Daniel J Salvat

The neutron lifetime problem: where do we stand?

INDIANA UNIVERSITY BLOOMINGTON

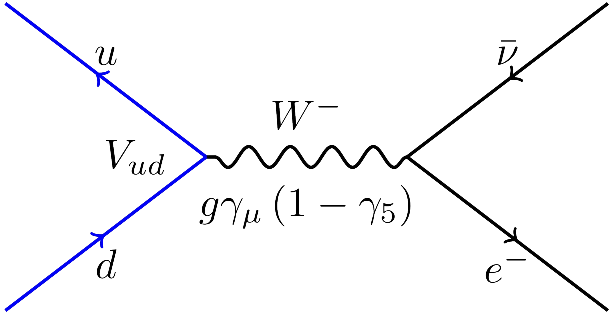
CONFXV 6 Aug 2022

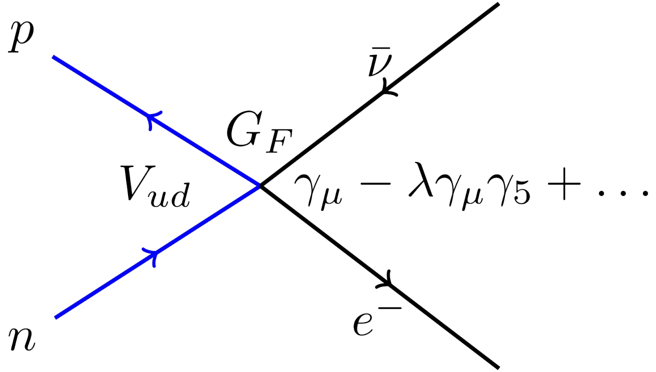
Neutron β-decay

	$g_A^{u,p}$	$g_A^{d,p}$	$g_A^{s,p}$
HERMES 2006	0.842(12)	$-0.427(13)$	$-0.085(18)$
χQCD 2018	0.847(37)	$-0.407(24)$	$-0.035(9)$
PNDME 2018	0.777(39)	$-0.438(35)$	$-0.053(8)$

- What do we know about the charges?
  - **Isospin symmetry**: $g_A^{u,p} = g_A^{d,n}$, $g_A^{d,p} = g_A^{u,n}$, $g_A^{s,p} = g_A^{s,n}$
  - Triplet from neutron decay: $g_A^{u,p} - g_A^{d,p} = g_A = 1.27641(56)$ PERKEO III 2018

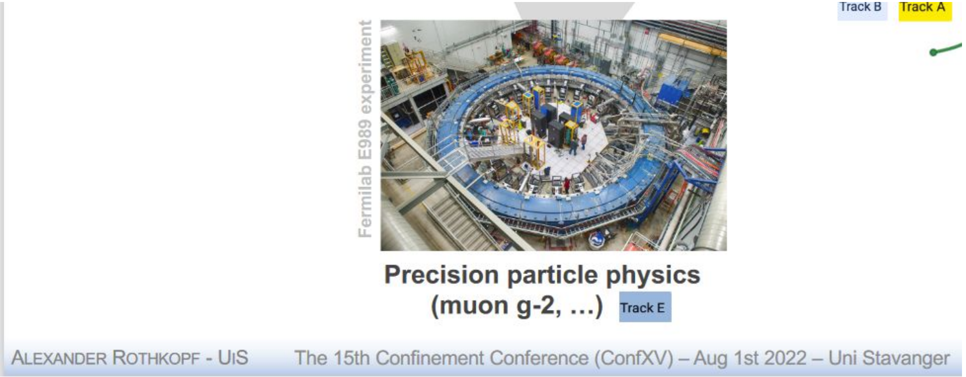
M. Hoferichter (Institute for Theoretical Physics) Neutrino physics: nuclear, EFTs, pheno, and lattice Aug 02, 2022 8



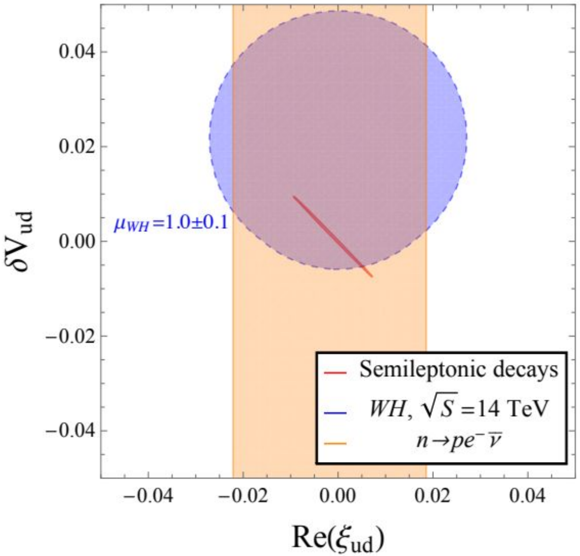


$$J^\mu = \bar{u}_n \left[g_V \gamma^\mu + \frac{g_M}{2M} \sigma^{\mu\nu} q_\nu + g_A \gamma^\mu \gamma_5 \right] u_p$$

Why neutron β-decay?

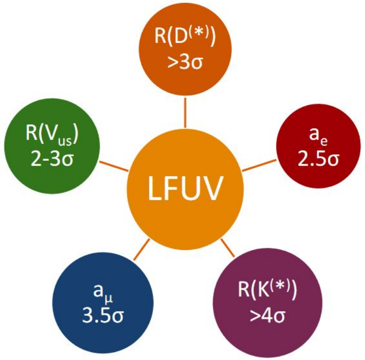


Right-handed charged currents in the era of the Large Hadron Collider



Beta decays as sensitive probes of lepton flavor universality

Andreas Crivellin[1,2] and Martin Hoferichter[3,4]



High-precision measurement of the *W* boson mass with the CDF II detector

CDF COLLABORATION†‡, T. AALTONEN, S. AMERIO, D. AMIDEI, A. ANASSTASSOV, A. ANNOVI, J. ANTOS, G. APOLLINARI, J. A. APPEL, [...] S. ZUCCHELLI +389 authors

Authors Info & Affiliations

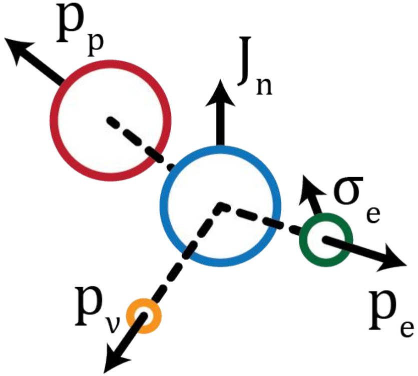
Beta-decay implications for the W-boson mass anomaly

Vincenzo Cirigliano,[a] Wouter Dekens,[a] Jordy de Vries,[b,c] Emanuele Mereghetti,[d] Tom Tong[e]

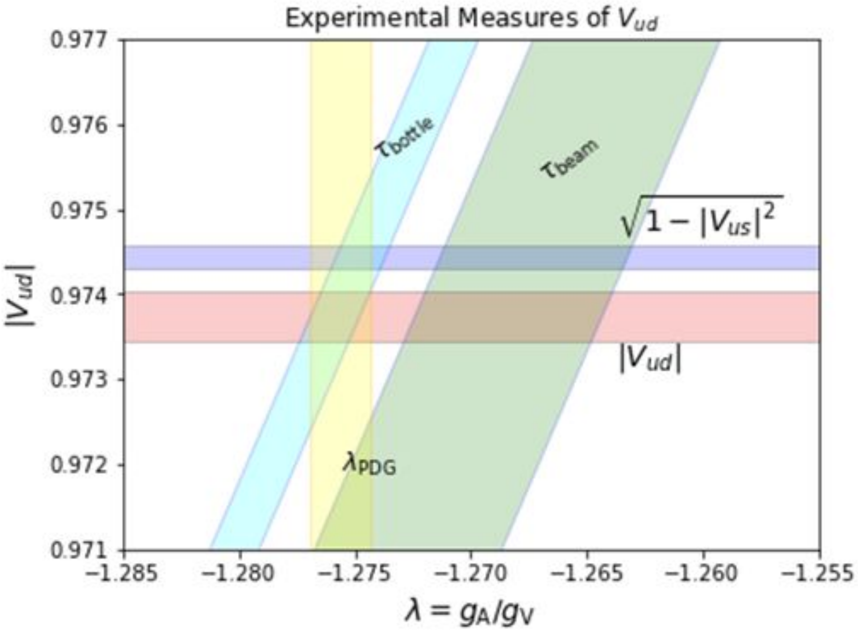
The axial coupling

$$J^\mu = \bar{u}_n \left[g_V \gamma^\mu + \frac{g_M}{2M} \sigma^{\mu\nu} q_\nu + g_A \gamma^\mu \gamma_5 \right] u_p$$

$$\tau_n^{-1} = \frac{|V_{ud}|^2 \left(1+3\lambda^2\right)\left(1+\Delta_R\right)}{5099.3\ \mathrm{s}}$$



$$A = -2\frac{\lambda(\lambda+1)}{1+3\lambda^2}$$



Letter | Published: 30 May 2018

A per-cent-level determination of the nucleon axial coupling from quantum chromodynamics

C. C. Chang, A. N. Nicholson, E. Rinaldi, E. Berkowitz, N. Garron, D. A. Brantley, H. Monge-Camacho, C. J. Monahan, C. Bouchard, M. A. Clark, B. Joó, T. Kurth, K. Orginos, P. Vranas & A. Walker-Loud

Nature **558**, 91–94 (2018) | Cite this article

Radiative corrections and hadronic physics

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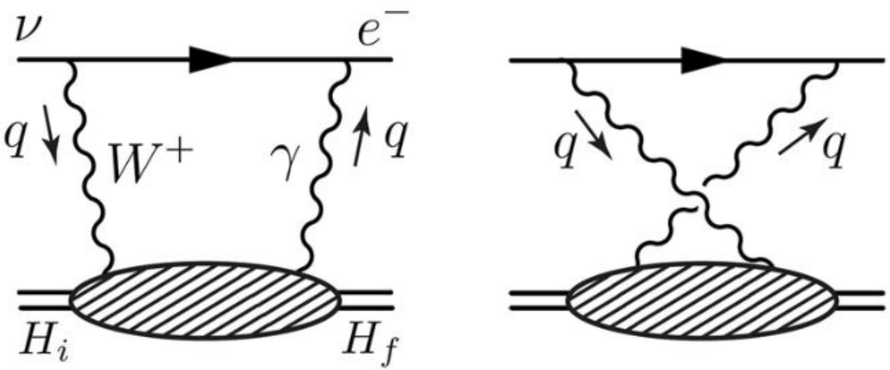
QCHS22, Stavanger

non–perturbative calculations of radiative corrections in weak decays

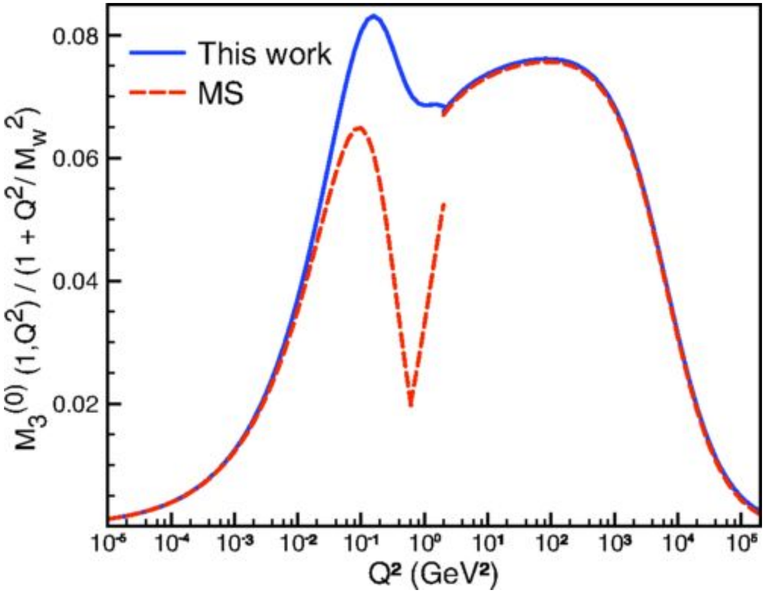


Reduced Hadronic Uncertainty in the Determination of V_{ud}

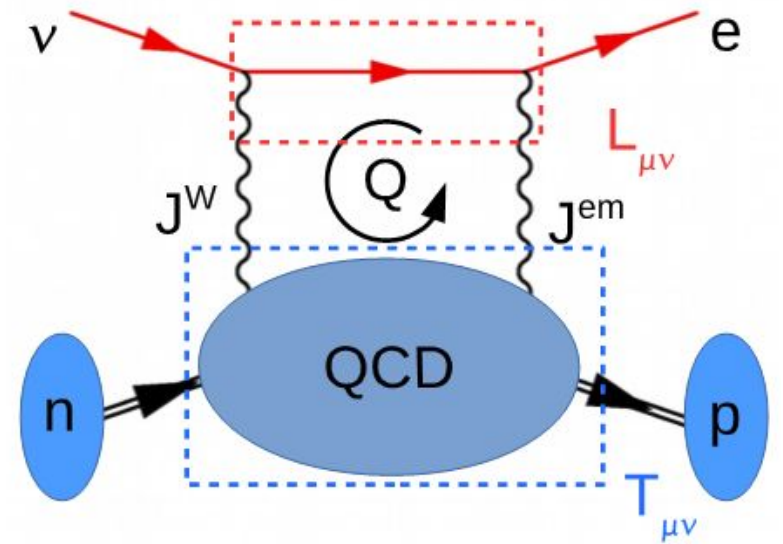
Chien-Yeah Seng, Mikhail Gorchtein, Hiren H. Patel, and Michael J. Ramsey-Musolf
Phys. Rev. Lett. **121**, 241804 – Published 14 December 2018

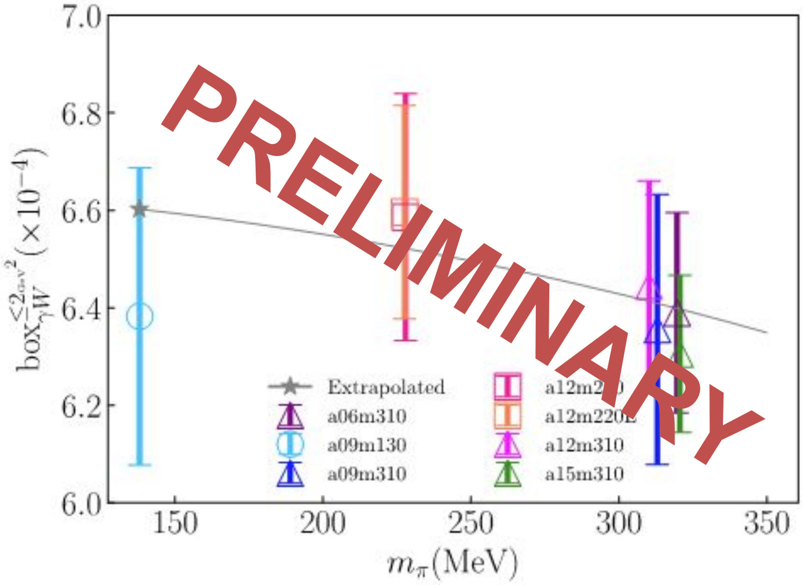
Dispersive evaluation of the inner radiative correction in neutron and nuclear β decay

Chien-Yeah Seng, Mikhail Gorchtein, and Michael J. Ramsey-Musolf
Phys. Rev. D **100**, 013001 – Published 16 July 2019



Radiative correction from lQCD at LANL

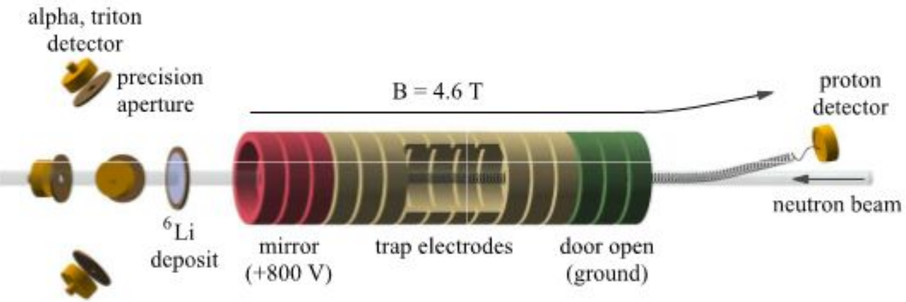




- Have calculated γW-box diagram for pion decay 2.819(28)×10^{-3} [J. Yoo, *et al.*, in prep] consistent with Xu Feng, et al, PRL124, (2020) 192002
- Simulations of γW-box diagram for neutron decay are in progress

The "beam" and "bottle" techniques

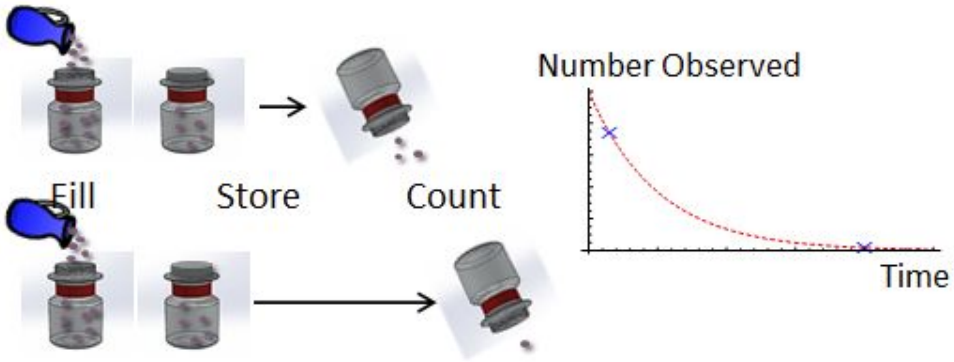
$$\tau_n = \frac{L}{v_n}\frac{\dot{N}_n/\epsilon_n}{\dot{N}_p/\epsilon_p}$$



"It sounds hard, and it is hard"
Geoff Greene

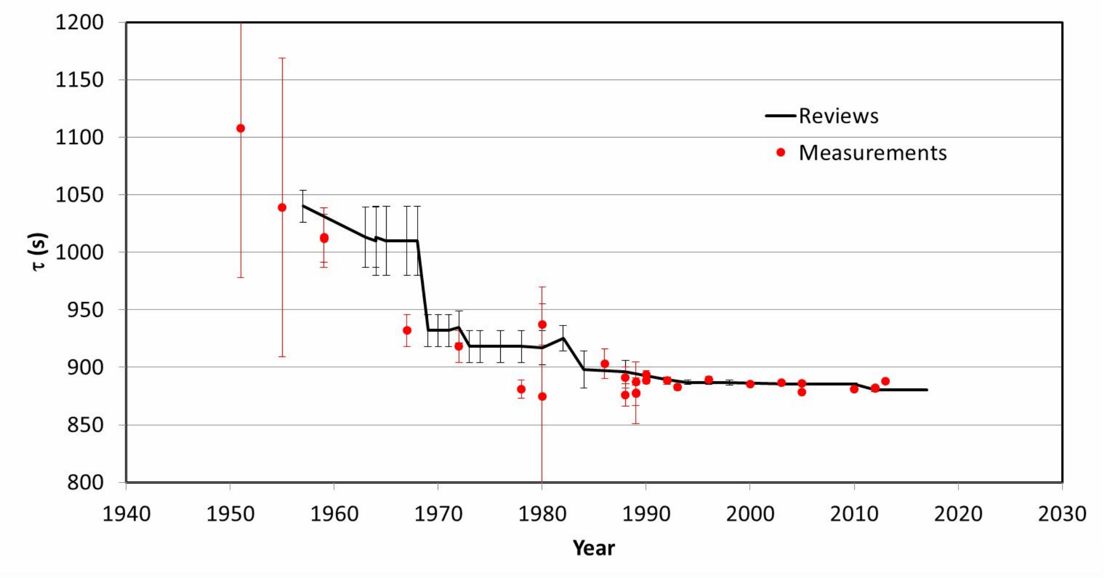
$$Y(t) = Y_0 e^{-t/\tau_{meas}}$$

$$\tau_{meas}^{-1} = \tau_n^{-1} + \tau_{loss}^{-1}$$

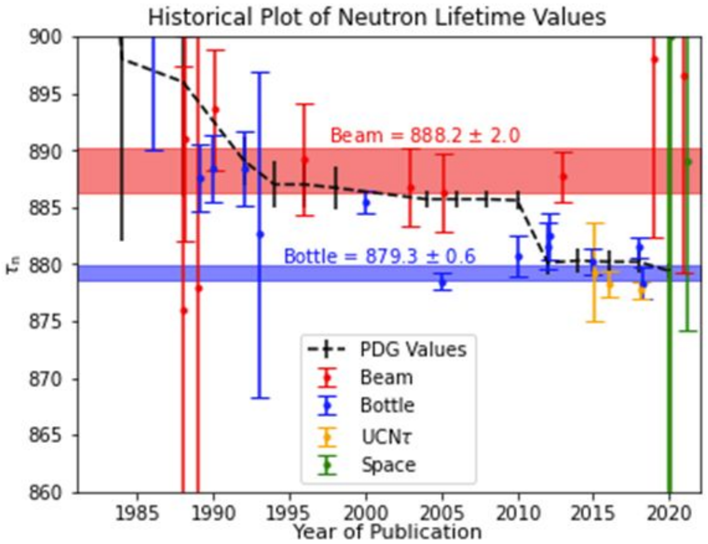


"It sounds easy, and it is hard"
Geoff Greene

A problem

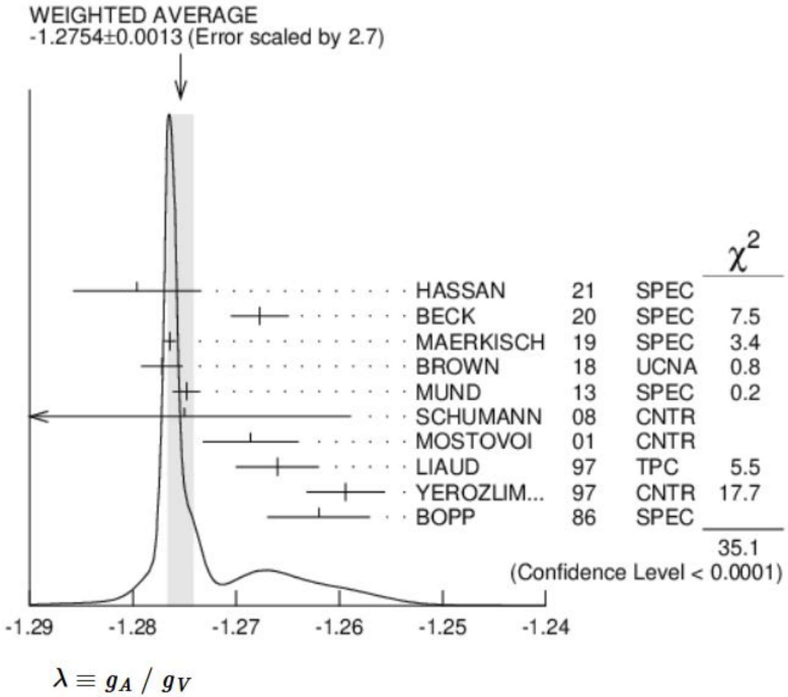


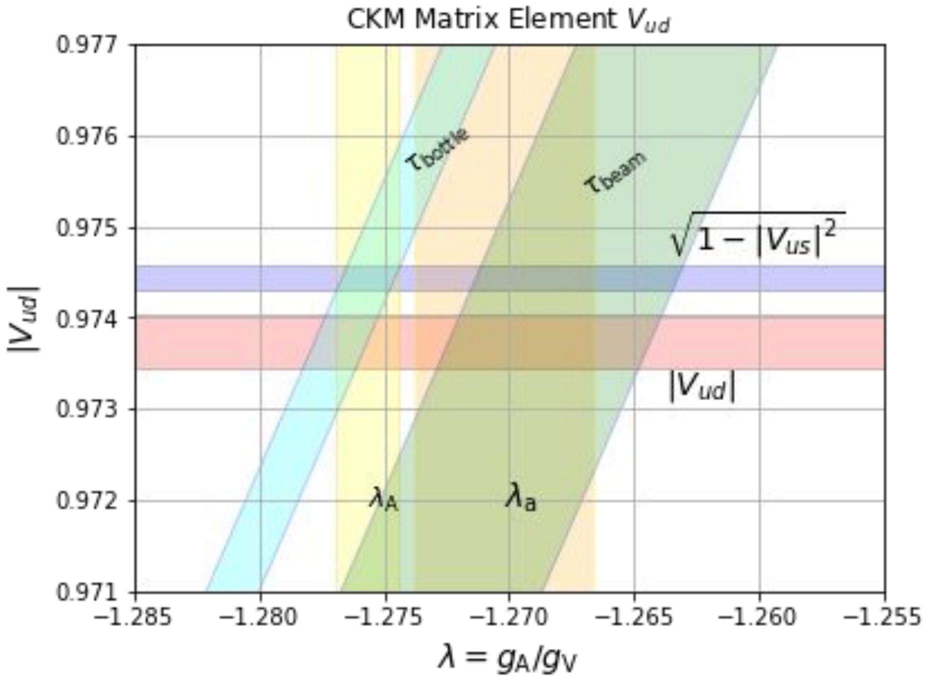
Reviews
Measurements
τ (s)
Year
1200
1150
1100
1050
1000
950
900
850
800
1940
1950
1960
1970
1980
1990
2000
2010
2020
2030



