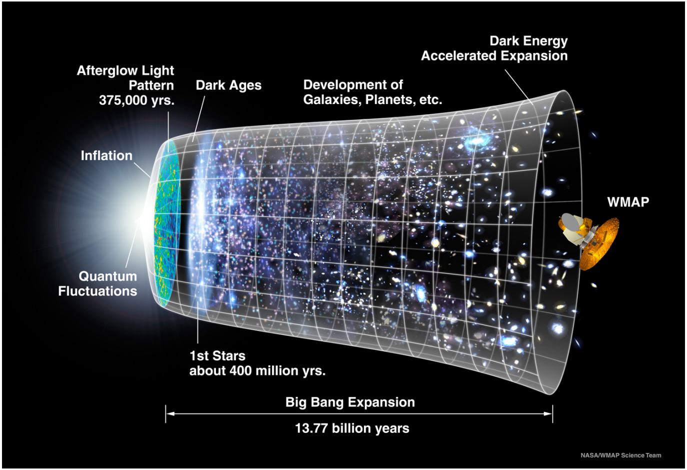
- Gravity
  - $102.5\,\mathrm{neV\,m^{-1}}$
- Magnetism
  - Spin polarization with strong magnetic fields.
  - $\mu_n = -60.3\,\mathrm{neV\,T^{-1}}$

Why Neutron Lifetime?

a) Big Bang Nucleosynthesis (He abundance)
[Cyburt et al., doi:10.1103/RevModPhys.88, 2016]

Big Bang Nucleosynthesis



$@t = 2\,\text{min}$: $n/p \simeq 1/6$ $@t = 4\,\text{min}$: $n/p \simeq 1/7$

Neutron Lifetime

Why n-lifetime?

a) Big Bang Nucleosynthesis (He abundance)
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b) CKM Unitarity (V_{ud})
[Czarnecki, Marciano, Sirlin, doi:10.1103/PhysRevD.100.073008, 2019]

Cabibbo–Kobayashi–Maskawa matrix

$$\begin{bmatrix} |V_{ud}| & |V_{us}| & |V_{ub}| \\ |V_{cd}| & |V_{cs}| & |V_{cb}| \\ |V_{td}| & |V_{ts}| & |V_{tb}| \end{bmatrix}$$

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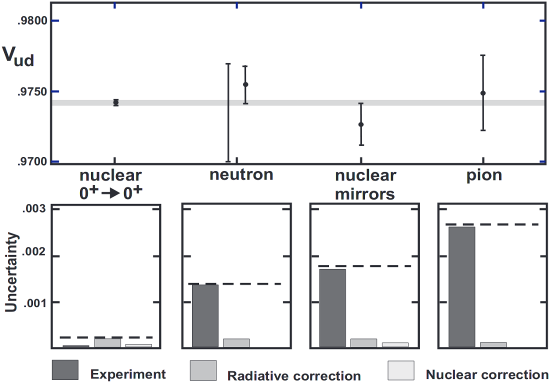
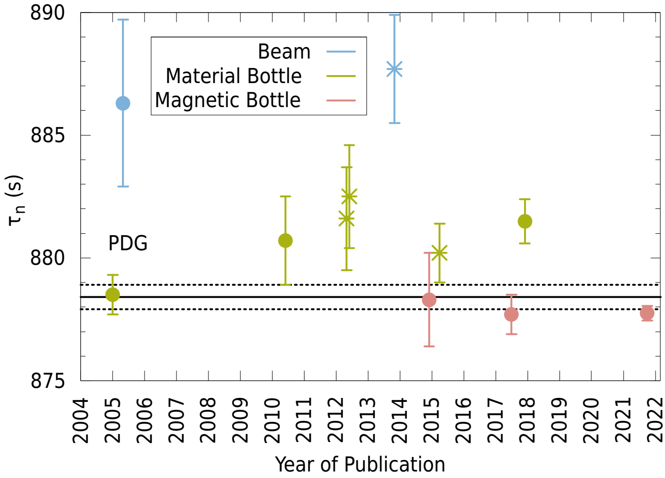


[Hardy and Towner, doi:10.48550/arXiv.1807.01146, 2018]

The Lifetime Puzzle



Neutron Lifetime

Why n-lifetime?