Historical Plot of Neutron Lifetime Values
Beam = 888.2 ± 2.0
Bottle = 879.3 ± 0.6
PDG Values
Beam
Bottle
UCNτ
Space
τn
Year of Publication
900
895
890
885
880
875
870
865
860
1985
1990
1995
2000
2005
2010
2015
2020

More problems





Tackling the problem

Connections Between
QCD & BSM Physics

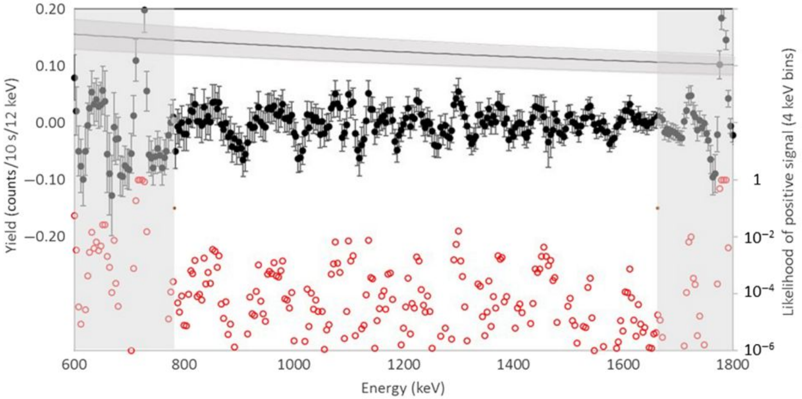
Susan Gardner

Department of Physics and Astronomy
University of Kentucky
Lexington, KY

$n \to \chi\gamma; n \to \chi\chi\chi; nn \to \chi\chi \;....$

PHYSICAL REVIEW LETTERS **121**, 022505 (2018)

Search for the Neutron Decay $n \to X + \gamma$, Where X is a Dark Matter Particle



PHYSICAL REVIEW C **97**, 052501(R) (2018)

Rapid Communications

Search for dark matter decay of the free neutron from the UCNA experiment: $n \to \chi + e^+e^-$

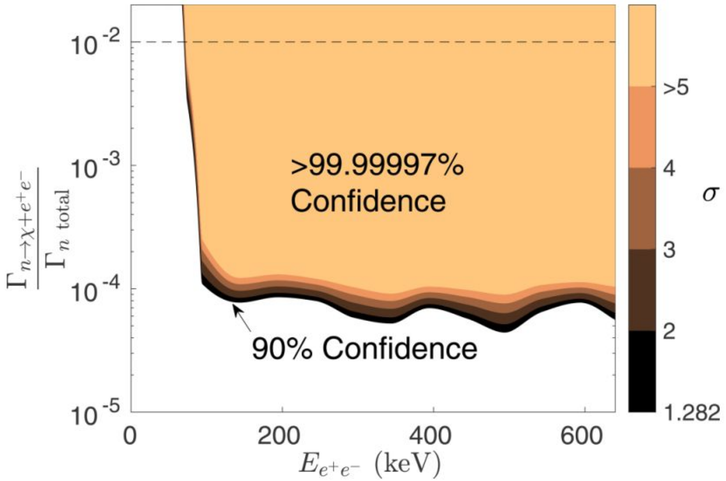


FIG. 5. Confidence limits on the branching ratio of the neutron dark decay channel, as a function of the kinetic energy of the produced e^+e^- pair. This is directly related to the proposed χ mass by $m_\chi = m_n - 2m_e - E_{e^+e^-}$, which has a range of $937.900 < m_\chi < 938.543$ MeV. A branching ratio of 10^{-2}, which would be required to explain the neutron lifetime anomaly if $n \to \chi + e^+e^-$ were the only allowed final state, is shown by the dashed line.

Where do we stand (rhetorically)?

Chess-playing robot breaks young boy’s finger during match in Moscow

PUBLISHED MON, JUL 25 2022•3:22 PM EDT

NBC NEWS | Dylan Butts and Tatyana Chistikova

The incident happened after the boy hurried the artificial intelligence-powered robot, the president of the Moscow Chess Federation told the Russian state news agency Tass. “The robot broke the child’s finger — this, of course, is bad,” Sergey Lazarev said.

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"Recent neutron decay experiments broke the Standard Model – this, of course, is bad." I said.

Where do we stand (rhetorically)?

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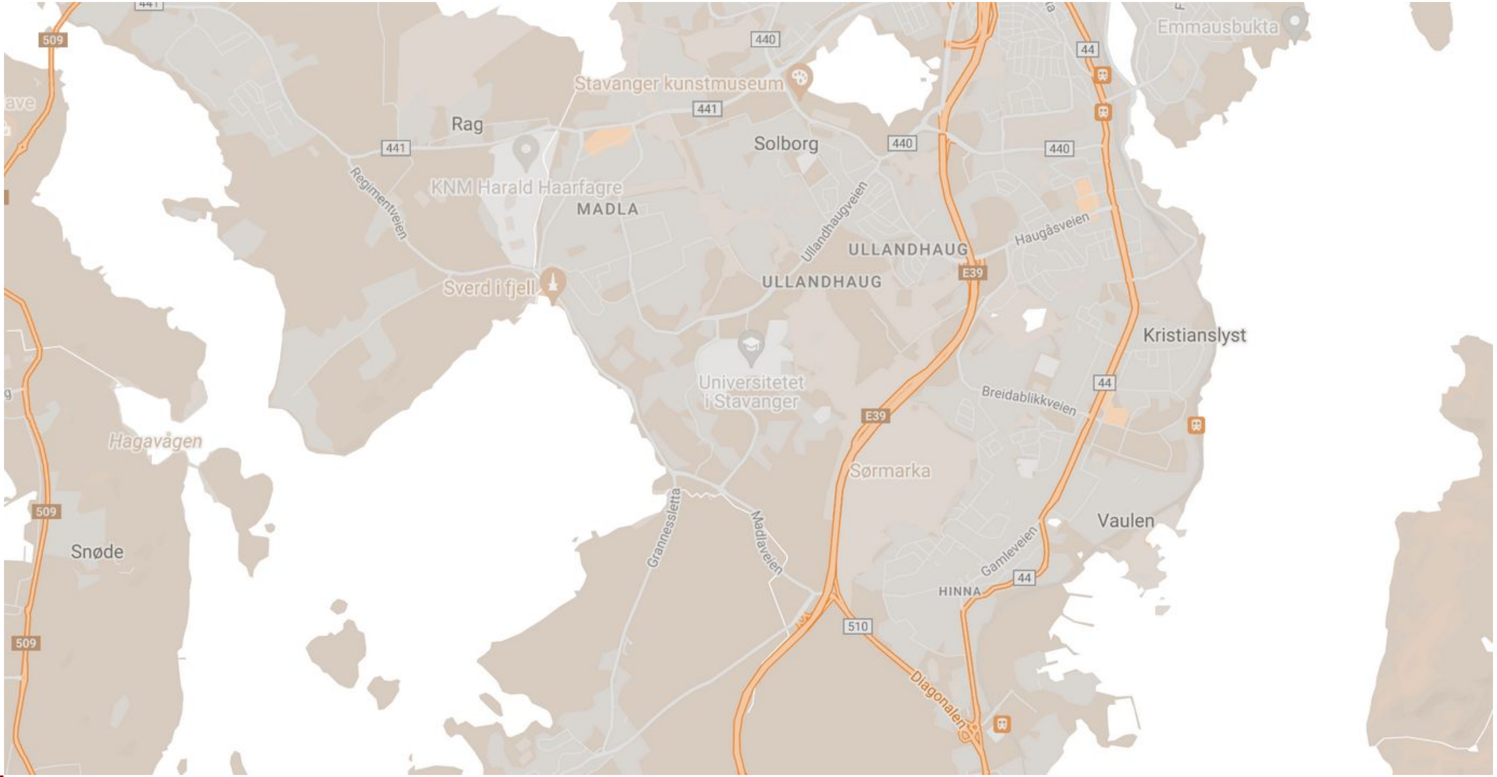
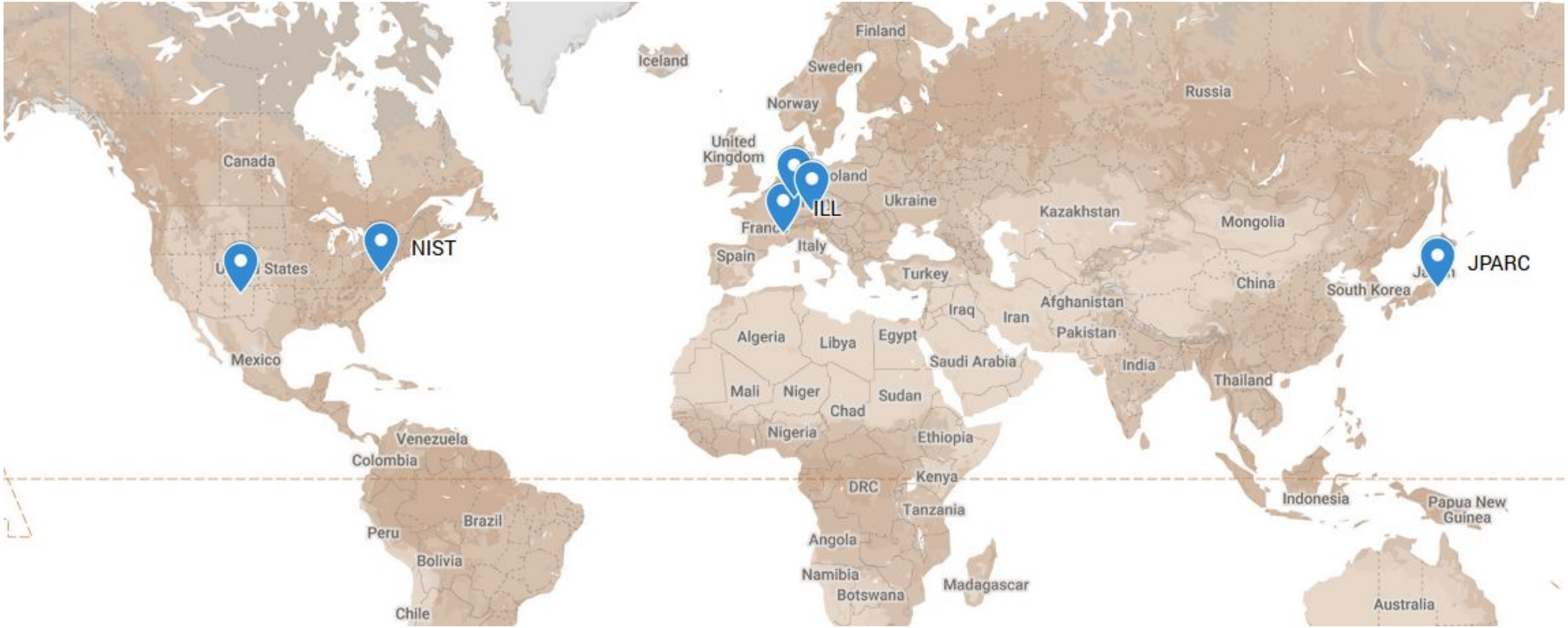
"Recent neutron decay experiments broke the Standard Model – this, of course, is bad…" I said.

"...but," I continued, "advancements in the assessment of electroweak radiative corrections and diverse experimental efforts promise to resolve the problem and probe BSM physics."

Where do we stand (geographically)?

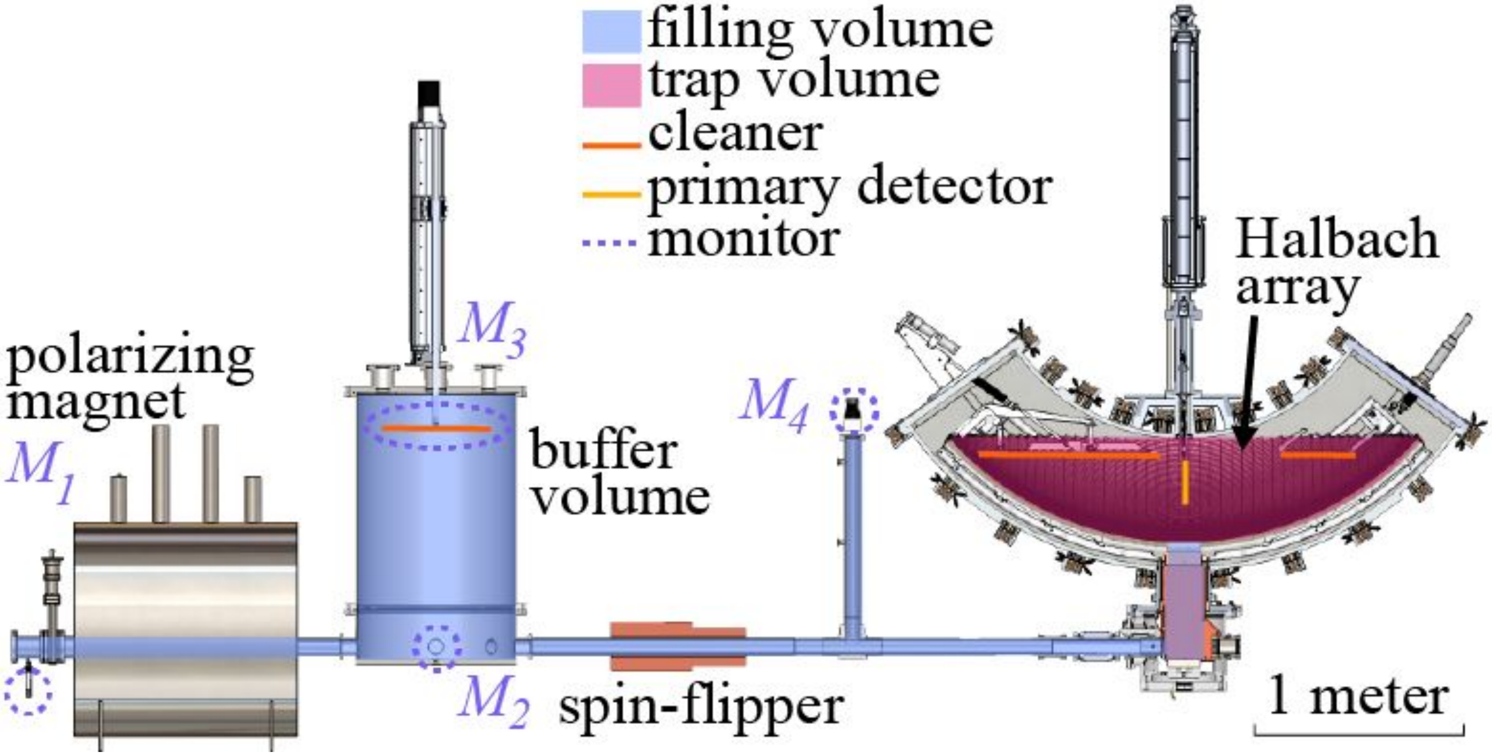


Where do we stand (geographically)?



Where do we stand (geographically)?

The UCNτ experiment



Three analyses


Frank Gonzalez
(IU)


Eric Fries
(Caltech)

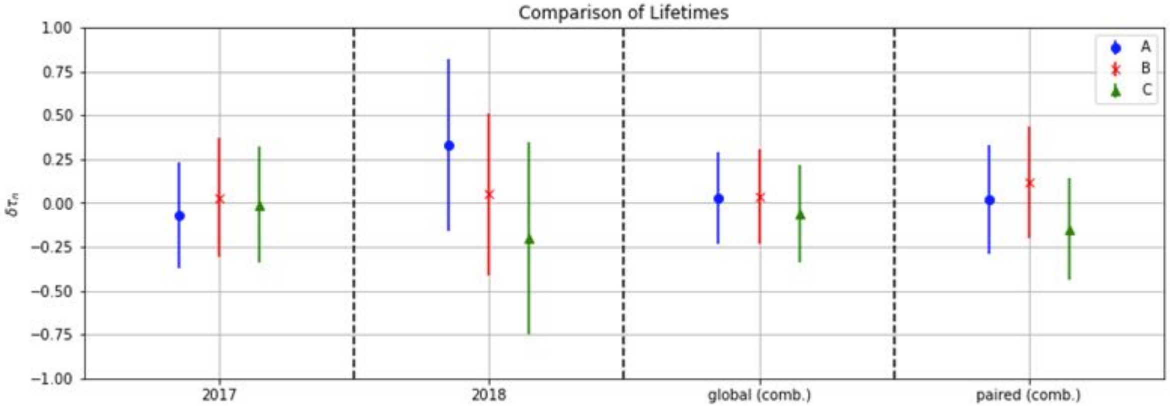

Chris Morris
(LANL)

Blinded data:

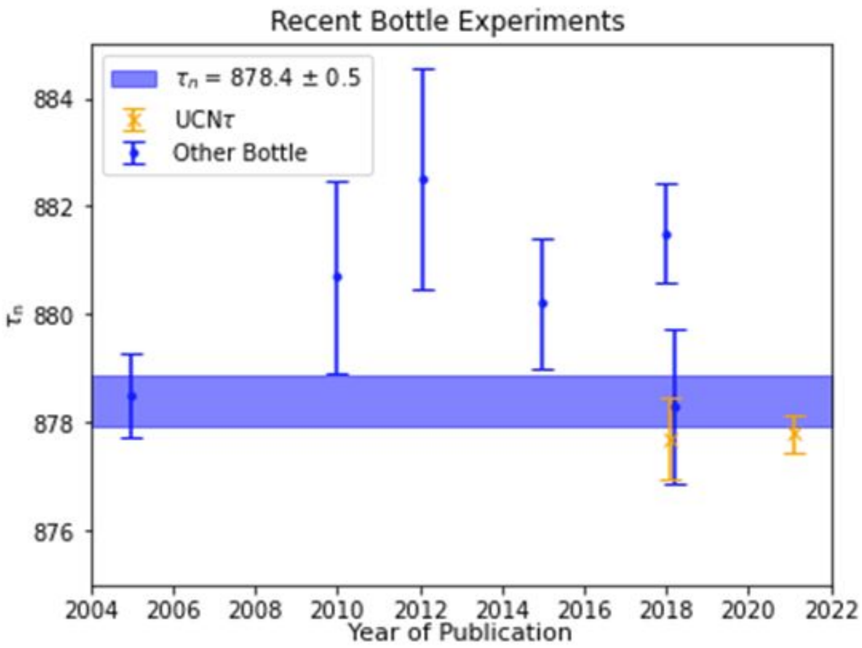
- Holding time is modified
- blinded by up to ±15 s

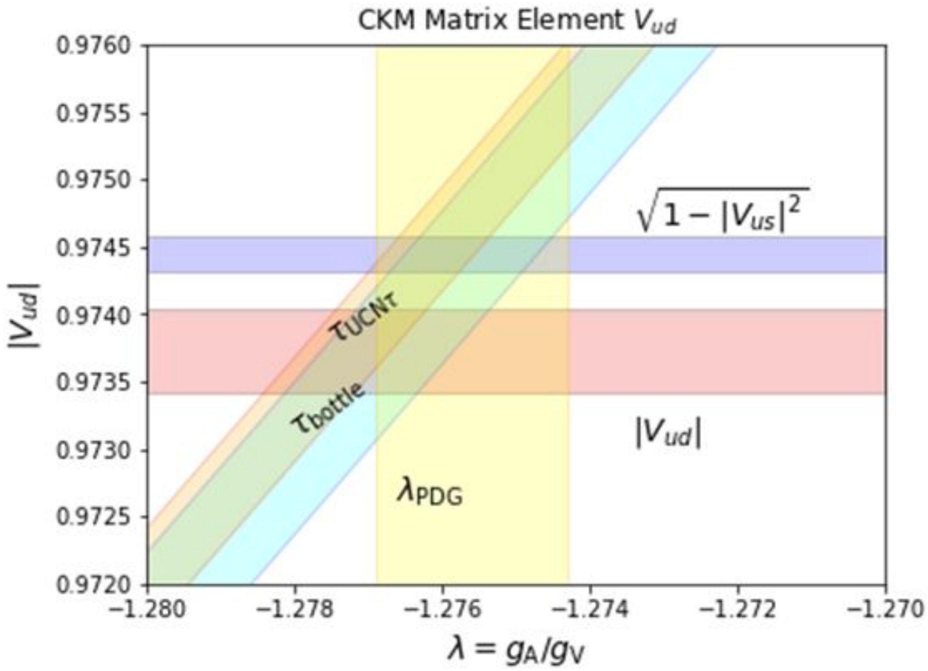
Unblinding Criteria:

- Three complete (statistical and systematic) analyses
- After cross-checking analyses, take unweighted average, use largest uncertainties



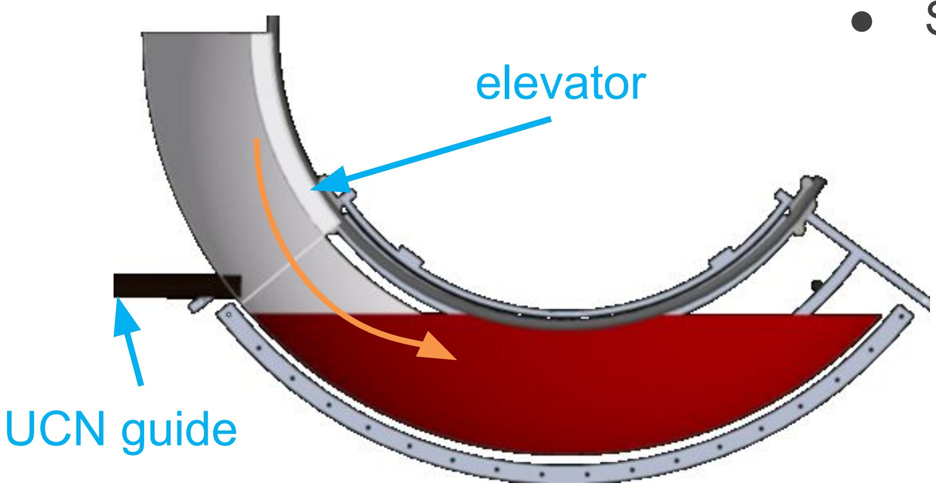
877.75 seconds

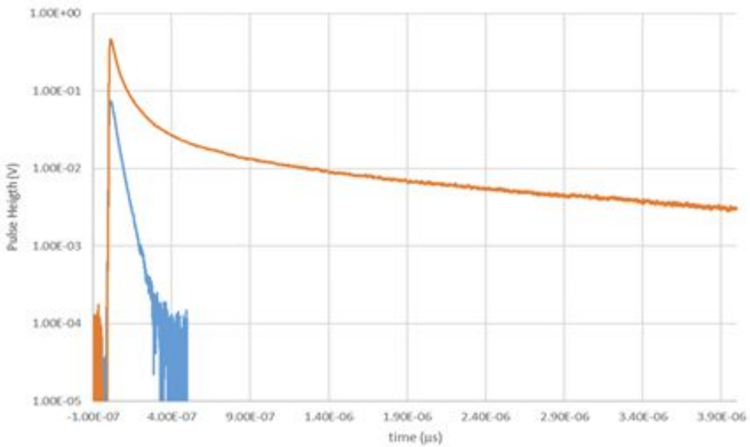




UCNτ+ and UCNA+

- New Loading Mechanisms to maximize statistics
- Anticipate 10× counts
- New detectors to count UCN faster and mitigate rate dependent effects
- Faster scintillator (LYSO, plastic)
- Segmented SiPM-based detector

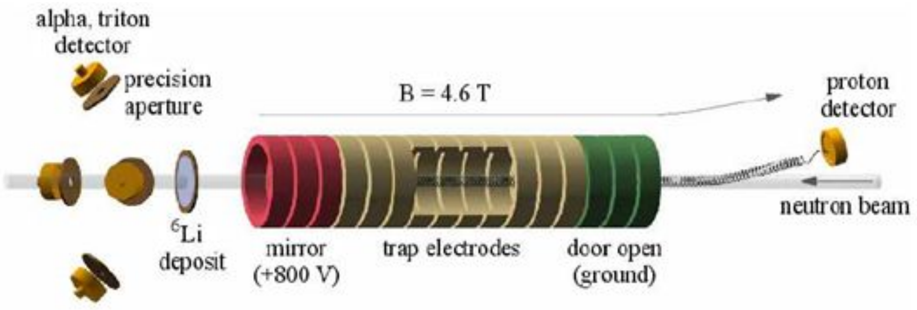




Bring UCNτ+ to a lifetime sensitivity of $\Delta\tau$<0.15s *from Nadia Fomin*

The BL2 experiment at NIST

- Data taking with Mark II trap complete
  - Mark III trap was installed right before unplanned NCNR outage
- Cold Source Upgrade timeline limits remaining data taking

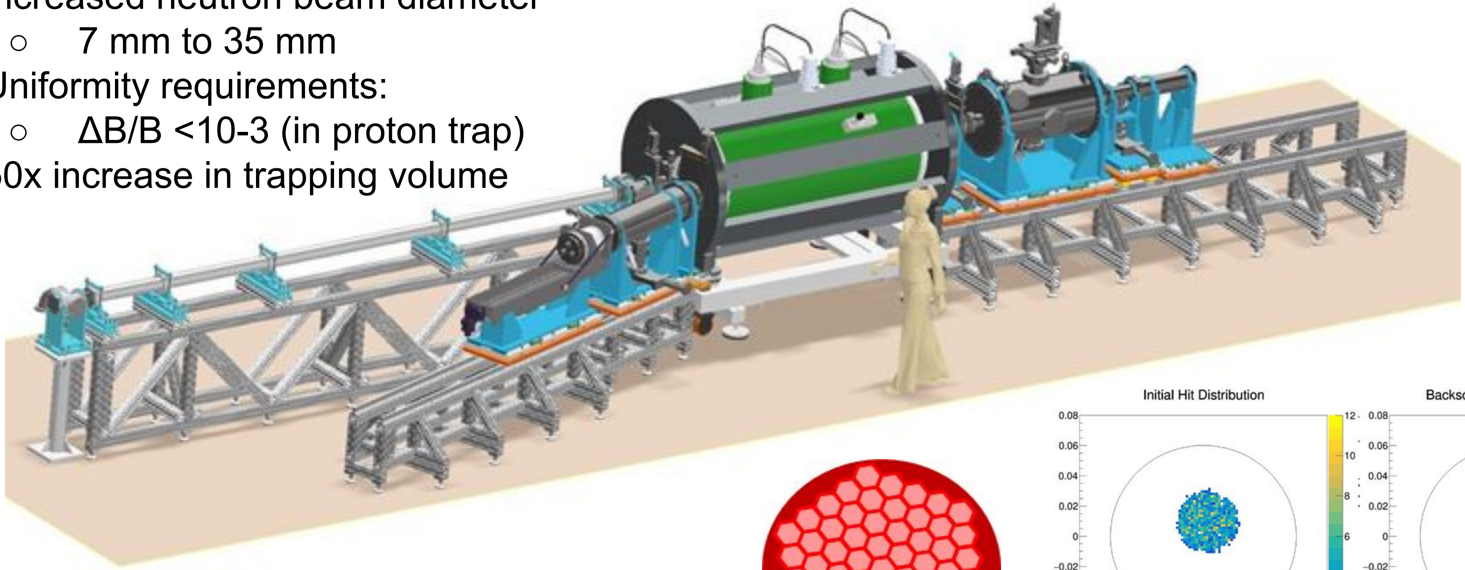


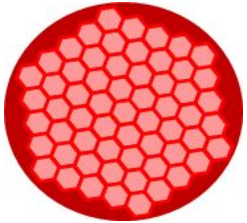
- Neutron flux monitor efficiency – 2.7s
  - Alpha-Gamma technique (0.5s)
- Neutron absorption by 6Li – .8s
  - Measured neutron spectrum, thinner foils (0.6s)
- Neutron beam halo – 1.0s
  - Larger proton detector, simulation, better imaging methods (0.2s)
- Electrode trap nonuniformity – 0.8s
  - Use 9 electrodes, Mark 3 trap (0.2s)
- Proton counting statistics – 1.2s
  - Larger neutron flux, longer run time, more stable detection system (TBD)

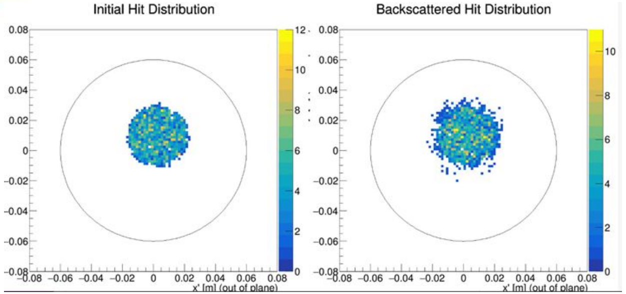
from Nadia Fomin

The BL3 experiment

- Increased neutron beam diameter
  - 7 mm to 35 mm
- Uniformity requirements:
  - ΔB/B <10-3 (in proton trap)
- 50x increase in trapping volume

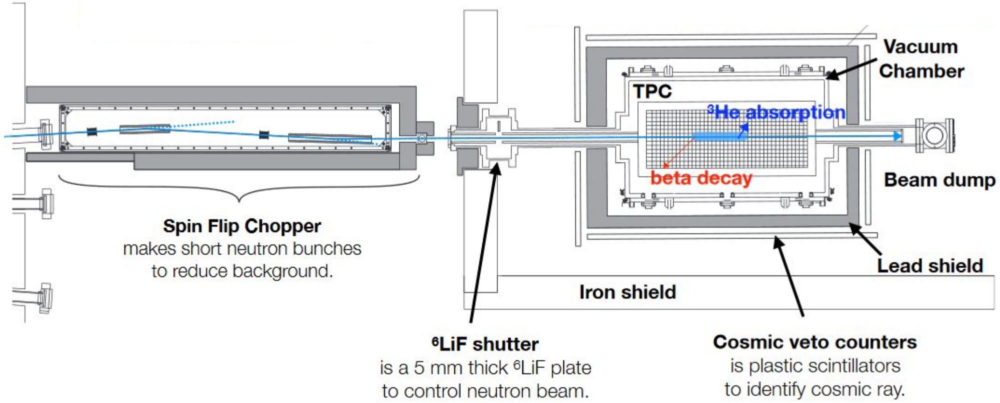






Successful project review at NSF completed – recommended for full funding!

The JPARC TPC

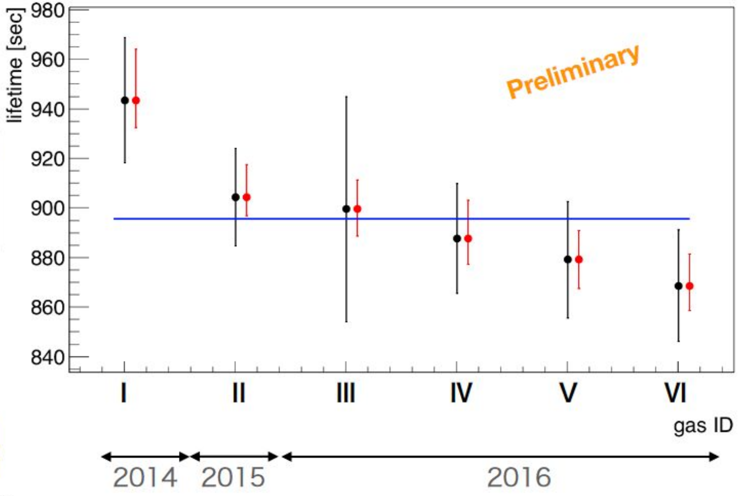


↓ Data analysis

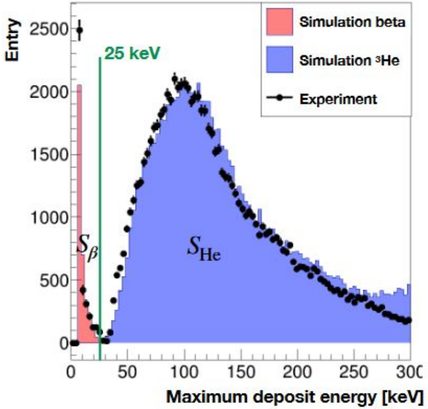
$$\tau_n = \frac{1}{\rho\sigma v}\left(\frac{S_{\mathrm{He}}/\varepsilon_{\mathrm{He}}}{S_\beta/\varepsilon_\beta}\right)$$

Injected ³He ↑ ↑Literature value 5333 ± 7 barn 2200 m/s ↑ Simulation analysis

$$\tau_n = 896 \pm 10\,(\mathrm{stat})\,{}^{+14}_{-10}\,(\mathrm{syst})\ \mathrm{sec}$$



- beam optics upgrade (5x stats)
- low-P operation, improved amps
- solenoid for background suppression



The gravitrap at the ILL

- Only remaining material bottle experiment
- lifetime of $881.5(0.7)_{stat}(0.6)_{syst}$ s (3.2σ higher than 2008)
- Plans to cool to *10* K, repeat measurement

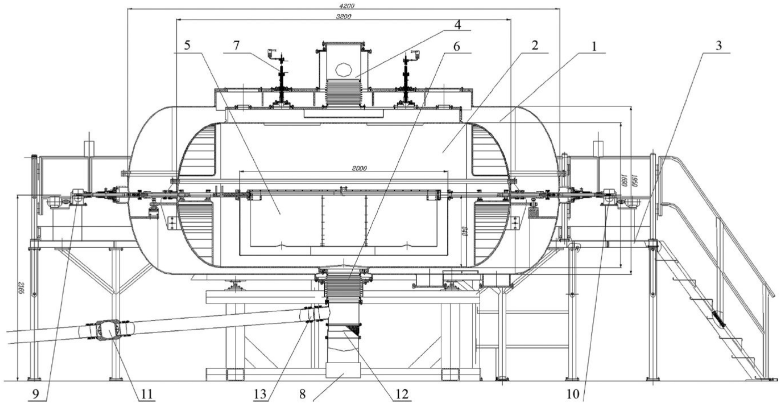


FIG. 2. 1 external vacuum vessel, 2–internal vacuum vessel, 3–platform for service, 4–gear for pumping out internal vessel, 5–trap with insert in low position, 6–neutron guide system, 7–system of coating of trap and insert, 8–detector, 9–mechanism for turning trap, 10–mechanism for turning insert, 11–turbine shutter, 12–detector shutter, 13–neutron guide shutter.

$$\tau_{st}^{-1}(E) = \tau_n^{-1} + \tau_{\text{loss}}^{-1}(E) \qquad \tau_{\text{loss}}^{-1} = \eta(T)\gamma(E)$$

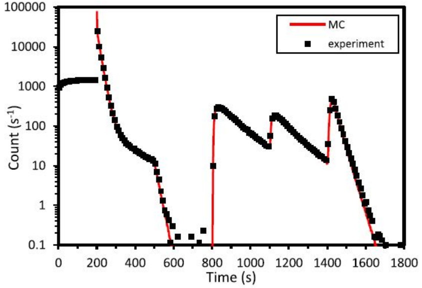


FIG. 5. Simulated and measured UCN registered by the detector.

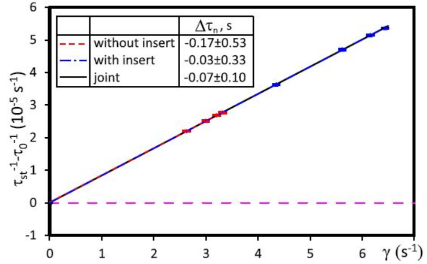


FIG. 7. The results of the MC model self-consistence test.

PHYSICAL REVIEW C **97**, 055503 (2018)

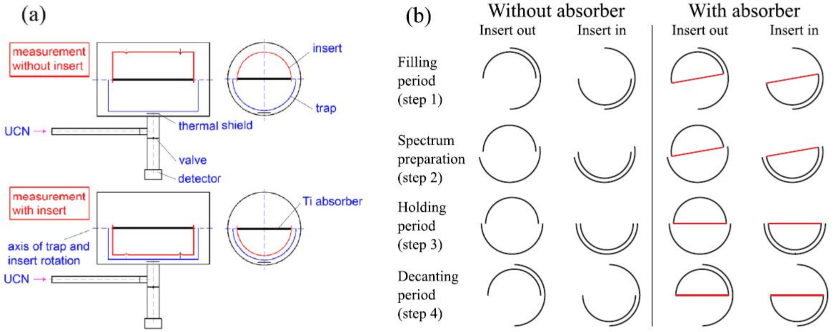


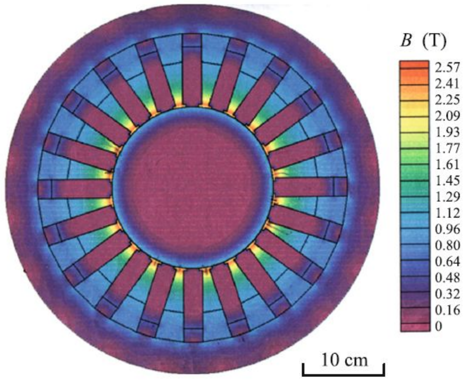
FIG. 1. Basic scheme of inner part of the apparatus (a) with conceptual scheme for the measuring procedures (b)

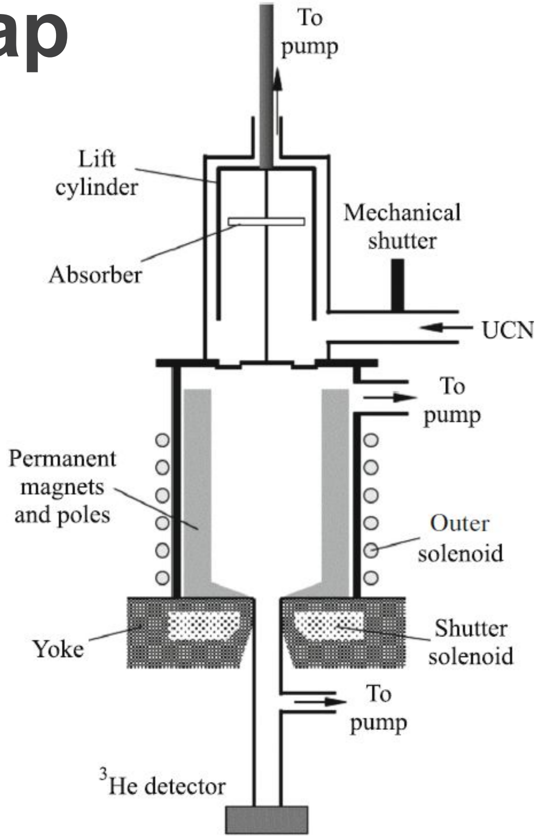
Neutron lifetime measurements with a large gravitational trap for ultracold neutrons

A. P. Serebrov,[1,*] E. A. Kolomensky,[1] A. K. Fomin,[1] I. A. Krasnoshchekova,[1] A. V. Vassiljev,[1] D. M. Prudnikov,[1] I. V. Shoka,[1] A. V. Chechkin,[1] M. E. Chaikovskiy,[1] V. E. Varlamov,[1] S. N. Ivanov,[1] A. N. Pirozhkov,[1] P. Geltenbort,[2] O. Zimmer,[2] T. Jenke,[2] M. Van der Grinten,[3] and M. Tucker[3]

The ILL magneto-gravitational trap

- Permanent magnet Halbach array, regular conducting coils
- Novel “elevator” loading system
- 3.7 s extrapolation to final result from known UCN losses due to spin flips. Monitored *in situ* with the detector
    - lifetime of *878.3(1.6)(1.0)* s
- A new trap with increased volume has been proposed





FIELDS, PARTICLES, AND NUCLEI

Measurement of the Neutron Lifetime with Ultracold Neutrons Stored in a Magneto-Gravitational Trap[1]

V. F. Ezhov[a, b, *], A. Z. Andreev[a], G. Ban[c], B. A. Bazarov[a], P. Geltenbort[d], A. G. Glushkov[a], V. A. Knyazkov[a], N. A. Kovrizhnykh[e], G. B. Krygin[a], O. Naviliat-Cuncic[c, f], and V. L. Ryabov[a]

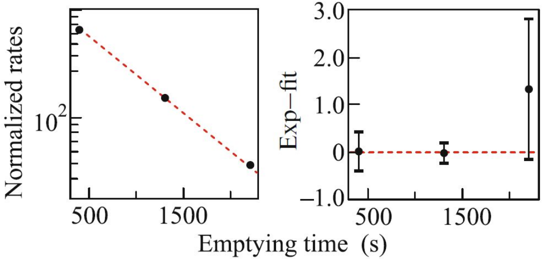
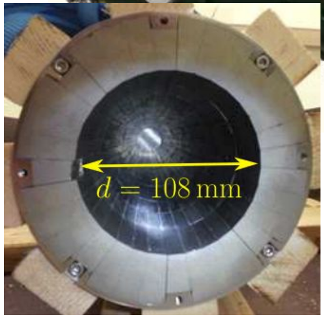
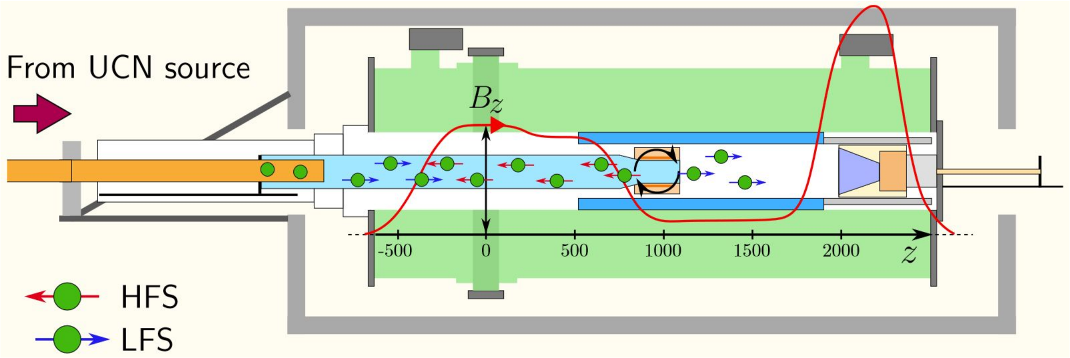


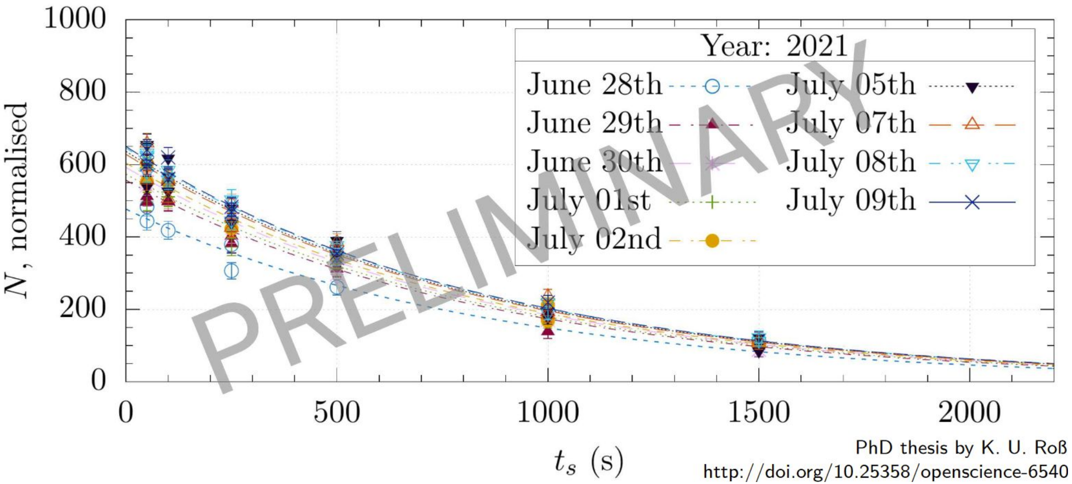
Fig. 3. (Color online) (a) Normalized rates and fit from run A. (b) Differences between experimental data and fit.

from Kim Ulrike Ross

τSPECT in Mainz







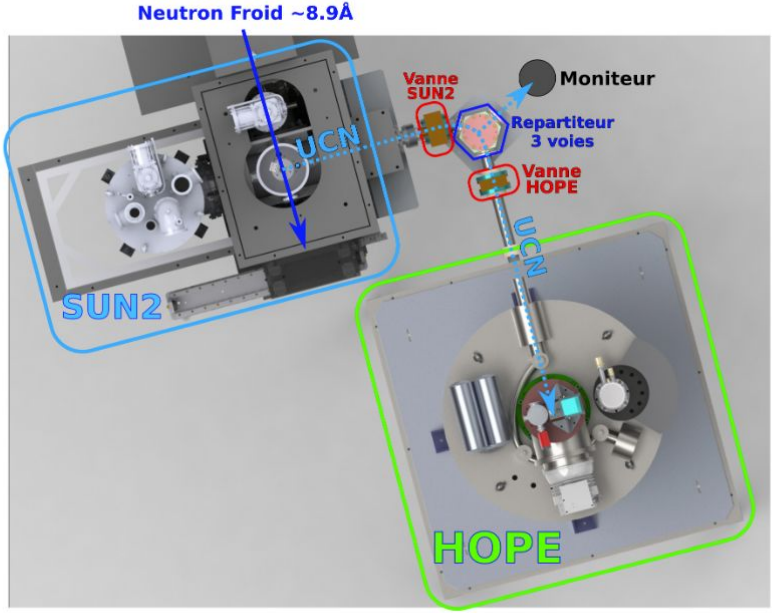
$$\tau = 858.6(15.5)\,\mathrm{s}\ (\chi^2/\mathrm{ndf} = 1.14,\ \mathrm{ndf} = 109)$$