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b) CKM Unitarity (V_{ud})
[Marciano and Sirlin, doi:10.1103/PhysRevLett.96.032002, 2006]

c) "It's 2024. We cannot agree on τ_n to better than 10s?!"

$$\tau_{\text{n,beam}} = 887.7 \pm 1.2 \pm 1.9\text{s}$$
$$\neq$$
$$\tau_{\text{n,stored}} = 877.75 \pm 0.28 \pm 0.22\text{s}$$

τSPECT

Concept:

- 3-D magnetic storage
  - Two solenoids + Octupole

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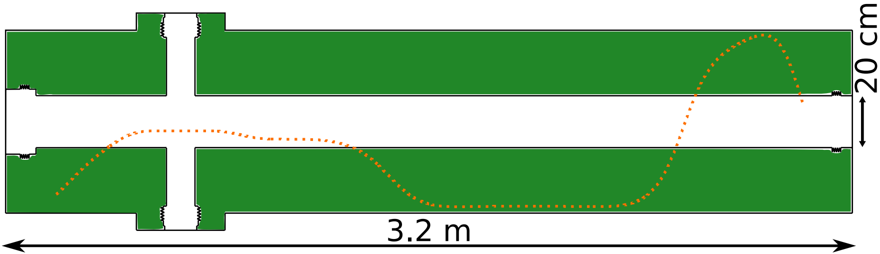
- 3-D magnetic storage
  - Two solenoids + Octupole
- Spinflip-loading
  - Holding field polarizes neutrons
  - Fast adiabatic spinflip as loading mechanism
- In-situ UCN detection
  - Minimizes extraction losses
  - High detector requirements wrt temp. & B-field

τSPECT fields



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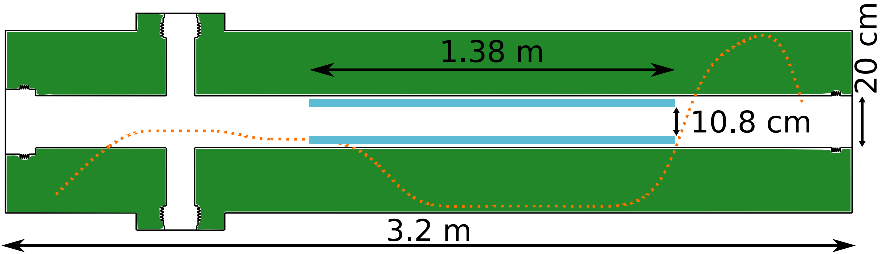

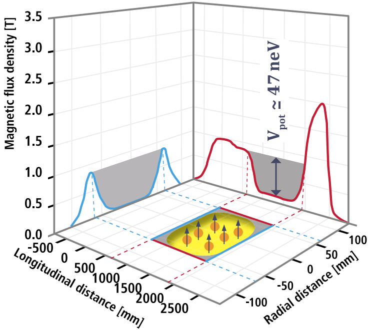

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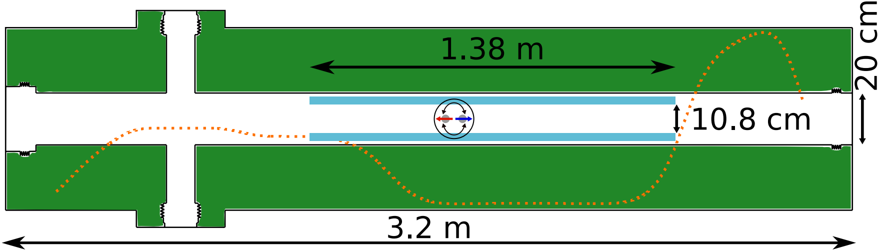
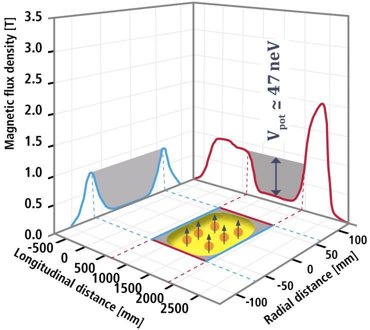
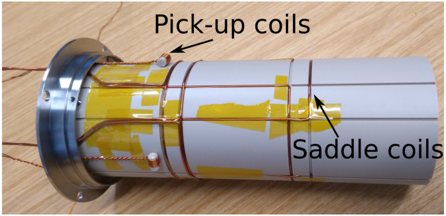
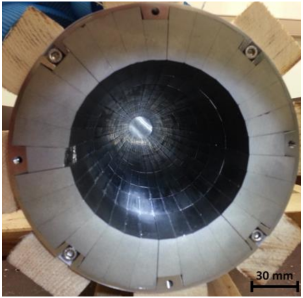