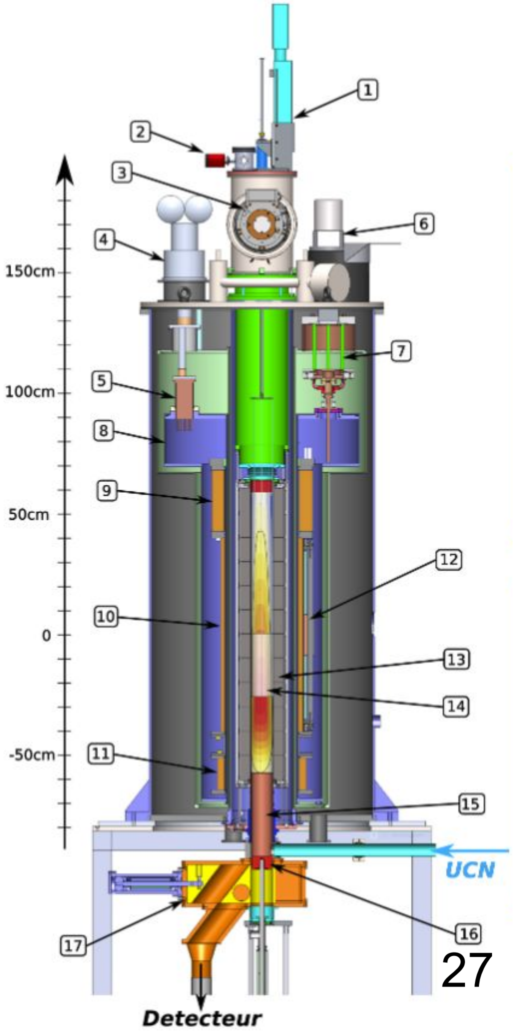
- 10L octupole trap using former aSPECT solenoids
- Novel spin-flip loading scheme
- Moveable *in situ* detector
- First results forthcoming, need to address quasi-stable neutron trajectories

Loris Babin, PhD dissertation (2019)

HOPE at the ILL

- Permanent magnet octupole, superconducting end coils
- Preliminary storage time measurements of 899(19) s and 882(17) s
- Expect sub-second stat error per reactor cycle
- Changing to horizontal configuration with regular conducting coils, larger trap volume and reduced vibration

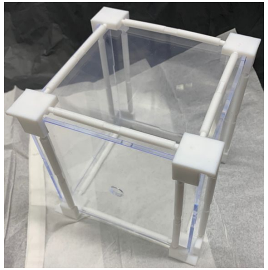


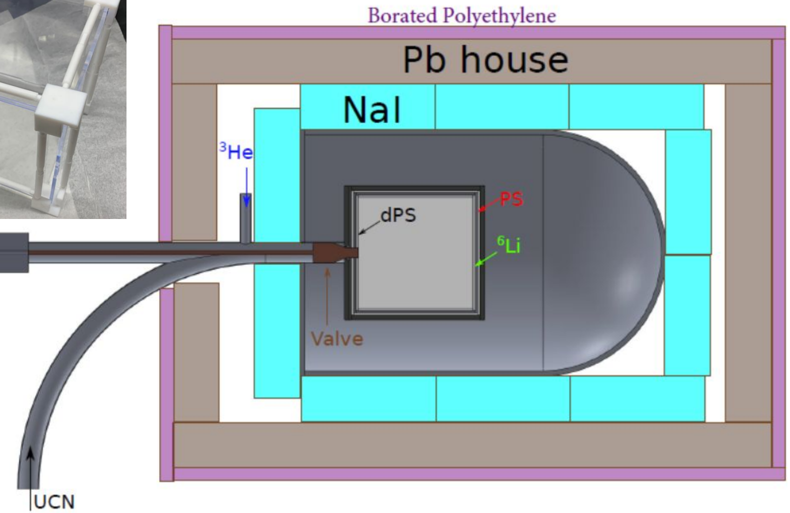


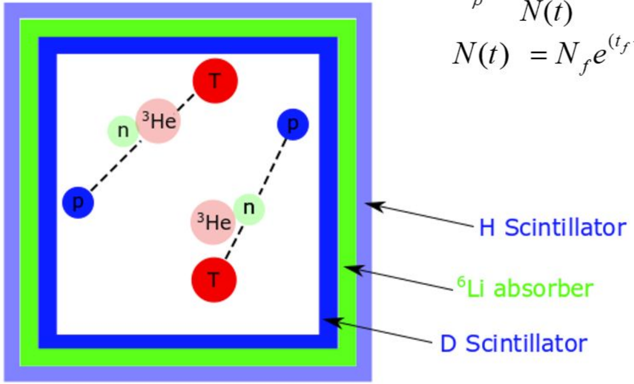
from Zhaowen Tang

UCNProBe at LANL

- 4π scintillator UCN volume
- Normalize number of βs to absolute measurement of UCN using ^{3}He gas
- Absolute measurement requires knowledge of scintillator dead layer, other inefficiencies
- Requires considerable background mitigation
- Currently procuring scintillator, electronics for feasibility demonstration with $\alpha/\beta/\gamma$ sources

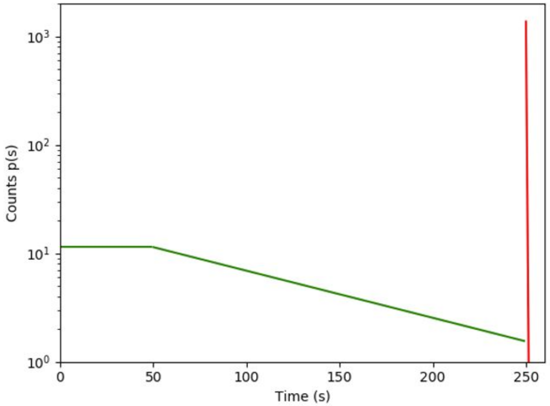






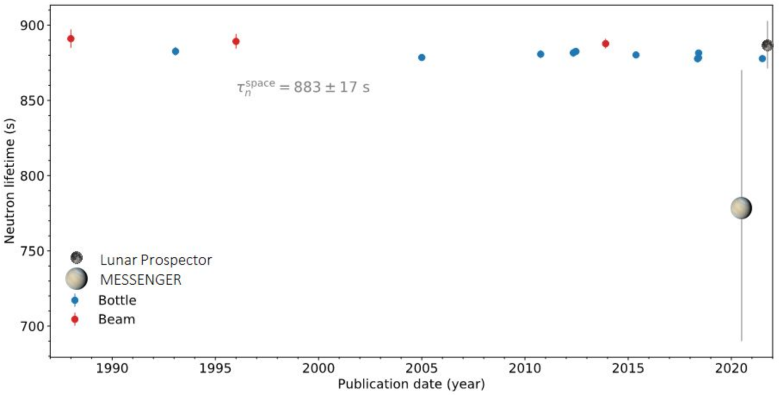
$$\tau_\beta = \frac{\beta(t)}{N(t)}$$

$$N(t) = N_f e^{(t_f - t)/\tau}$$



from Jack Wilson

Neutrons



- Compare MCNP model of neutron flux from moon's surface as detected by the Lunar Prospector as a function of altitude
- Treat neutron lifetime as a free parameter in comparing the model
  - $\tau_n = 887 \pm 14_{\text{stat}}\ {}^{+7}_{-3\ \text{syst}}$ s
- Considering venusian or terrestrial orbit experiment, lunar surface experiment

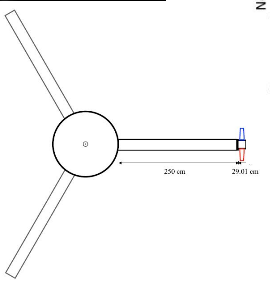
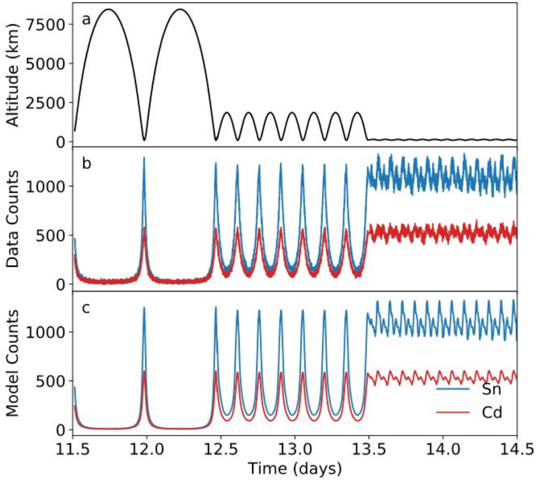


FIG. 5. A cartoon of the LP spacecraft and NS looking along the spacecraft rotation axis. The locations of the Sn-covered and Cd-covered tubes are shown in red and blue, respectively. The axis of rotation, pointing out of the page, is indicated with the circled dot.



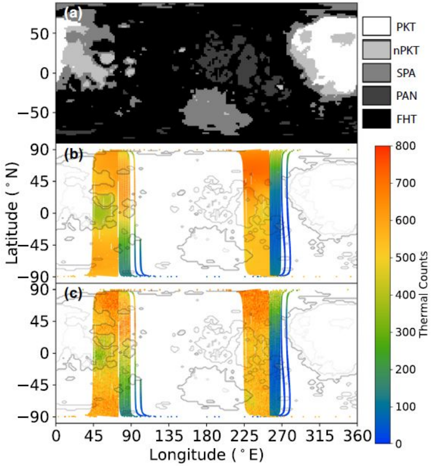


FIG. 3. (a) The five regions with distinct compositions included in the neutron count-rate models: procellarum KREEP terrane (PKT), south pole Aitken terrane (SPAT), Feldspathic highland terrane (FHT), pure anorthosite terrane (PAN), and non-PKT maria (nPKT). (b) The model thermal neutron counts, i.e., the difference between the Sn-covered and Cd-covered detectors. (c) The measured thermal detector counts. The grey contours in (b) and (c) show the regions defined in (a).

PHYSICAL REVIEW C **104**, 045501 (2021)

Measurement of the free neutron lifetime using the neutron spectrometer on NASA's Lunar Prospector mission

Jack T. Wilson,* David J. Lawrence, and Patrick N. Peplowski
The Johns Hopkins Applied Physics Laboratory, 11101 Johns Hopkins Road, Laurel, Maryland 20723, USA

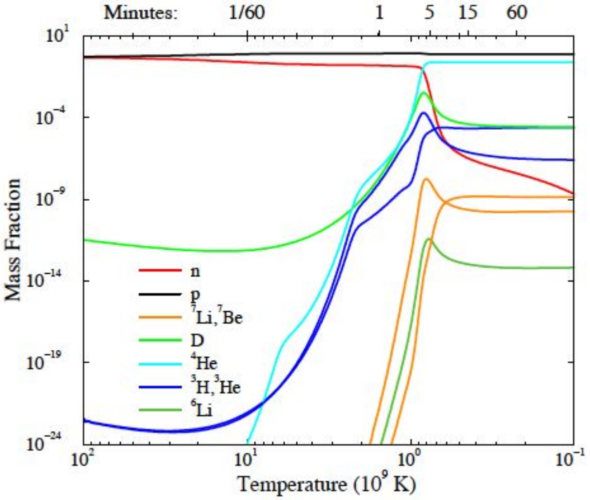
Vincent R. Eke and Jacob A. Kegerreis
Institute for Computational Cosmology, Durham University, South Road, Durham DH1 3LE, United Kingdom

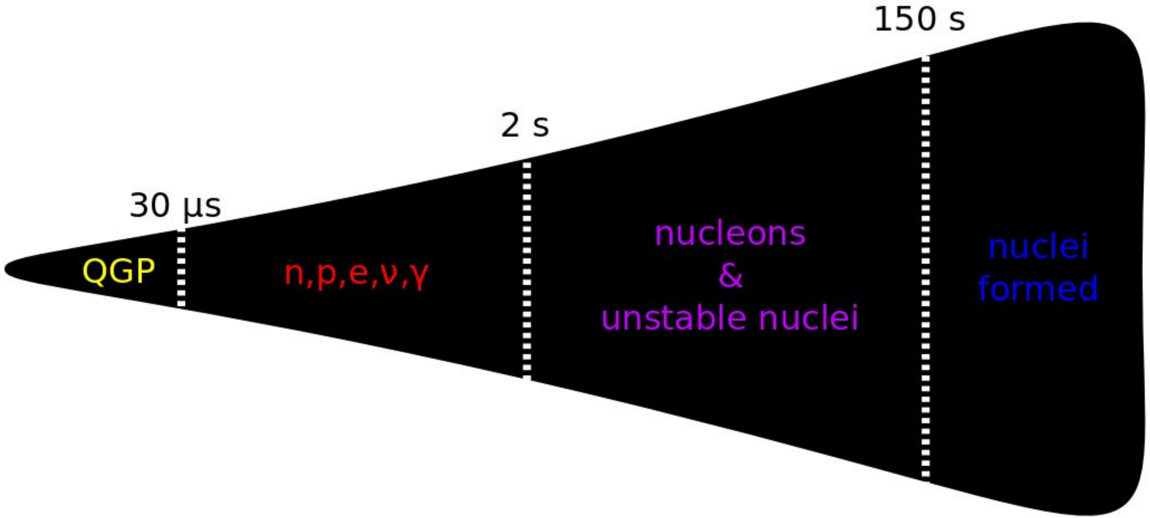
So where do we stand, really?

- Neutron lifetime measurements promise to test the standard model due to improved experiments and theory free from nuclear structure effects
- Neutron decay fits within the broader landscape of understanding the weak response of the nucleon, addressing timely investigations of BSM physics
- Calculations of g_A on the lattice have improved substantially, allowing for probes of BSM physics approaching that from the LHC
- UCNτ is to date the most precise measurement, and promises to improve by mitigating rate dependent effects and increasing statistical sensitivity
- The “problem” persists, but new experiments can provide a resolution
- EW radiative corrections are crucial for the interpretation of experiments

Backup

Big bang nucleosynthesis





PHYSICAL REVIEW VOLUME 74, NUMBER 9 NOVEMBER 1, 1948

Proceedings of the American Physical Society

Minutes of the Meeting at Washington, April 29 to May 1, 1948

F12. On the Radioactive Decay of the Neutron. Arthur H. Snell and L. C. Miller, *Clinton National Laboratories.*—A collimated beam of neutrons, three inches in diameter, emerges from the nuclear reactor and passes axially through a thin-walled, aluminum, evacuated cylindrical tank. A transverse magnetic field behind the thin entrance window cleans the beam of secondary electrons. Inside the vacuum, axially arranged, an open-sided cylindrical electrode is held at +4000 volts with respect to ground. Opposite the open side a smoothed graphite plate is held at −4400 volts. The field between these electrodes accelerates and focuses protons which may result from decay of neutrons, so that they pass through a $2\frac{7}{8}\times 1\frac{5}{8}$ inch aperture in the center of the graphite plate, and strike the first dynode of a secondary electron multiplier. The first dynode is specially enlarged so as to cover the aperture. Readings are taken (1) with and without a thin B^{10} shutter in the neutron beam; (2) with and without a thin foil over the multiplier aperture; (3) with and without the accelerating voltage. In a total counting rate of about 300 per min., about 100 are sensitive to operations (1), (2), and (3). In the absence of the accelerating field or with the foil (2) in, operation (1) does not change the counting rate. Assuming all of the 100 c.p.m. to be due to decay protons, preliminary estimates of the collecting and counting efficiency (10 percent) and of the number of neutrons in the sample (4×10^4) give for the neutron a half-life of about 30 minutes. It is at present much safer however to say that the neutron half-life must exceed 15 minutes. Coincidences are presently being sought between the disintegration betas and the collected protons.

Angular Correlation in the Beta Decay of the Neutron

J. M. Robson
Chalk River Laboratory, Atomic Energy of Canada Limited, Chalk River, Ontario, Canada

(Received August 22, 1955)

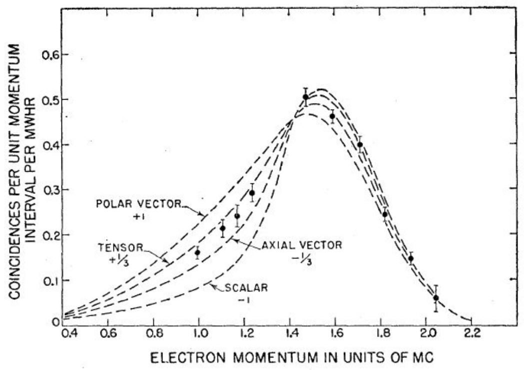
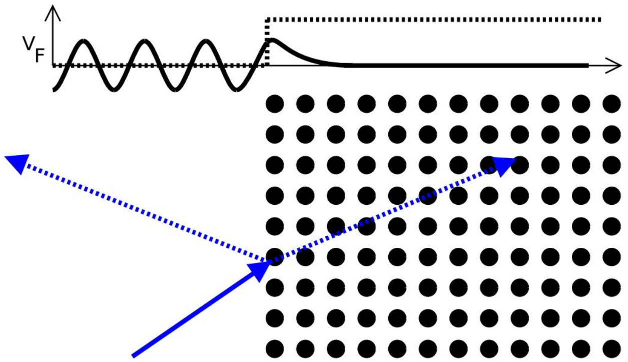
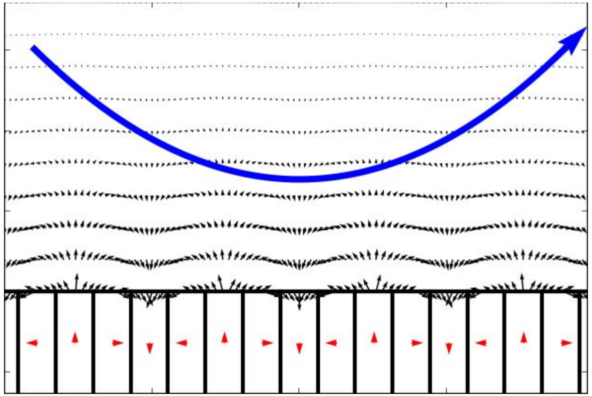


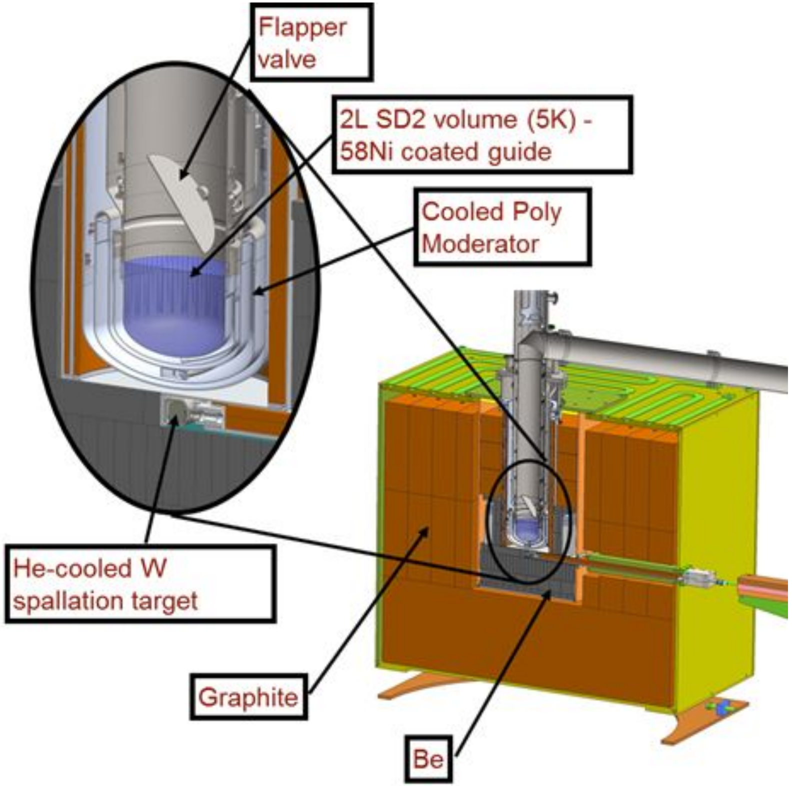
Fig. 3. The momentum spectrum of the electrons. The points represent the experimental data with standard deviations, and the dashed curves are the theoretical spectrum shapes for the pure interactions normalized by least squares.

(880 s)×ln2 ~ *10.2* minutes

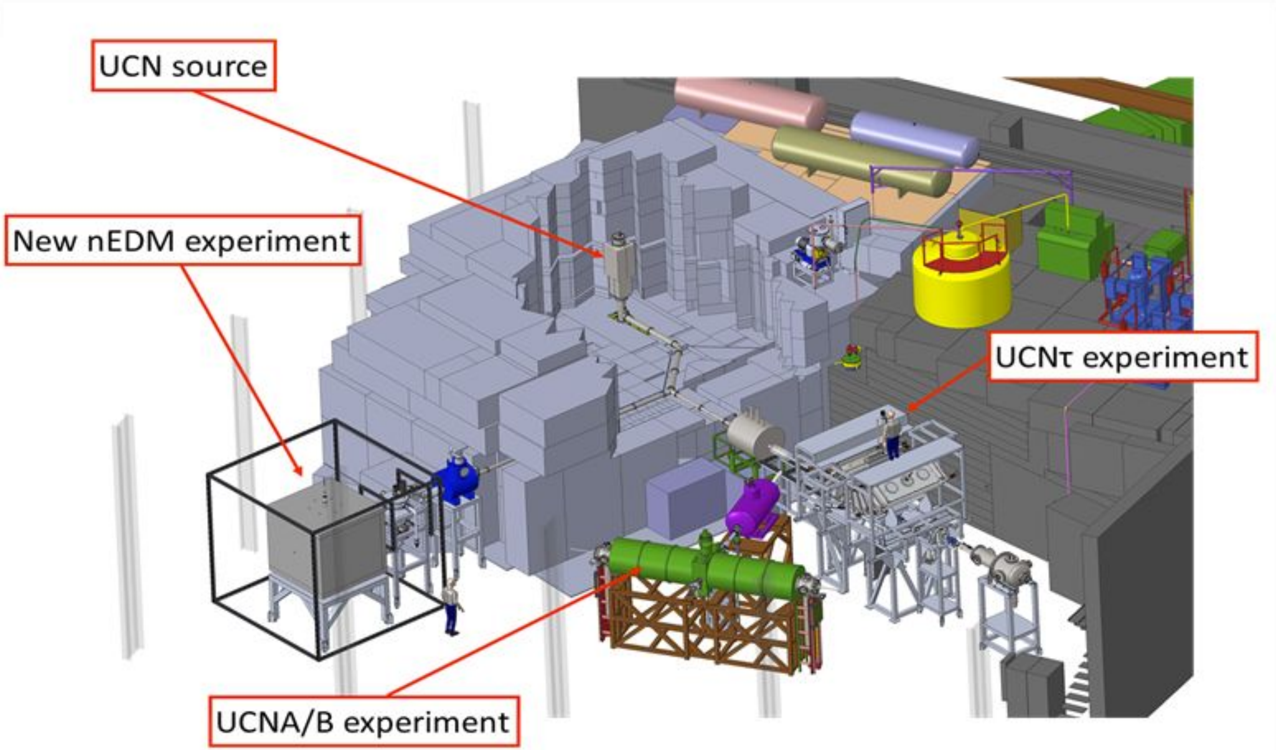
Ultracold neutrons





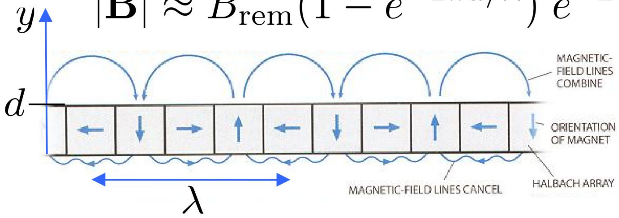


LANSCE Area B



The UCNτ "Halbach" array

$$|\mathbf{B}| \approx B_{\mathrm{rem}}(1 - e^{-2\pi d/\lambda})\, e^{-2\pi y/\lambda}$$

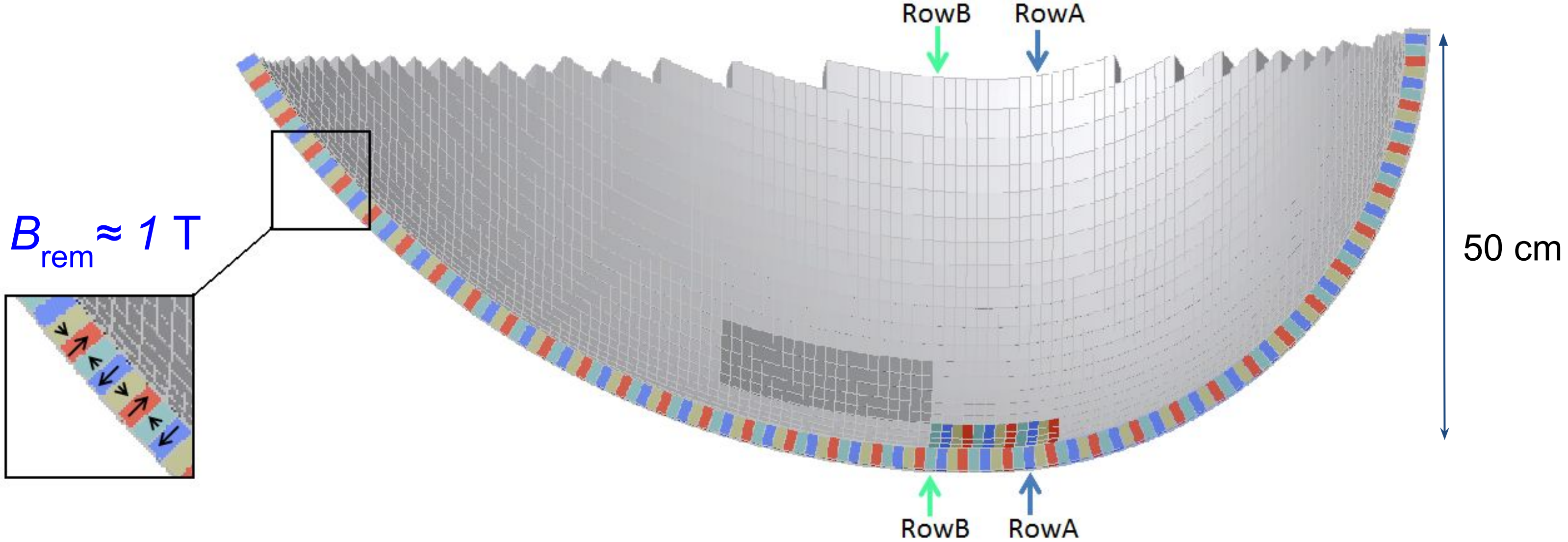


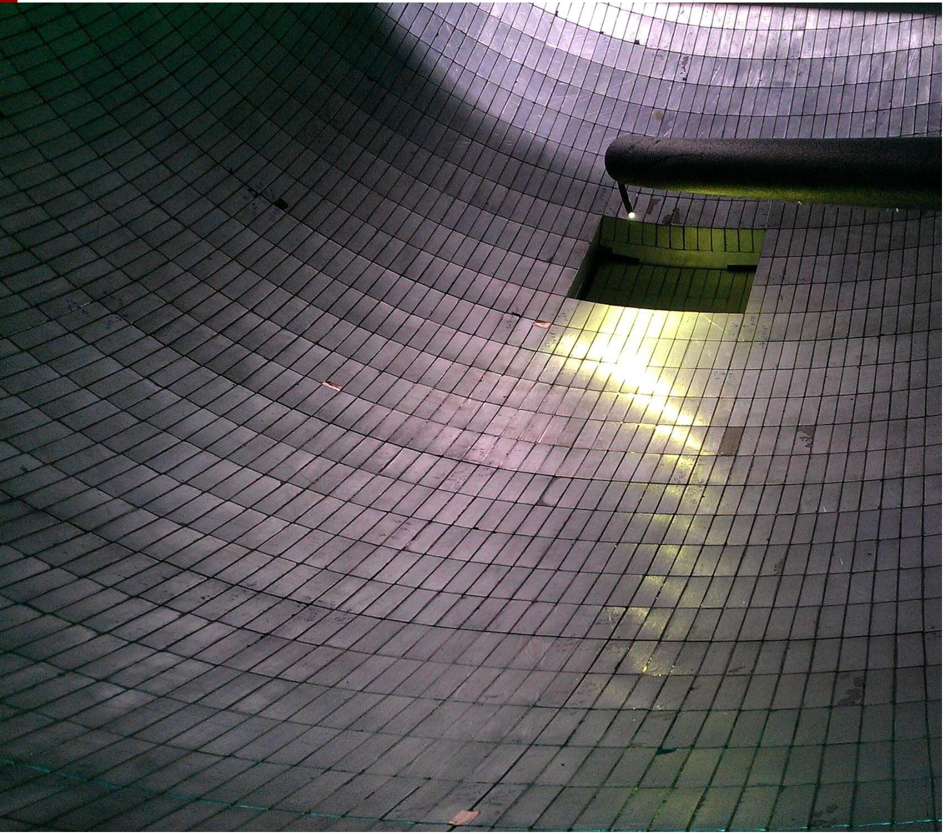
DESIGN OF PERMANENT MULTIPOLE MAGNETS WITH ORIENTED RARE EARTH COBALT MATERIAL*

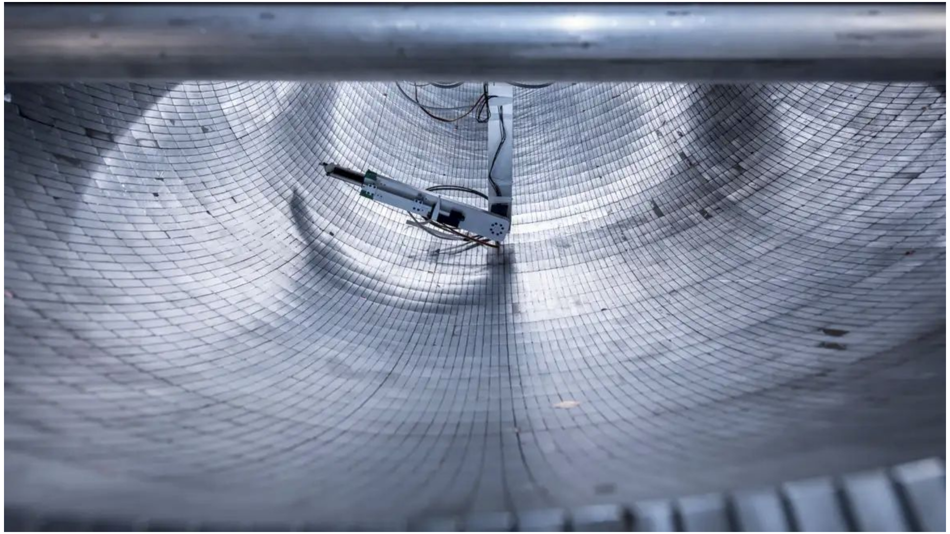
K. HALBACH

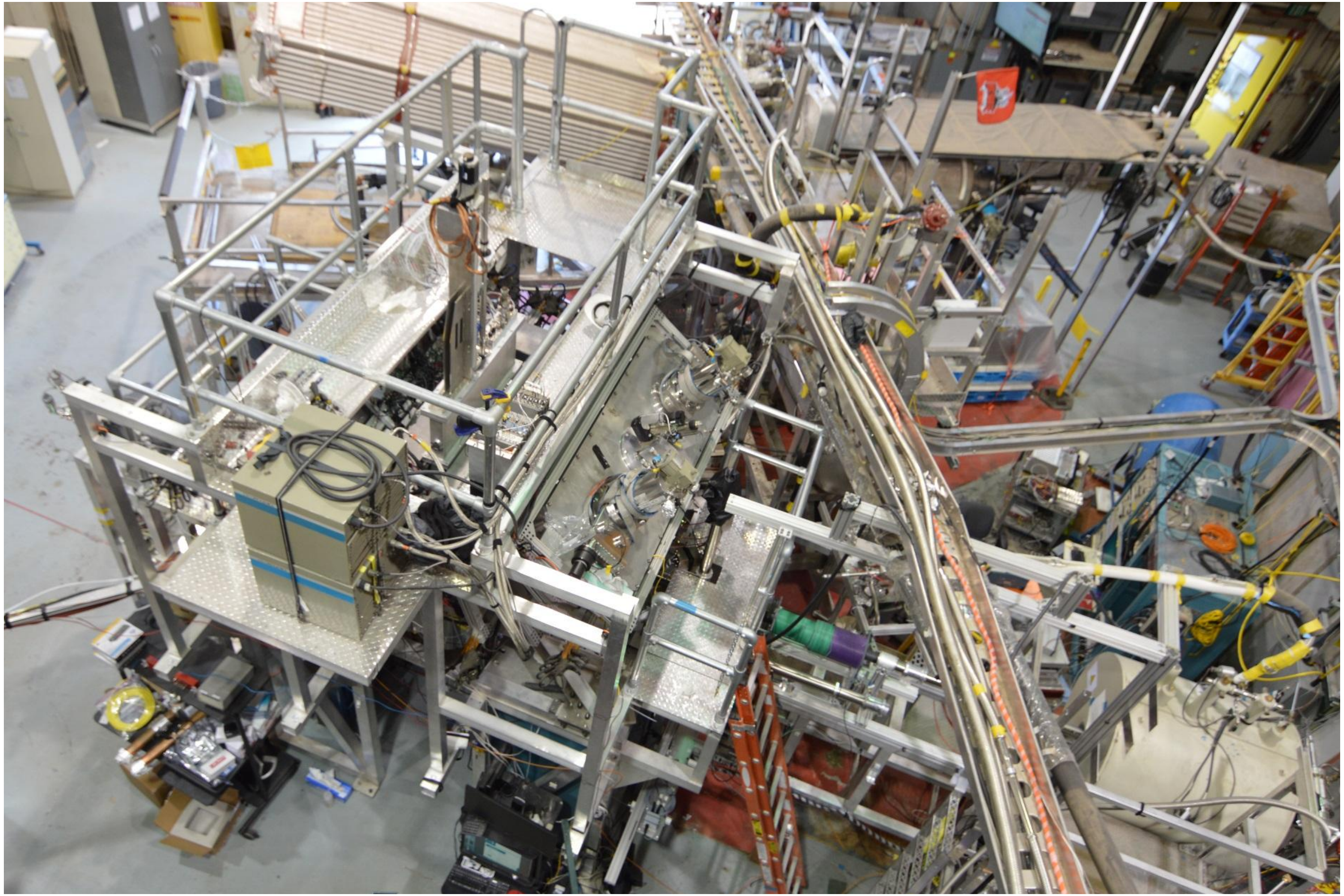
University of California, Lawrence Berkeley Laboratory, Berkeley, CA 94720, U.S.A.

Received 20 August 1979







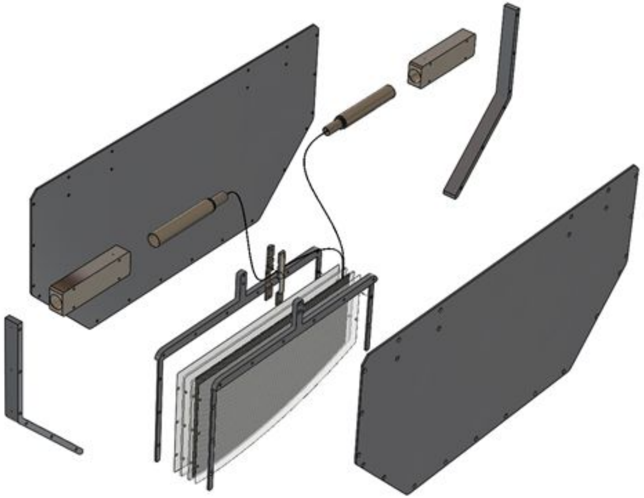


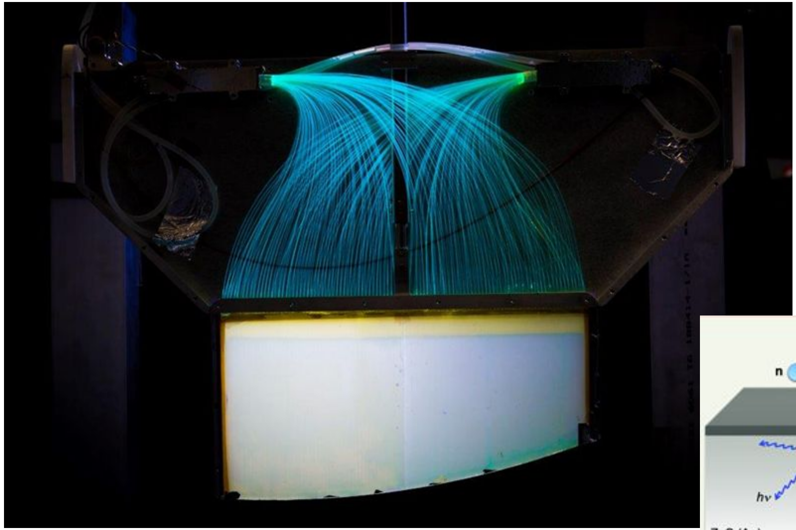
The “dagger” detector

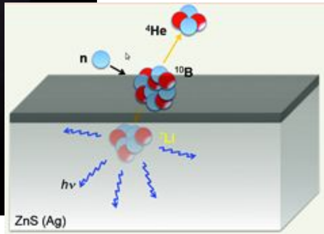
REVIEW OF SCIENTIFIC INSTRUMENTS **88**, 053508 (2017)

A new method for measuring the neutron lifetime using an *in situ* neutron detector

C. L. Morris,[1] E. R. Adamek,[2] L. J. Broussard,[3] N. B. Callahan,[2] S. M. Clayton,[1]

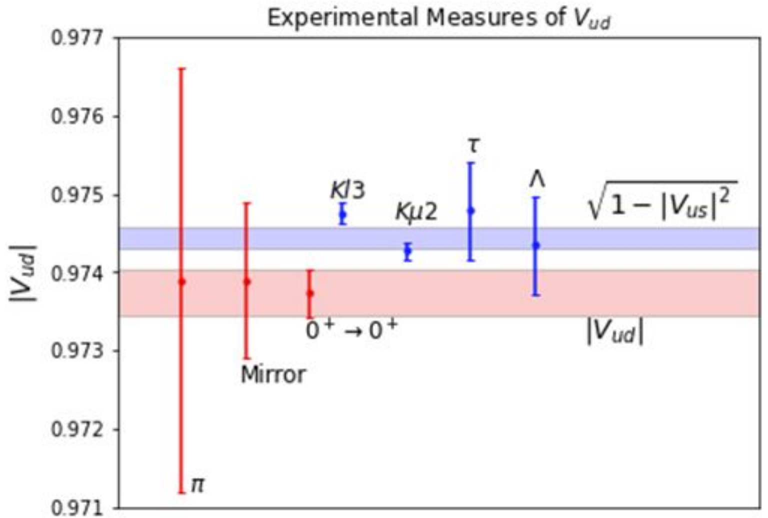






Permits UCN detection ***in the trap!***

Cabibbo-Kobayashi-Maskawa Matrix Unitarity



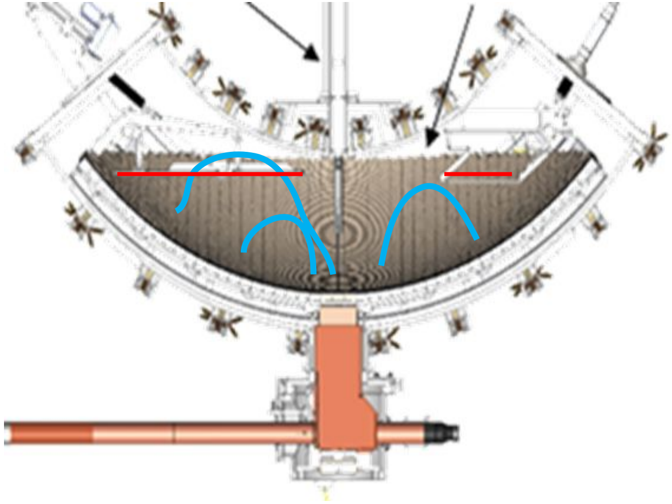
$$\begin{bmatrix} d' \\ s' \\ b' \end{bmatrix} = \begin{bmatrix} V_{\mathrm{ud}} & V_{\mathrm{us}} & V_{\mathrm{ub}} \\ V_{\mathrm{cd}} & V_{\mathrm{cs}} & V_{\mathrm{cb}} \\ V_{\mathrm{td}} & V_{\mathrm{ts}} & V_{\mathrm{tb}} \end{bmatrix} \begin{bmatrix} d \\ s \\ b \end{bmatrix}$$

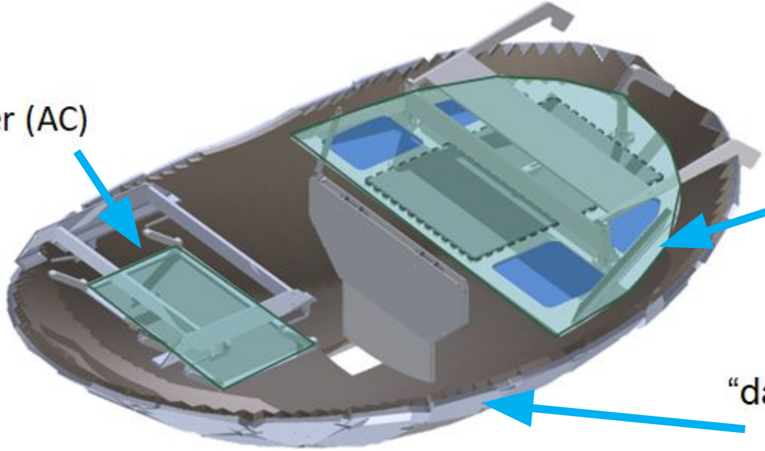
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1$$

The UCNτ collaboration

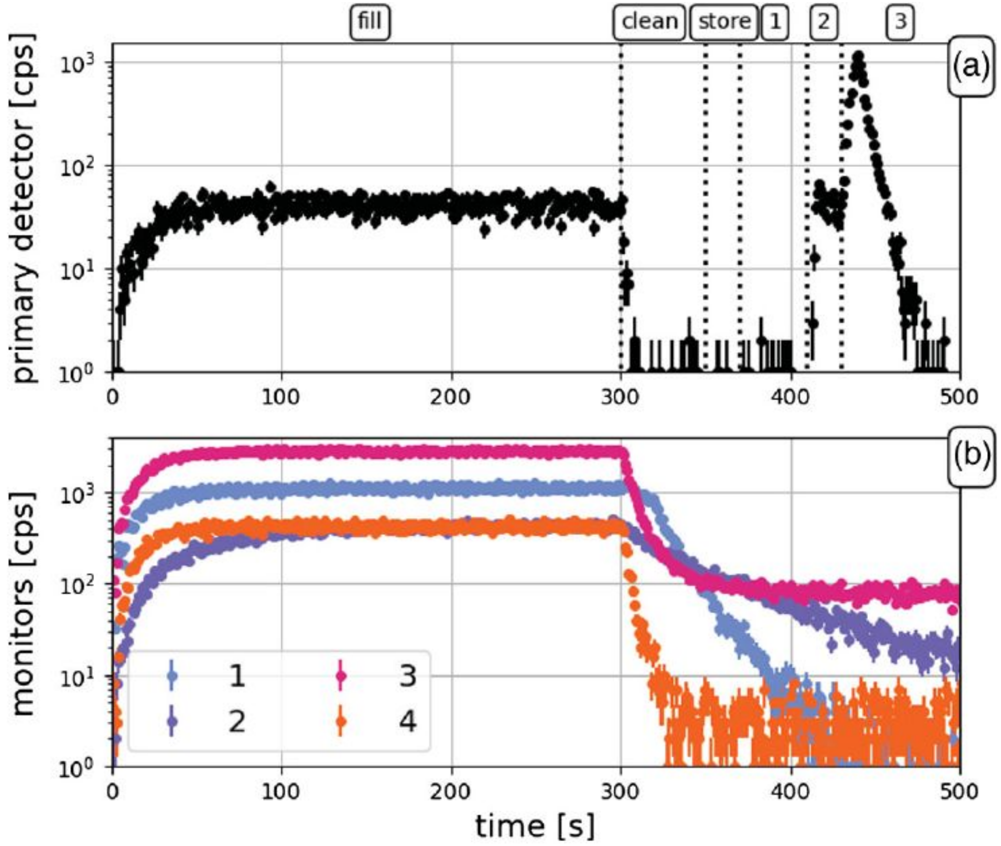
- **Argonne National Laboratory**
    - N Callahan
- **California Institute of Technology**
    - M Blatnik, B Filippone, E M Fries, K P Hickerson, S Slutsky, V Su, X Sun, C Swank, W Wei
- **DePauw University**
    - A Komives
- **East Tennessee State University**
    - R W Pattie, Jr
- **Indiana University and CEEM**
    - M Dawid, W Fox, C-Y Liu, F Gonzalez, D J Salvat, J Vanderwerp, G Visser
- **Institut Laue-Langevin**
    - P Geltenbort
- **Joint Institute for Nuclear Research**
    - E I Sharapov
- **Los Alamos National Laboratory**
    - S M Clayton, S A Curry, M A Hoffbauer, T M Ito, M Makela, C L Morris, C O'Shaughnessy, Z Tang, P L Walstrom, Z Wang
- **North Carolina State University**
    - T Bailey, J Choi, C Cude-Woods, L Hayen, R Musedinovic, A R Young
- **Oak Ridge National Laboratory**
    - L J Broussard, J Ramsey, A Saunders
- **Tennessee Technological University**
    - R Colon, D Dinger, J Ginder, A T Holley, M Kemp, C Swindell

How to “clean” UCN

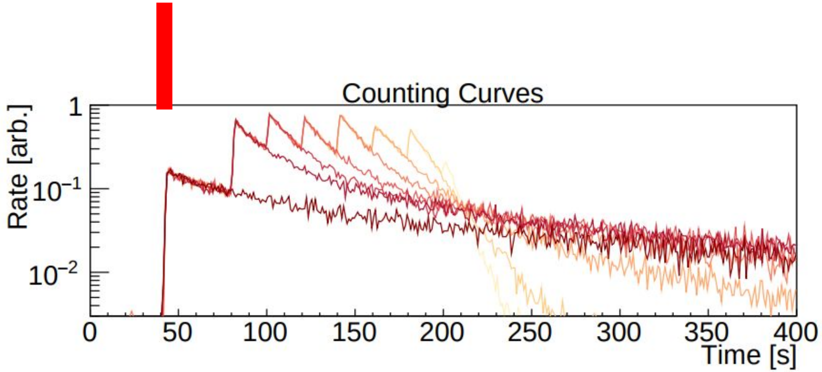


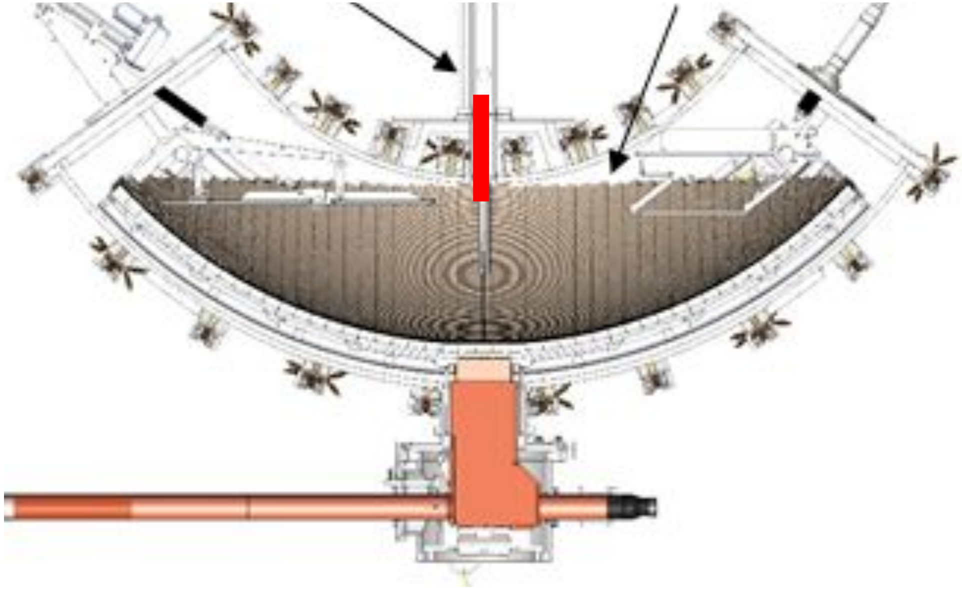


What do data look like?