K. U. Ross

Gradient compensation in SF region



work of K.U. Ross

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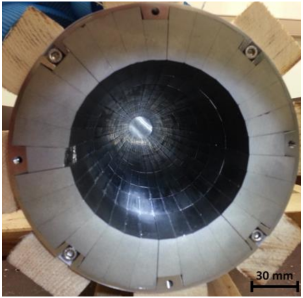

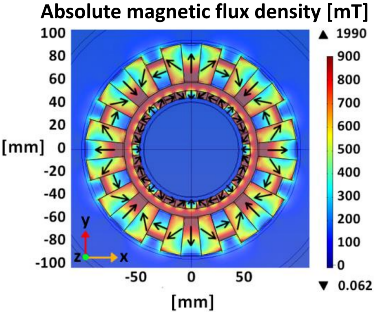

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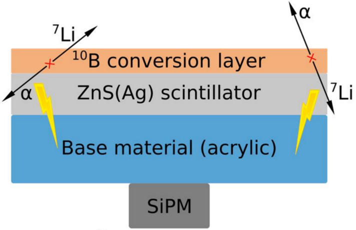

- Neutron capture on ^{10}B
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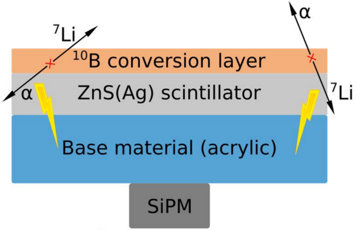

- Neutron capture on ^{10}B O(100 nm)
- Subsequent decay into $\alpha + {}^{7}$Li back-to-back
- Charged particle generates light in scintillator O(10 μm)
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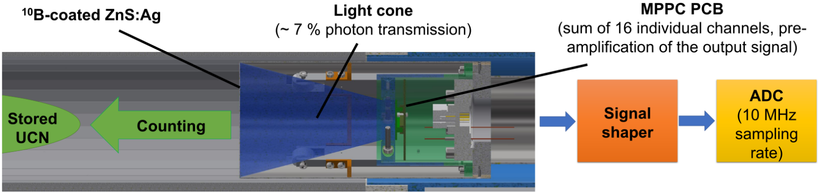
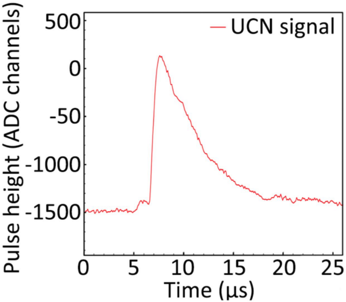
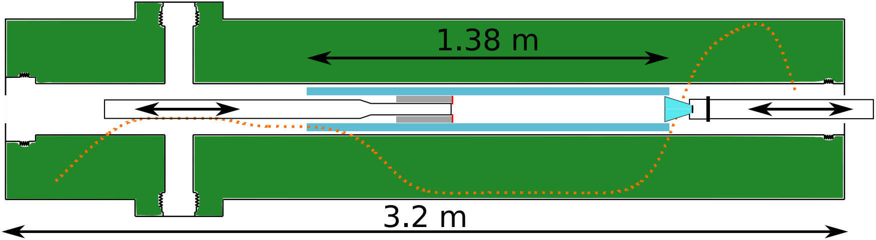
τSPECT Detector





PhD work of J. Kahlenberg

Measurement Procedure



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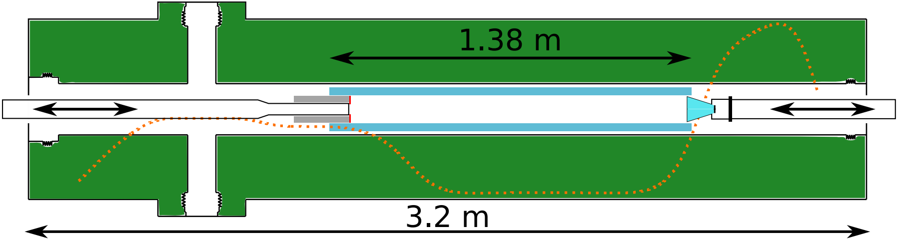

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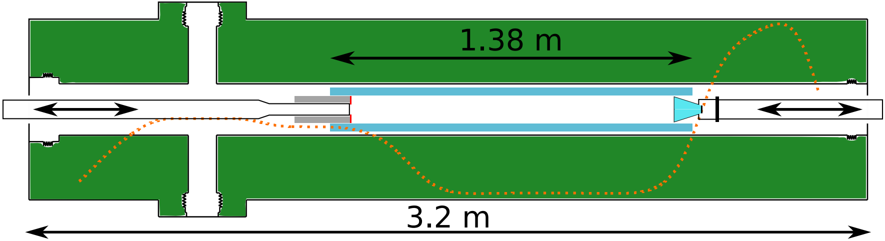

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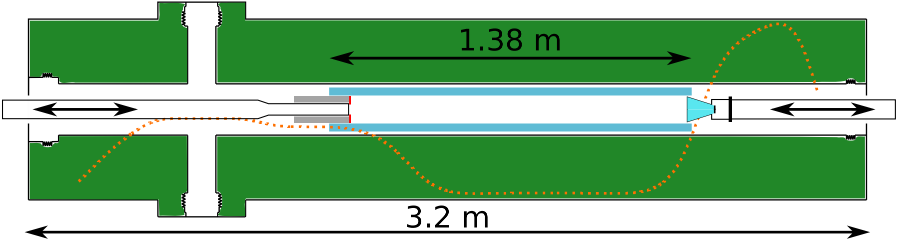

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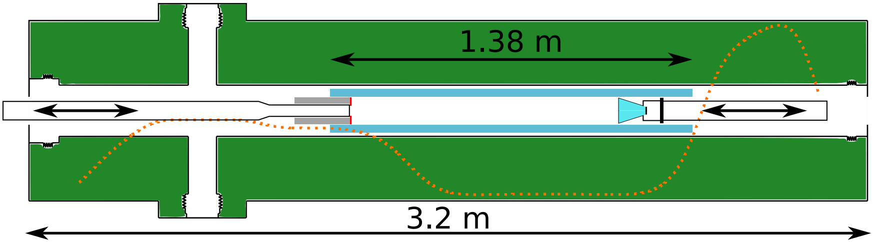

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4. Wait ...
5. Count UCN

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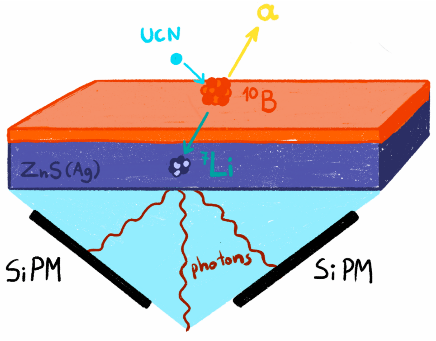

Illustrations: D. Kanta

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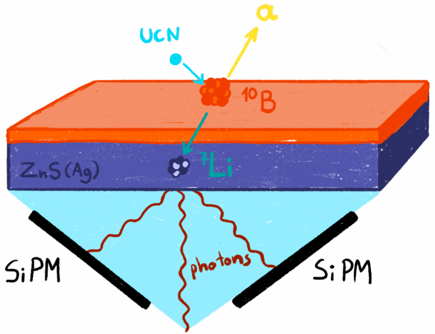