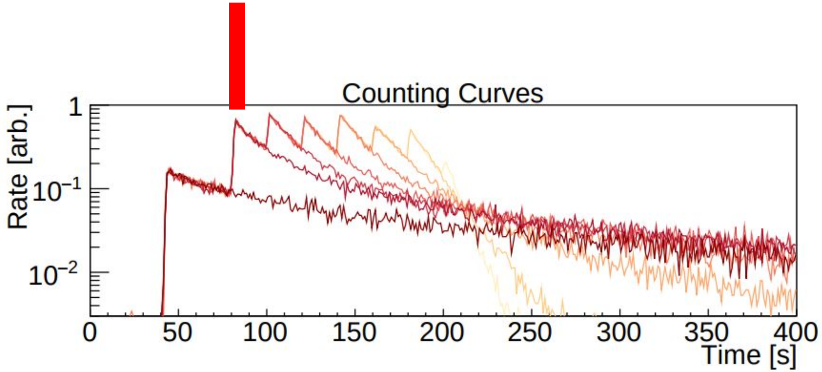


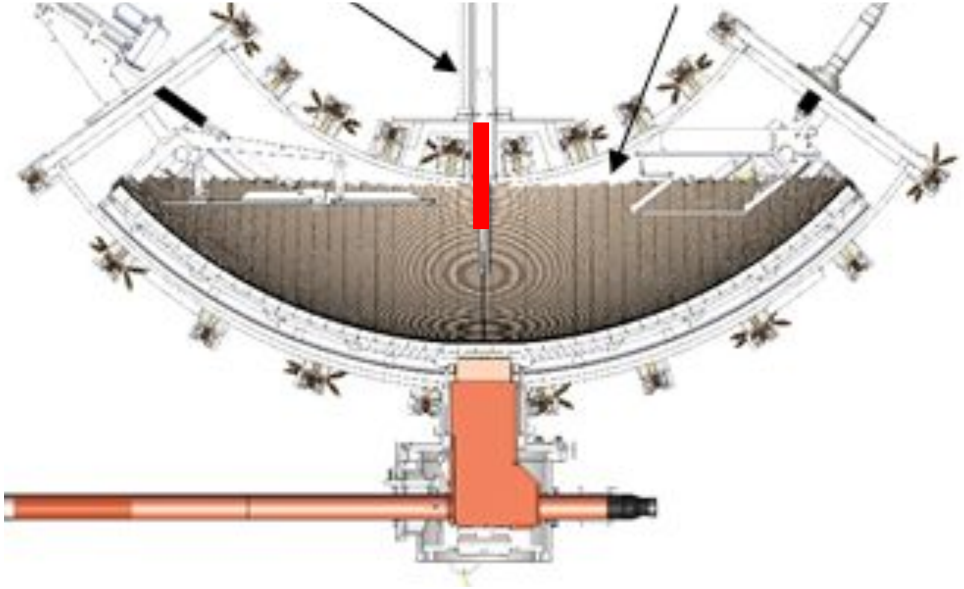
The dagger probes systematic effects



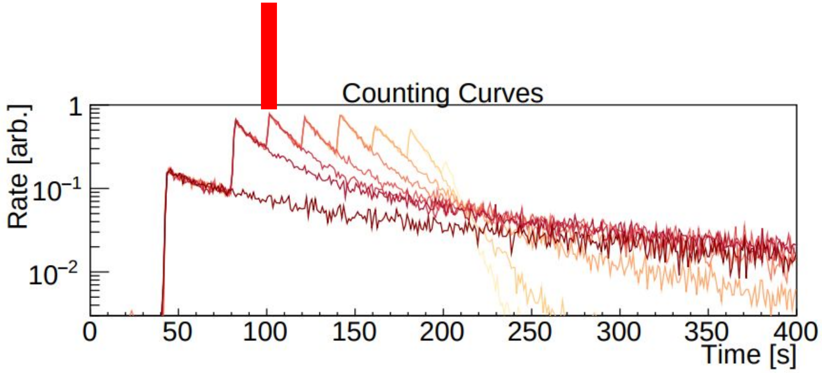


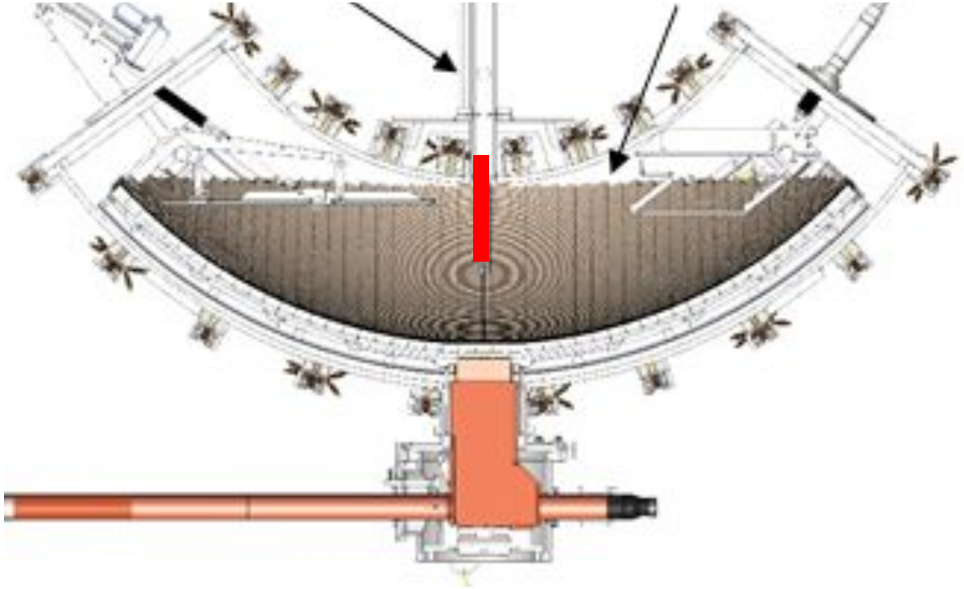
The dagger probes systematic effects





The dagger probes systematic effects



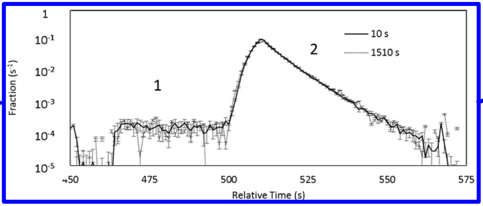


Analyzing data...

Background measurements

Single p.e. dagger counts

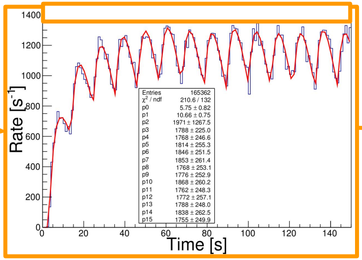
UCN events passing cuts



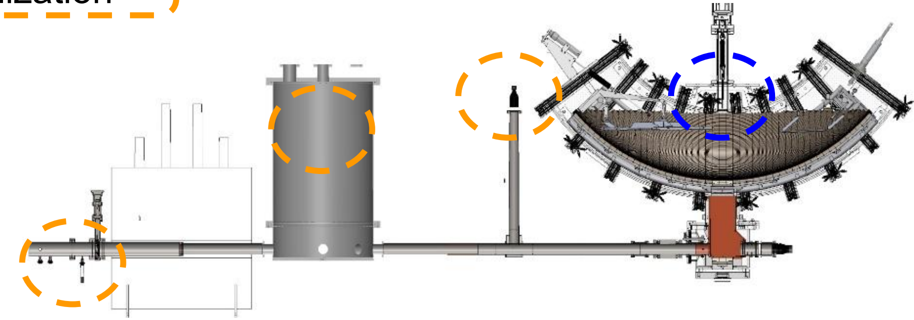
Dagger unload counts

$$Y_t = \frac{D_t - B}{M}$$

“Monitor” detector counts



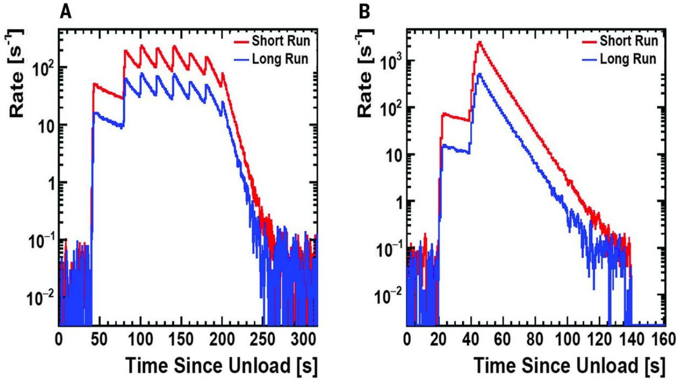
“**M**onitor” normalization



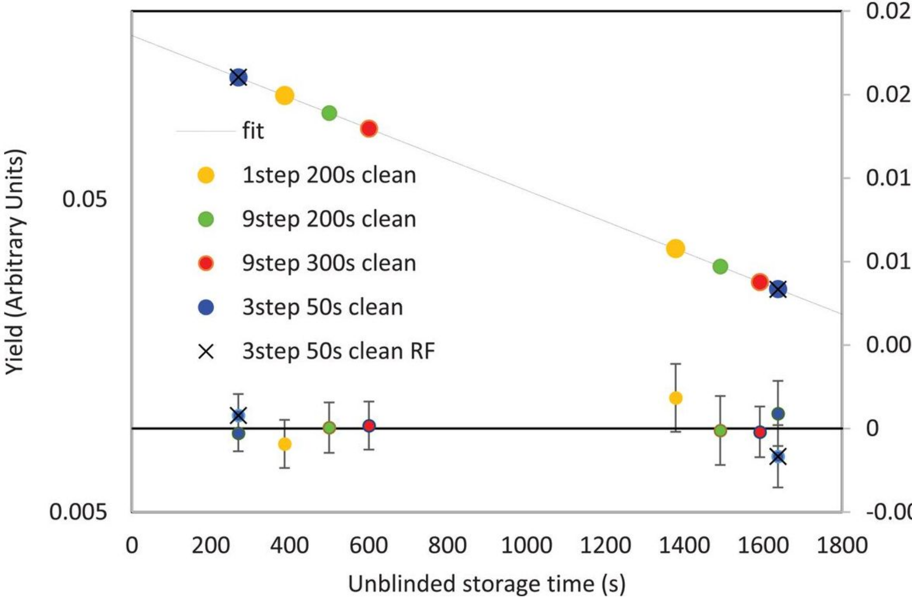
2015-2016 results

Table 2. Systematic uncertainties.

Effect	Upper bound (s)	Direction	Method of evaluation
Depolarization	0.07	+	Varied external holding field
Microphonic heating	0.24	+	Detector for heated neutrons
Insufficient cleaning	0.07	+	Detector for uncleaned neutrons
Dead time/pileup	0.04	±	Known hardware dead time
Phase space evolution	0.10	±	Measured neutron arrival time
Residual gas interactions	0.03	±	Measured gas cross sections and pressure
Background shifts	<0.01	±	Measured background as function of detector position
Total	0.28		(uncorrelated sum)



$$877.7 \pm 0.7\,(\text{stat})\ \boxed{+0.4/-0.2}\,(\text{sys})\ \text{s}$$



IU PhD Nathan Callahan (2018)

2015-2016 results

Table 2. Systematic uncertainties.

statistically driven!

Effect	Upper bound (s)	Direction	Method of evaluation
Depolarization	0.07	+	Varied external holding field
Microphonic heating	0.24	+	Detector for heated neutrons
Insufficient cleaning	0.07	+	Detector for uncleaned neutrons
Dead time/pileup	0.04	±	Known hardware dead time
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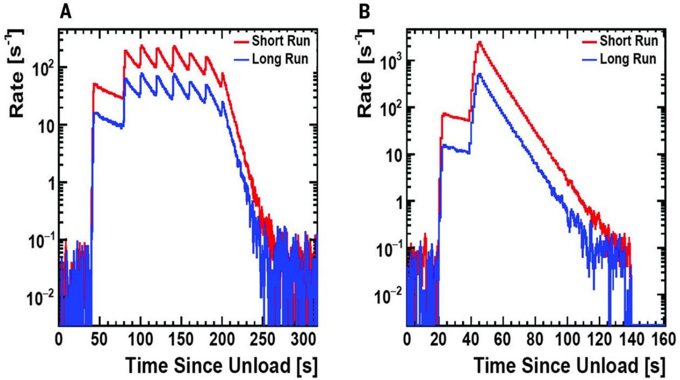
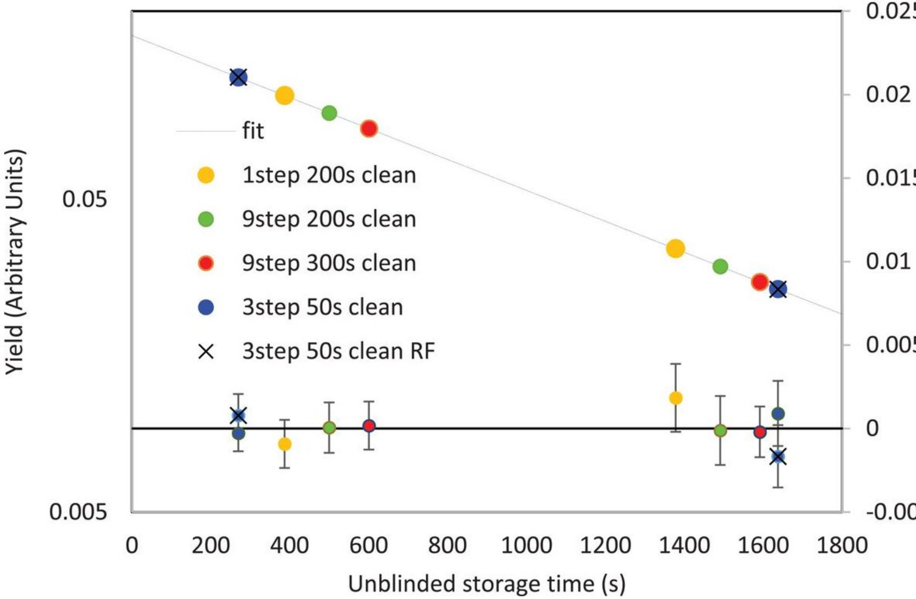
Residual gas interactions	0.03	±	Measured gas cross sections and pressure
Background shifts	<0.01	±	Measured background as function of detector position
Total	0.28		(uncorrelated sum)



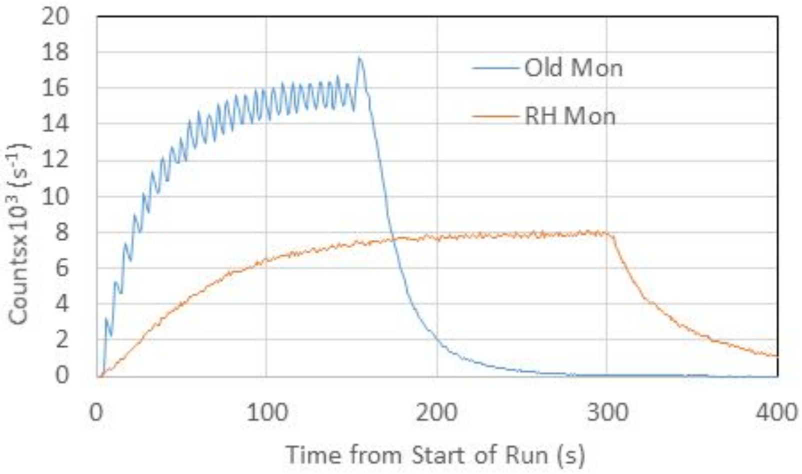
$$877.7 \pm 0.7\,(\mathrm{stat})\,\boxed{+0.4/-0.2}\,(\mathrm{sys})\ \mathrm{s}$$

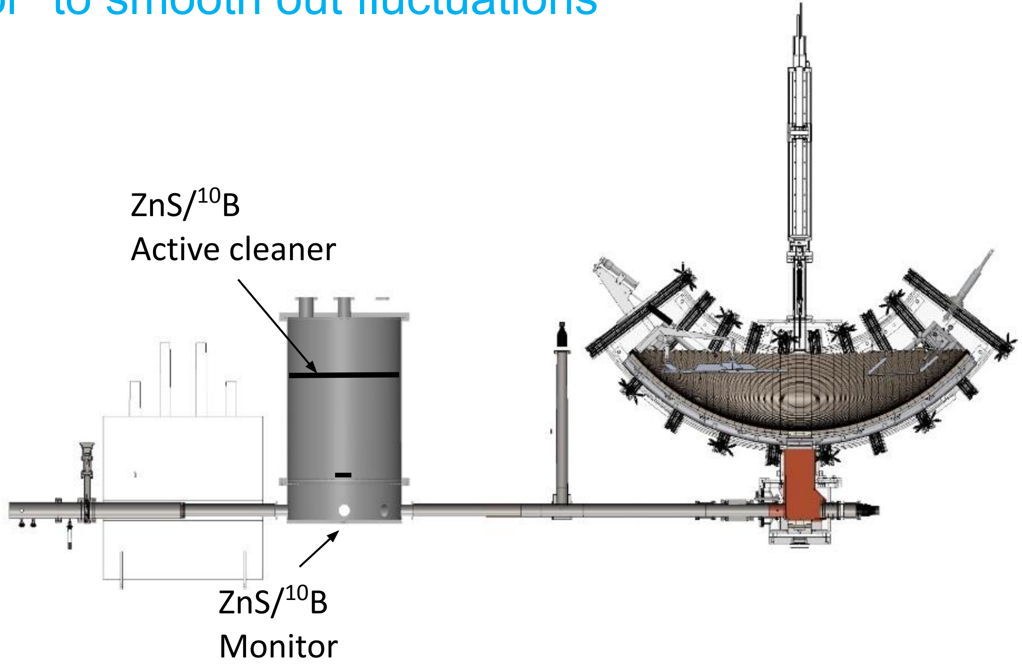


IU PhD Nathan Callahan (2018)

Improved stability

- Buffer volume serves as “capacitor” to smooth out fluctuations
- Pre-cleaner built in





Making a UCN out of photons

Suppress backgrounds by forming “coincidences”

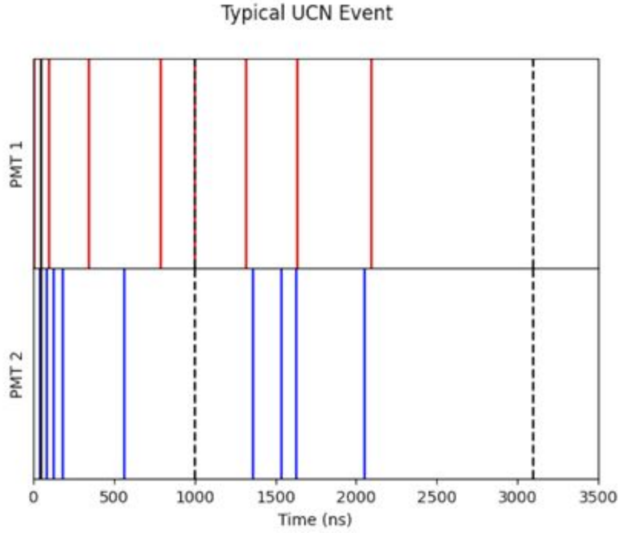
- “Initial Window” 50 ns (must trigger on both PMTs)
- Require ≥ 8 photons in first 1000 ns
- “Telescoping Window” 1000 ns

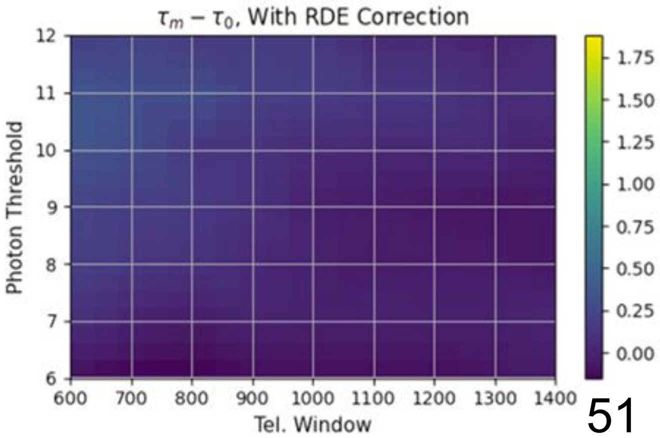
Need constant counting efficiency

- Peak neutron counting rate ~1 kHz
- ZnS:Ag scintillator has ~10^{-5} s “glow”

Correct rate dependent effects on per-event basis

- Monte Carlo studies resampling data
- Contributes to $\Delta\tau_{RDE}$=±0.13 s systematic uncertainty





Normalization

Want to find a lifetime using:

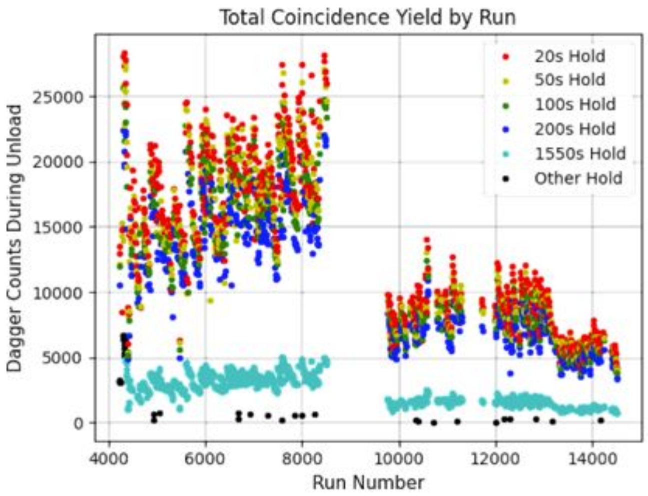
- $Y(t_i)=Y_i\, exp(-t_i/\tau_{meas})$
- Intermediate step: Find Y_i, the initial number of neutrons in the trap

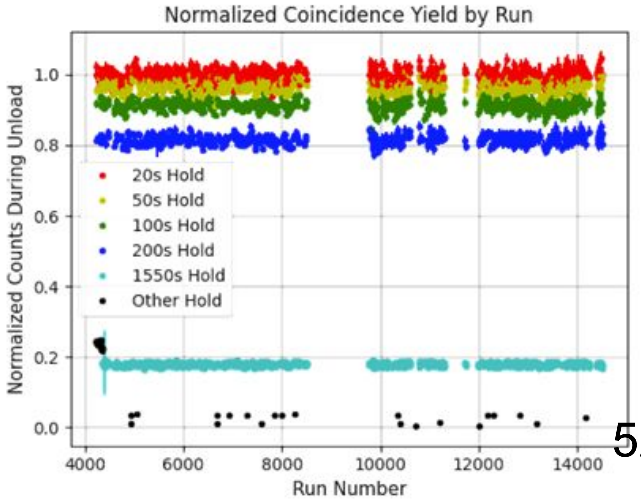
Have ~4000 runs to fit

- Reconstructed detector counts D_i
- Measure backgrounds B_i at end of run + dedicated runs

Incorporate normalization monitors with $f(M_i)$

- Exact form of $f(M_i)$ can differ by analyzer
- Example: $f(M_i)=\alpha\, m_{main}+\beta_s\, m_{spec}$
- Need to fit (likelihood or least squares) for α, β_s