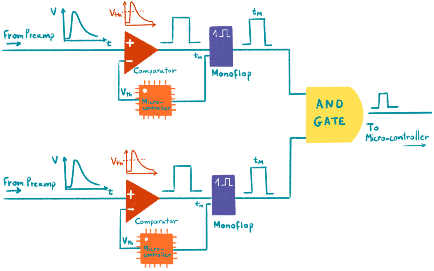

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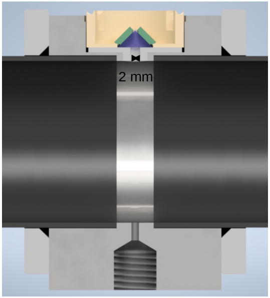

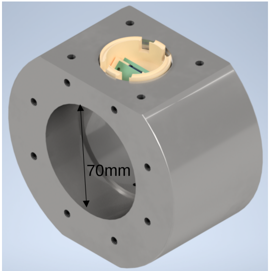

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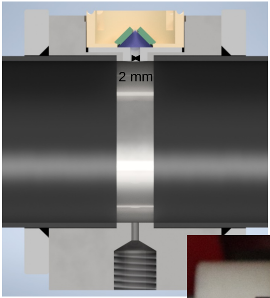

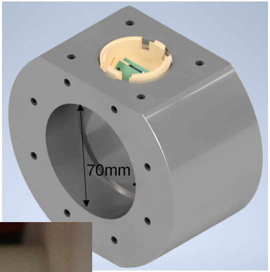

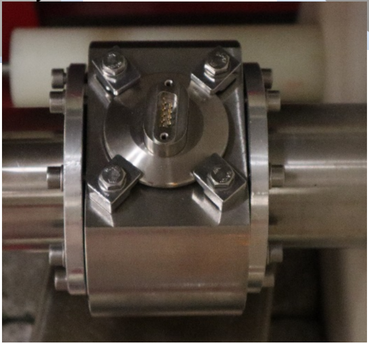

Systematics

- Gaps:
- Wall losses:

Systematics

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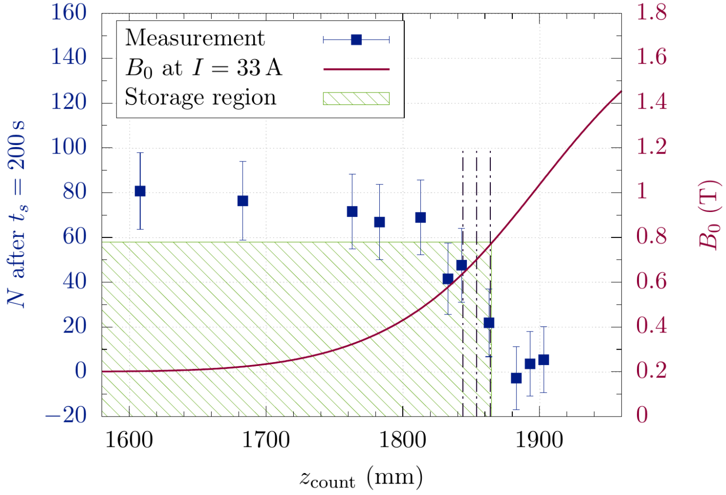
- Microphonic heating:
- Marginally trapped neutrons:

Systematics

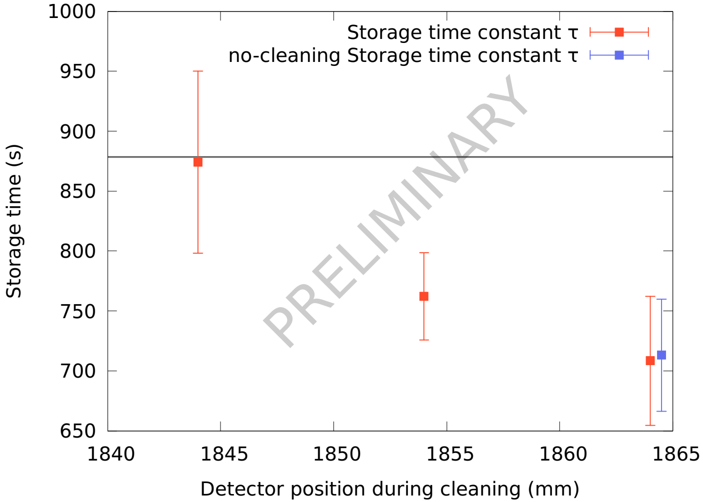
- Gaps: $\rightarrow 0$ ✓
- Wall losses: $\rightarrow 0$ ✓
- Depolarisation: $<< 0.1\,\mathrm{s}$ ✓
- Rest gas interactions: $\lesssim 0.1\,\mathrm{s}$ ✓
- Microphonic heating: Has not been observed, measure. ✓
- Marginally trapped neutrons: Spectrum cleaning necessary! ✓

Countermeasures



K. Ross

Countermeasures



Systematics Control

- Marginally trapped neutrons:
  - Clean spectrum with active detector before $t = 0$
  - Demonstrated to work
  - 2 parameters: position and duration
  - Too aggressive cleaning → lower statistics
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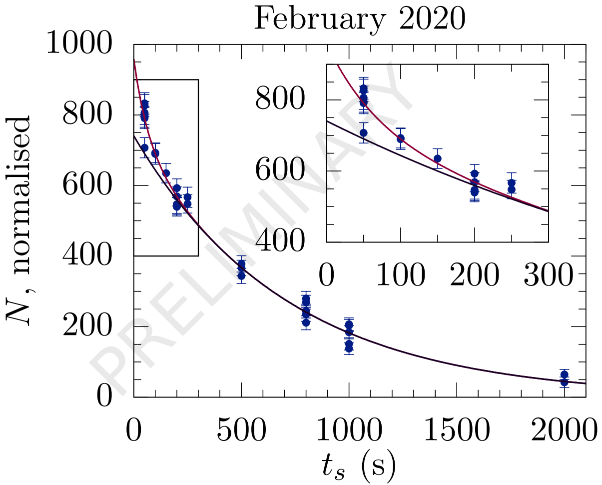
  - 2 parameters: position and duration
  - Too aggressive cleaning $\rightarrow$ lower statistics
  - Introduce asymmetry: τSPECT at a small tilt angle
- Microphonic heating:
  - Microphonic heating has not been observed
  - Can be measured via change in arrival time
  - Can be measured by "cleaning" again!
  - New τSPECT timing controller can do that.

Without Energy Spectrum Cleaning



Decay times:
Fast:
$\tau = 64.5\,\mathrm{s}$
Slow:
$\tau = 740(47)\,\mathrm{s}$

$\chi^2 = 1.6$

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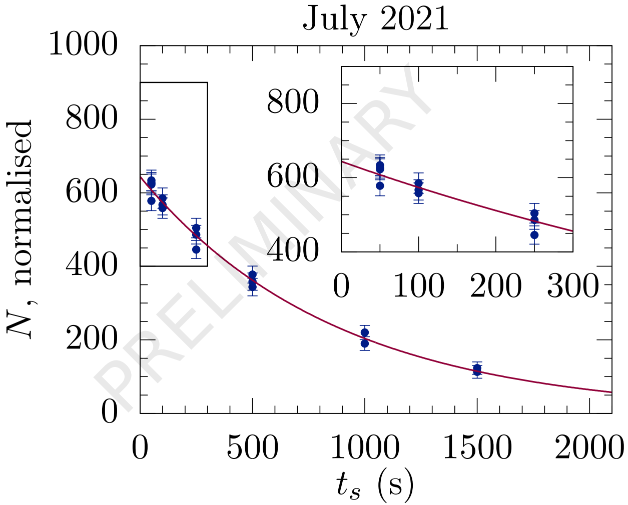
With Energy Spectrum Cleaning



Decay times:

$\tau = 869(29)\,\mathrm{s}$

$\chi^2 = 0.6$

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τSPECT at PSI

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Goal: Show statistical reach and systematics control for a physics run aiming for a precision of 0.3 s in the next years.

Future

- τSPECT still statistically limited at PSI.
- UCN source energy spectrum and guides not optimized
- next generation in preparation:
  - Larger volume 10 L to 60 L
  - Stronger magnets 1 T to 3 T
  - almost-4π loss detector on magnet inside
  - 0.1 s and below

Team

+ W. Heil & P. Blümler & B. Lauss & S. Vanneste

Team

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[2] Institute of Nuclear Chemistry, Johannes Gutenberg University Mainz, Germany
[3] Paul Scherrer Institute, Villigen, Switzerland

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Thank you for your attention!

Backup