“Paired” & “global” analyses

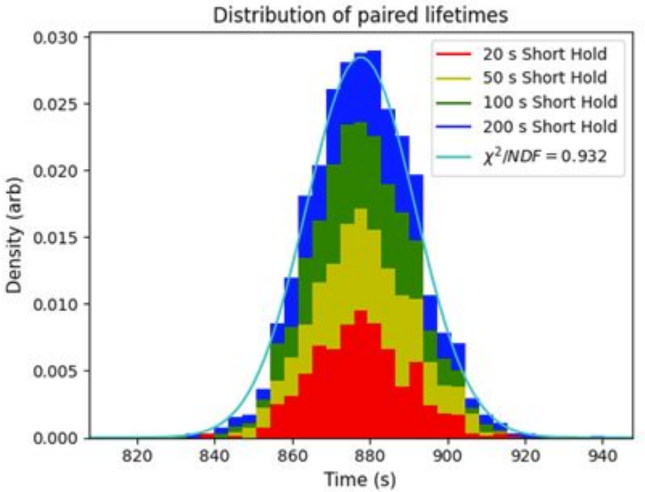
Finally time to solve for τ_{meas}

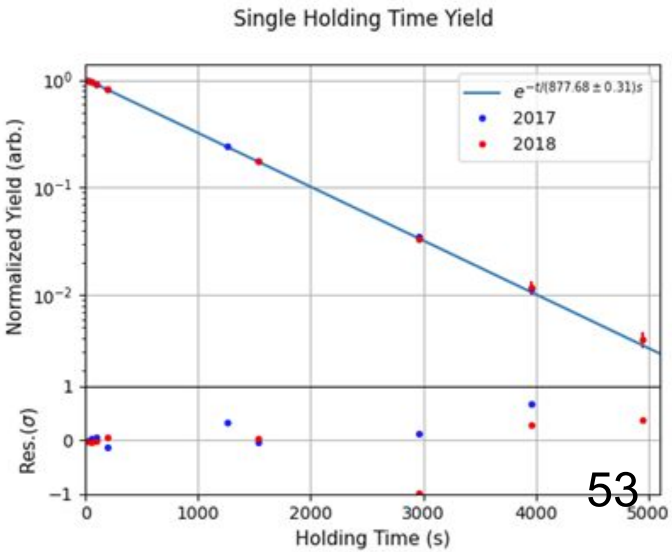
Method 1: pair together short and long holding cycles

- $\tau_{meas}=(t_L-t_S)/\ln(Y_S/Y_L)$

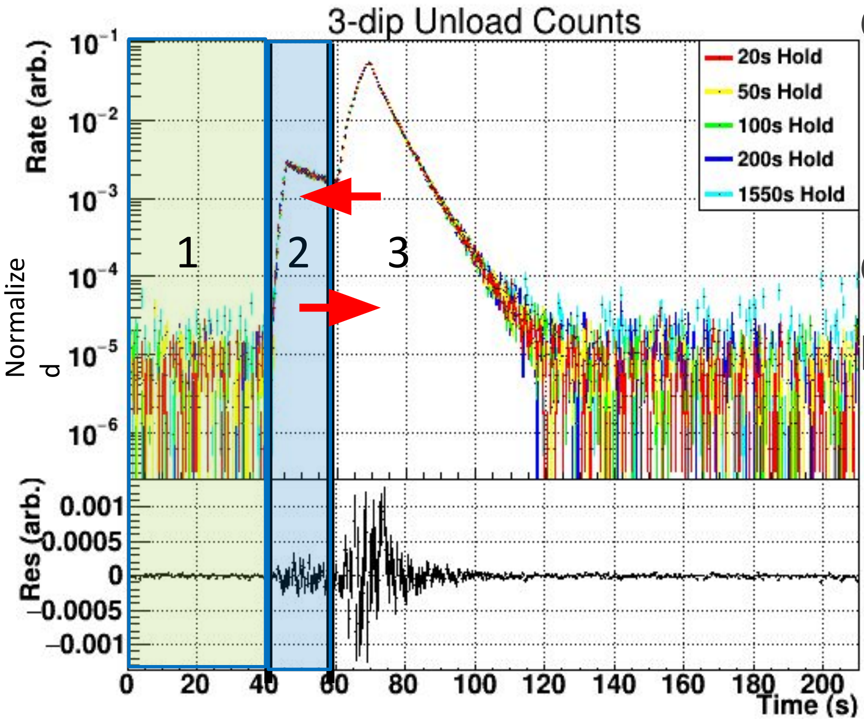
Method 2: Maximum Likelihood analysis to get a “global” lifetime

- Simultaneously fit τ_{meas} and additional parameters from $f(M_i)$





"Heating" and "cleaning" effects



Overthreshold UCN above cleaning height

- "Heated" UCN (long times): $\Delta\tau_{heat}$=0+0.08 s
- "Uncleaned" UCN (short times): $\Delta\tau_{unc}$=0+0.11 s

Overthreshold neutrons <2×10^{-5}!

Require constant detection efficiency

- Phase space couples to counting time
- Use mean arrival time during unload
- $\Delta\tau_{PSE}$=0.02±0.01 s

The error budget

Effect	Previous Reported Value (s)	New Reported Value (s)	Notes
τ_{meas}	877.5 ± 0.7	877.58 ± 0.28	Uncorrected Value!
UCN Event Definition	0 ± 0.04	0 ± 0.13	Single photon analysis vs. Coincidence analysis
Normalization Weighting	--	0 ± 0.06	Previously unable to estimate
Depolarization	$0 + 0.07$	$0 + 0.07$	
Uncleaned UCN	$0 + 0.07$	$0 + 0.11$	
Heated UCN	$0 + 0.24$	$0 + 0.08$	
Phase Space Evolution	0 ± 0.10	--	Now included in stat. uncertainty
Al Block	--	0.06 ± 0.05	Accidentally dropped into trap…
Residual Gas Scattering	0.16 ± 0.03	0.11 ± 0.06	
Sys. Total	$\mathbf{0.16^{+0.4}_{-0.2}}$	$\mathbf{0.17^{+0.22}_{-0.16}}$	
TOTAL	$\mathbf{877.7 \pm 0.7^{+0.4}_{-0.2}}$	$\mathbf{877.75 \pm 0.28^{+0.22}_{-0.16}}$	

A cross check

Fill and dump measurement of the neutron lifetime using an asymmetric magneto-gravitational trap

C. Cude-Woods, F. M. Gonzalez, E. M. Fries, T. Bailey, M. Blatnik, N. B. Callahan, J. H. Choi, S. M. Clayton, S. A. Currie, M. Dawid, B. W. Filippone, W. Fox, P. Geltenbort, E. George, L. Hayen, K. P. Hickerson, M. A. Hoffbauer, K. Hoffman, A. T. Holley, T. M. Ito, A. Komives, C.-Y. Liu, M. Makela, C. L. Morris, R. Musedinovic, C. O'Shaughnessy, R. W. Pattie Jr., J. Ramsey, D. J. Salvat, A. Saunders, 5 E. I. Sharapov, S. Slutsky, V. Su, X. Sun, C. Swank, Z. Tang, W. Uhrich, J. Vanderwerp, P. Walstrom, Z. Wang, W. Wei, A. R. Young

The past two decades have yielded several new measurements and reanalyses of older measurements of the neutron lifetime. These have led to a 4.4 standard deviation discrepancy between the most precise measurements of the neutron decay rate producing protons in cold neutron beams and the lifetime measured in neutron storage experiments. Measurements using different techniques are important for investigating whether there are unidentified systematic effects in any of the measurements. In this paper we report a new measurement using the Los Alamos asymmetric magneto-gravitational trap where the surviving neutrons are counted external to the trap using the fill and dump method. The new measurement gives a free neutron lifetime of . Although this measurement is not as precise, it is in statistical agreement with previous results using in situ counting in the same apparatus.

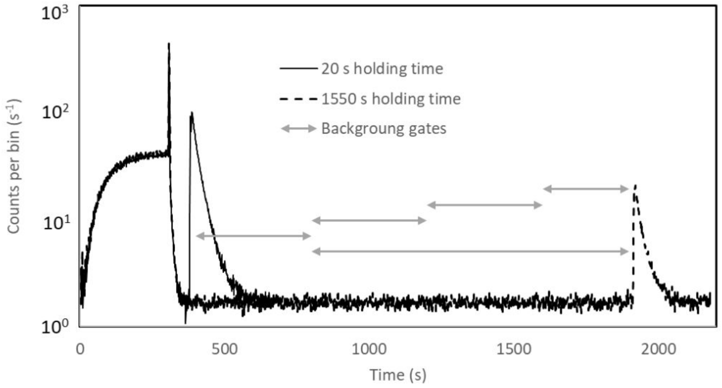


Figure 4. The figure shows a comparison of the average of the short holding time runs with the long holding time runs. The gray double arrows show the background gates that have been used in the analysis.

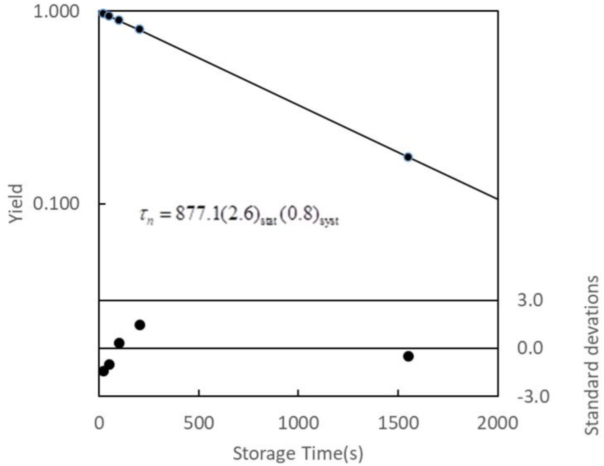
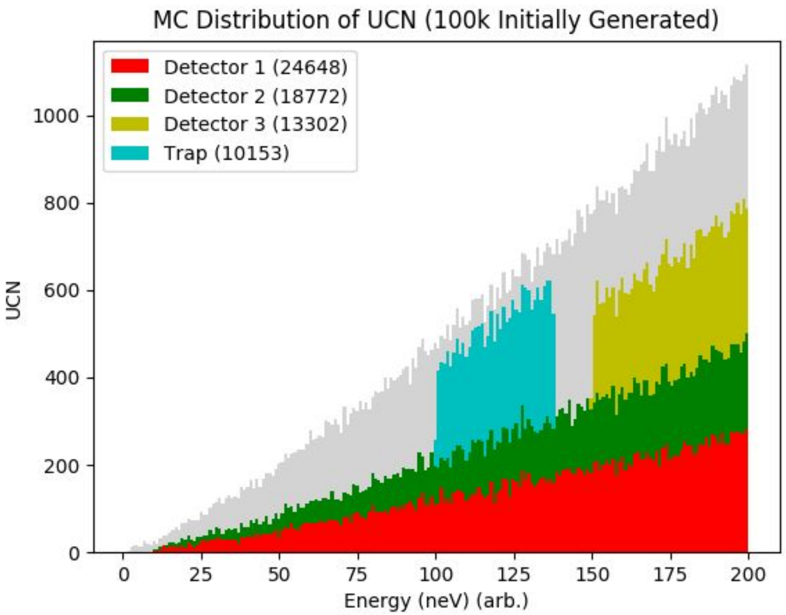


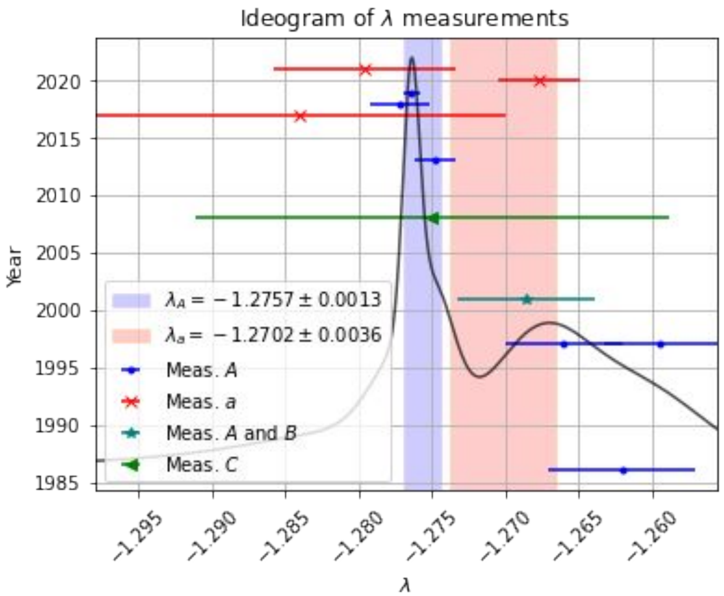
Figure 6. Plot of average yield vs time, lifetime fit, and residuals.

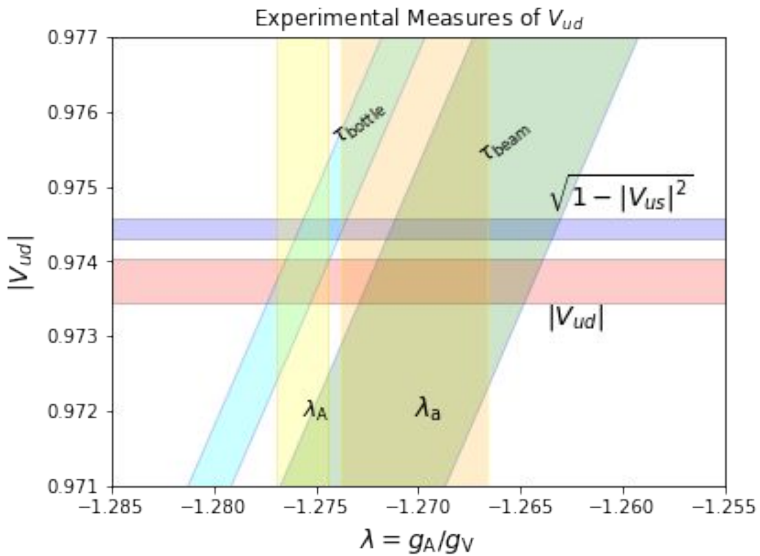
Monitor detectors and UCN spectrum



FAQ:
Doesn't CKM unitarity exclude τ_{beam}?

- Measurements of λ also disagree…





Magnetic Fields of Trap

- For “low-field seeking” polarized neutrons

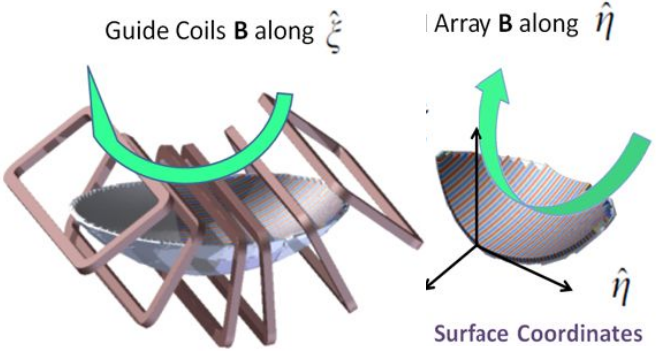
$$\vec{F} = \vec{\mu} \cdot (\nabla \vec{B})$$

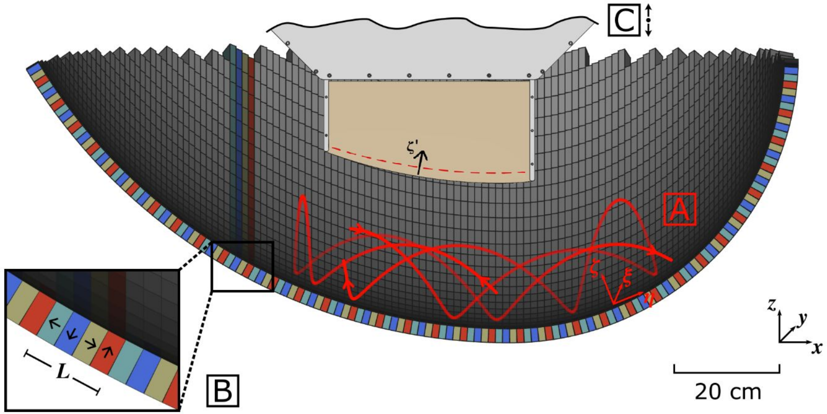
Permanent Magnet Halbach Array:

$$\boldsymbol{B} = \frac{4B_{rem}}{\pi\sqrt{2}} \sum_{n=1}^{\infty} \frac{(-1)^{n-1}}{4n-3} \left(1 - e^{-k_n d}\right) e^{-k_n \zeta} \left(\sin k_n \eta\, \hat{\boldsymbol{\eta}} + \cos k_n \eta\, \hat{\boldsymbol{\zeta}}\right)$$

Guide field coils along axis:

$$B_{\xi} = \frac{B_0(r+R)}{\sqrt{x^2+y^2}}\, \hat{\boldsymbol{\xi}}$$

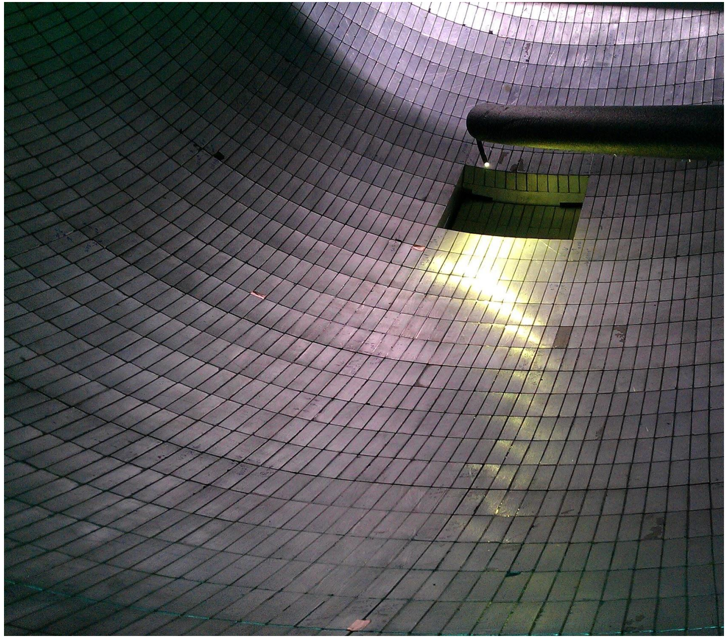




Inside of the Array

- ~ 4000 individual Nd magnets
  - Each magnet has size $(1 \times 2 \times 0.5)$ in^3
  - Each has $B_{rem} = 1.35$ T

Total trap volume ~ 420 L
  - Toroidal segments of radii 0.5 m and 1 m
  - Depth 0.5 m



Signals From the Dagger

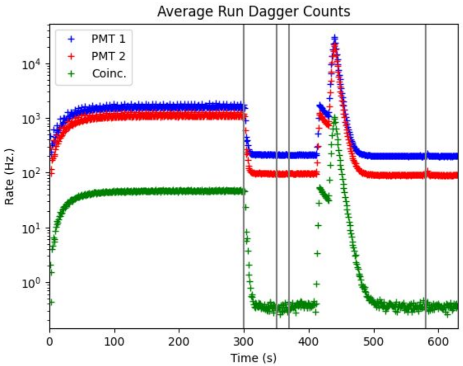
- Integrate unload counts from the two PMTs to find "dagger counts," D_i

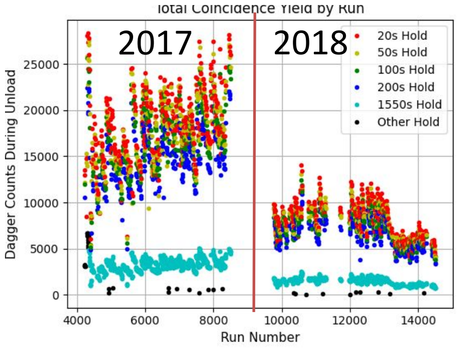
"Singles"

- Summing up individual counts on each PMT. Can separate out each PMT individually as well
- Advantage: Minimal rate dependent effects (16 ns hardware deadtime)
- Disadvantage: Signal-to-noise ratio is only $\sim 10\times$ for short runs, $\sim 3\times$ for long runs. Very background dependent!

"Coincidences" between the two PMTs

- Integrate counts inside a time window to reject non-UCN events
- Advantage: Signal-to-noise ratio is $\sim 1000\times$ for short runs, much less sensitive to backgrounds
- Disadvantage: Longer window means rate dependent effects are more important



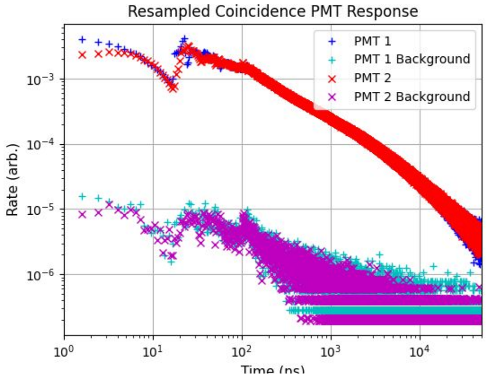


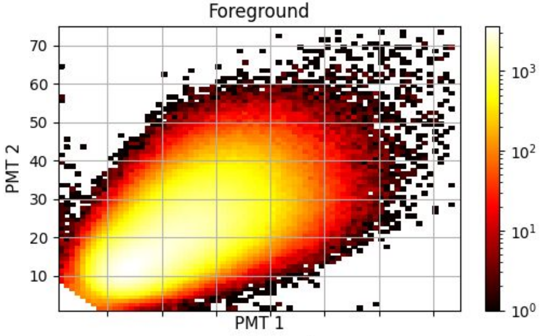
How Do We Reconstruct UCN Events?

- Form "Coincidences" by requiring multiple photons in a window
  - "Initial Window" 50 ns (must trigger on both PMTs)
  - Require ≥ 8 photons in first 1000 ns
  - "Telescoping Window" 1000 ns (either PMT, continues while photons arrive faster than this)

Structure of Events
  - ZnS:Ag Scintillator has a long "tail" ($\sim 10^{-5}$ s)
  - Typically see 20-30 events in each PMT

Reduces backgrounds by $O(100\times)$



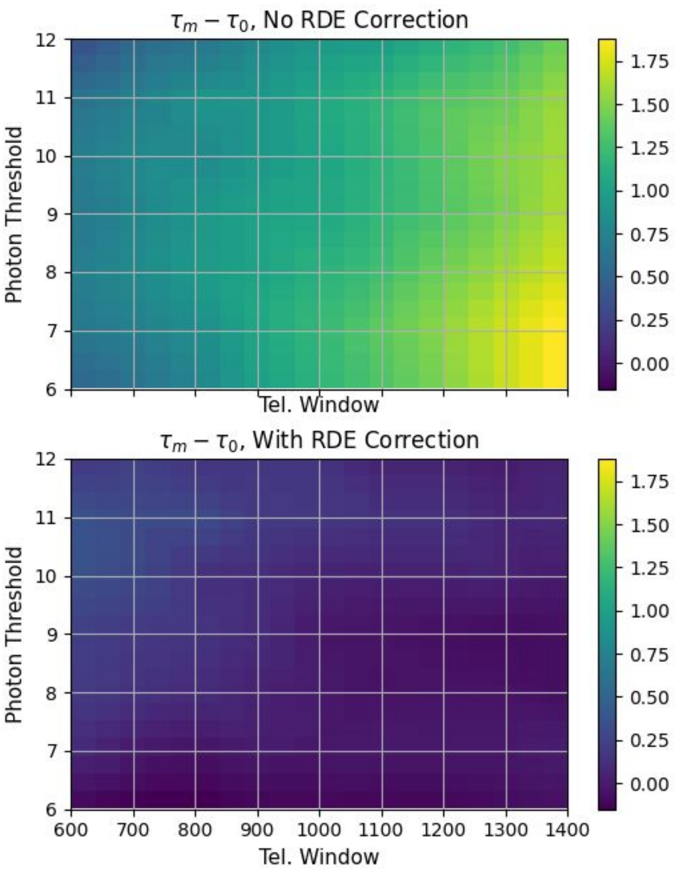


Accounting For Rate Dependent Effects

- Need constant efficiency between short/long
  - Peak neutron counting rate ~1 kHz
  - ZnS:Ag scintillator has ~10^{-5} s "glow"

Difficulties with coincidence algorithm's threshold and long window:
  - Deadtime: Two events close together might appear as one
  - Pileup: Photons in long tail can push noise over threshold

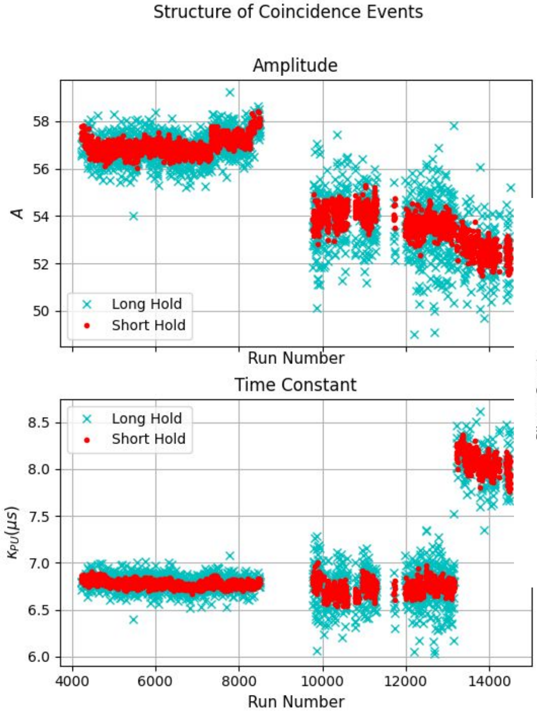
Correct for these on an event-by-event basis
  - Monte Carlo studies resampling data to study this shift
  - Contributes to $\Delta\tau_{RDE} = \pm 0.13$ s systematic uncertainty

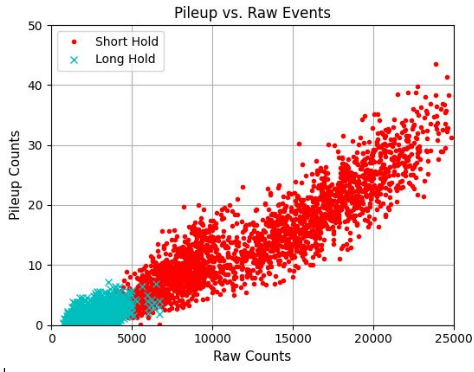


BONUS

Deadtime and Pileup Correction

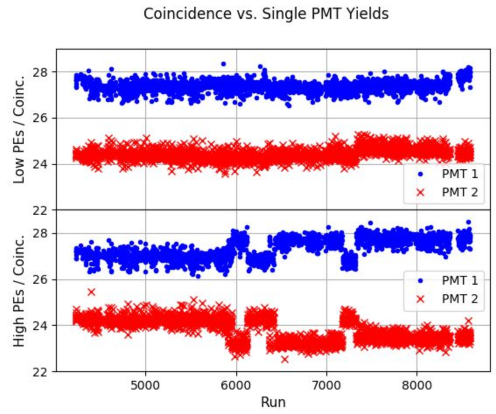
- Deadtime:
  - Can correct weights: $r = \frac{r_m}{1 - r_m \tau_{DT}}$
- Pileup:
  - De-weight coincidences by Poisson probability of extra photons:
    - $f = 1 - \sum_n^{thr.} \frac{\mu^n e^{-\mu}}{n!}$
  - Amplitude μ_i for each coincidence comes from:
    - $\mu_i = (A + \mu_{i-1}) \int_{t_{io}}^{t_{io}+t_{if}} P(t)dt'$
  - Overall amplitude:
    - $A = \frac{sing}{coinc}$
  - Assume single exponential probability:
    - $P(t) = e^{-t/\kappa_{PU}}$

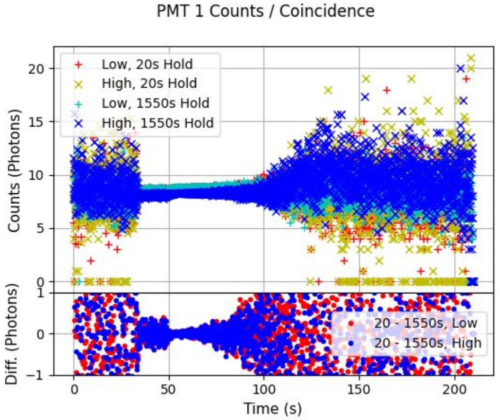




High and Low Threshol

- Two channels from the discriminator fed into datastream
  - One has low threshold, one has high threshold
- This analysis purely uses low threshold
  - High threshold shows evidence of gain shifts
  - Does not seem to be caused by rate-dependent gain shifts!

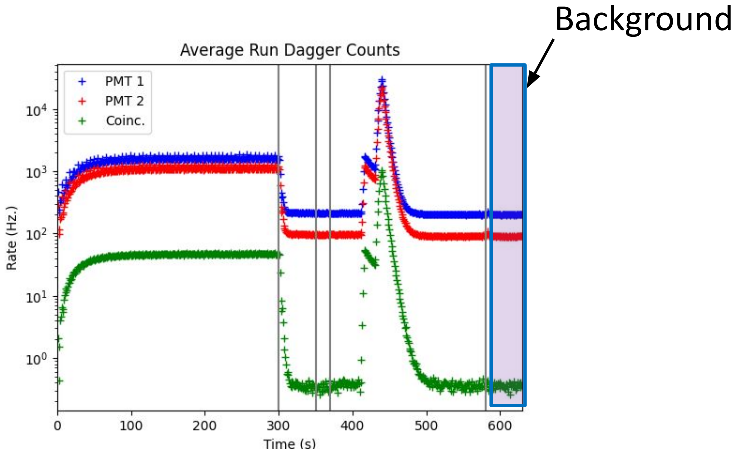


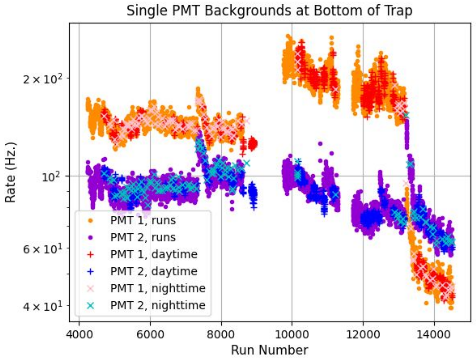


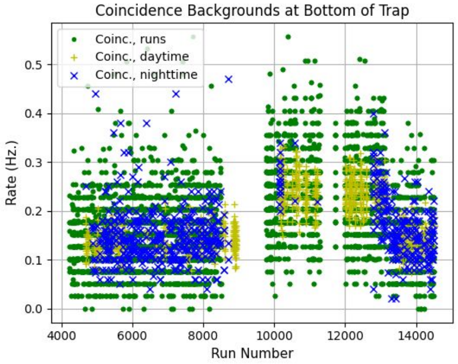
BONUS

Backgrounds During Production

- Various sources of backgrounds
  - PMT Dark Noise or Electronic effects
  - Cosmic rays
  - Other radiation in experimental area
- Must account for backgrounds on a run-by-run basis
  - At end of run, open trap to guides and count background rate
  - Dedicated background runs to understand position/time dependence
- Coincidence significantly improves stability of background!







$$Y_i = \frac{D_i - B_i}{f(M_i)}$$

Dedicated Background Runs

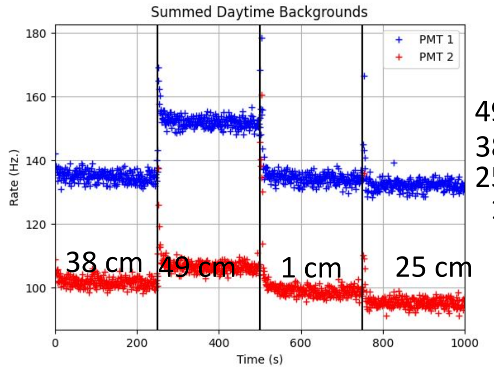
- In addition to end of run backgrounds, utilize dedicated background runs
  - Beam-off runs, moving dagger around
  - Beam-on runs, with the same timings as production

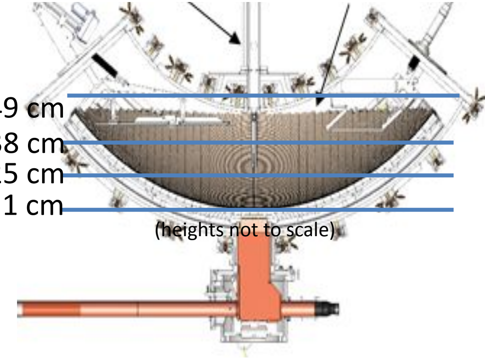
PMTs behave slightly differently depending on geometry, can't get this info from end of run!

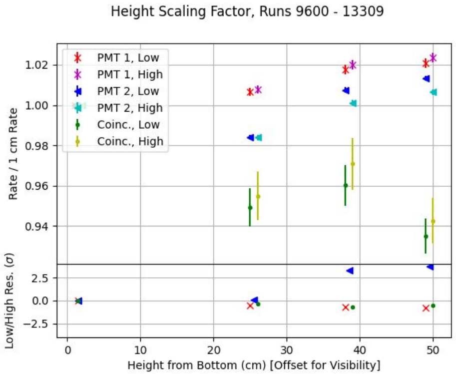
Background Model:

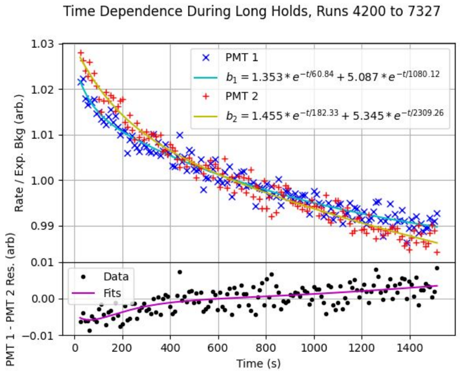
- $R(h,t) = f(h)\left(\sum_i \alpha_i e^{-t/\tau_i}\right)$
- For singles:
  - Height dependent $f(h)$ terms shift measured lifetime by ~ 1 s
  - Time dependent $\alpha_i e^{\frac{-t}{\tau_i}}$ terms shift measured lifetime by ~ 0.1 s

For coincidences $f(h)$ shifts lifetime by ~ 0.1 s

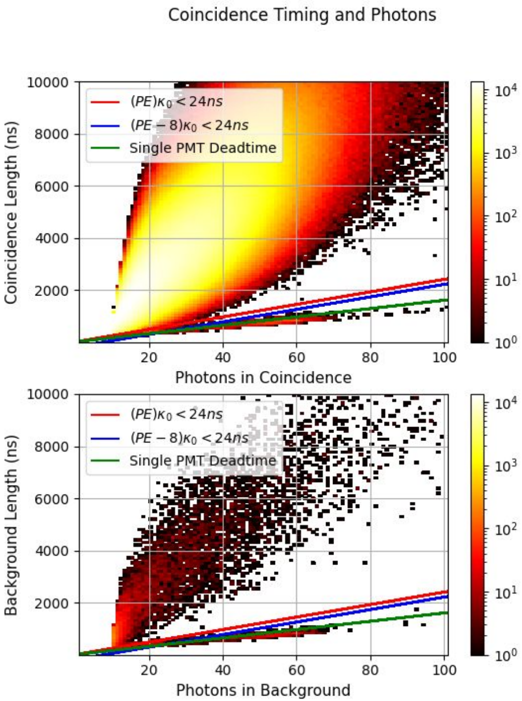








Types of Background Events



- Coincidence background rate ~ 0.1 Hz:
  - PMT Dark Noise only applies to singles analysis
  - Cosmic rays
  - Other radiation in experimental area

Some background events ($\sim 10^{-2}$ coincidence backgrounds) trigger at the fastest possible rate in detector

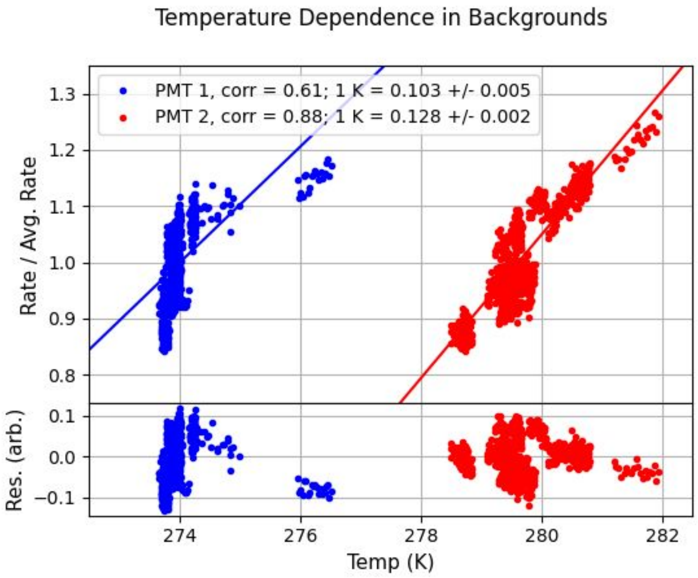
- Can reject these “Fast Coincidences” with a hard cutoff
- Occurs in both PMTs

Many backgrounds indistinguishable from UCN

BONUS

Backgrounds Temperature Dependence

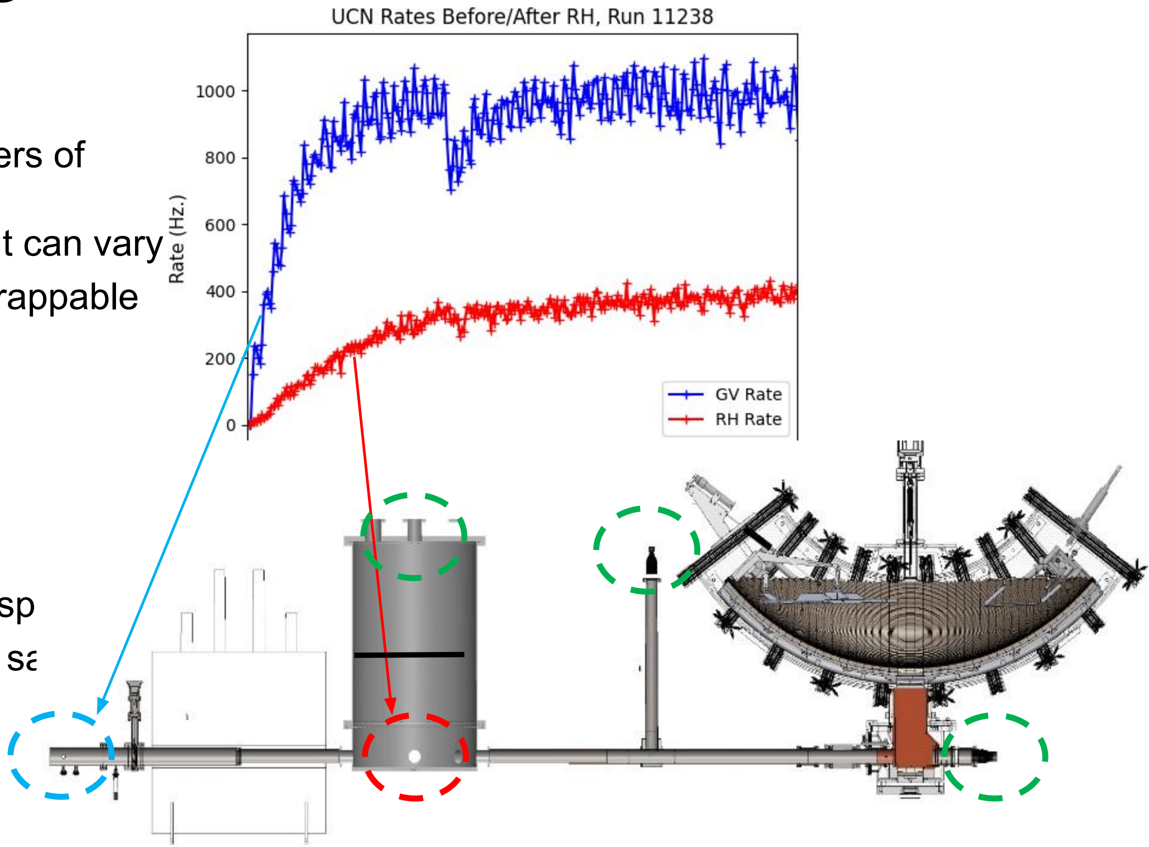
- Temperature dependence:
  - Have temperature monitoring for last couple hundred runs
  - Extracted Beam-off Rate Averages
- Temperature (cooling) not enough to account for height dependence
  - Not enough data to accurately fit
  - Point of improvement for future running
- Does not have a correlation with coincidence counting



BONUS

Filling With the Roundhouse

- Can't directly count the initial numbers of neutrons in the trap
  - Spallation source, so UCN output can vary
  - Utilize monitor detectors to see trappable neutrons from the source
- Between 2017 and 2018 introduced roundhouse buffer volume
  - Smooths the beam
  - Includes monitor detectors
  - New cleaner to precondition the sp
  - Filled for longer in 2018 to reach sa



BONUS

JA.00003

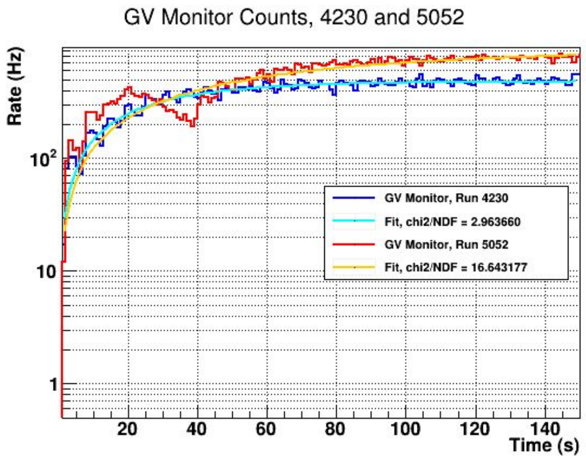
Run Selection

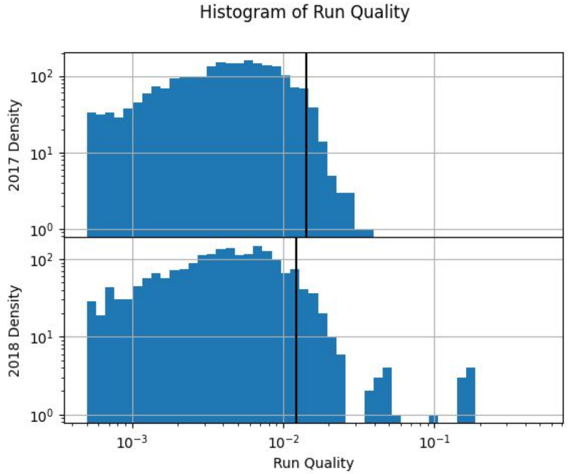
- Run-specific problems can cause poor normalization e.g.
  - Spallation source beam glitches
  - Trap door/Gate Valve failure
  - Light leaks

Glitches near the end of the fills affect yields more than at the beginning
  - Partially capture with monitor weighting function $w(t)$
  - $w(t)$ metric can vary by analyzer
    - Analysis A uses $w(t) = e^{\kappa t}$

Difficult to fully reconstruct these effects on the predicted yields
  - Need to remove “poor quality” runs
  - “Run Quality” metric can also vary by analyzer
    - Analysis A uses $\Phi_k = \left|\frac{D_k \,/\, M_k - \langle D/\,M\rangle}{\langle D\,/\,M\rangle}\right|$

In 2017, on-site shifters manually stopped runs, in 2018 this was not the case





Fitting the Spectral Parameters

- Want to use $M_i = \alpha\, m_m + \beta_s m_s$ to model initial counts in detector.

Least Squares Fitting:

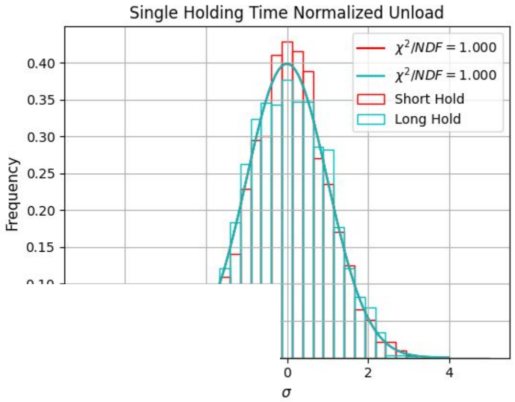
- Normalize to 20s holding times.
- Minimize (scipy curve_fit):

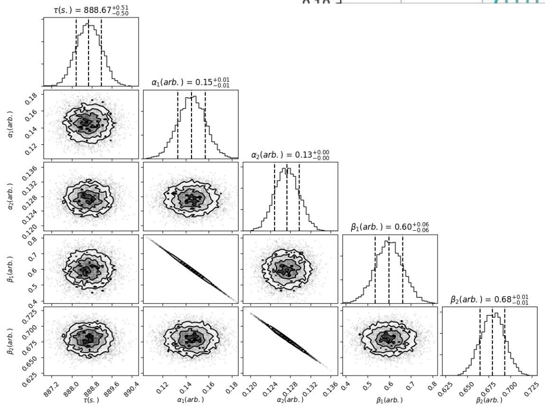
$$\chi^2 = \sum_i \left[\frac{(D_i - B_i) - (\alpha m_{m,i} + \beta_s m_{s,i})}{\sigma(D_i, B_i)} \right]^2$$

Likelihood Fitting:

- Normalize to all runs.
- Maximize (emcee Markov Chain Monte Carlo):

$$L\,(\tau; D_i, B_i, B, M_i) = \prod_i \frac{\left[M_i e^{-t/\tau} + B\right]^{D_i} e^{-[M_i e^{-t/\tau} + B]}}{D_i!} \times \frac{B^{B_i} e^{-B}}{B_i!}$$





Looking for Overthreshold UCN

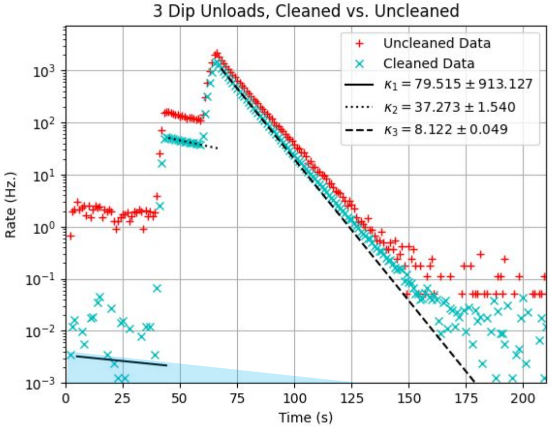
- Fit the counting times from uncleaned data and subtract these from normal production running
  - Separate long and short holding times
  - Very few counts in these regions

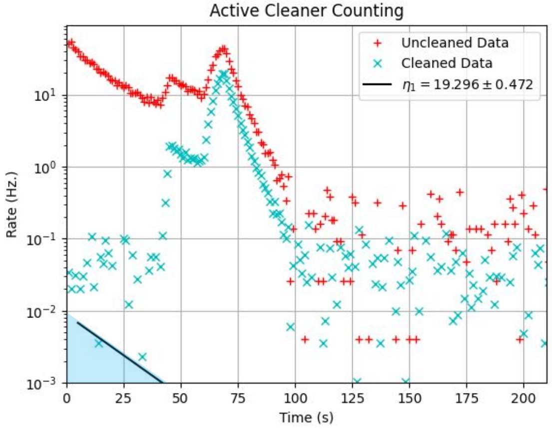
In 2018, also lowered AC with the first dip
  - More sensitive to peak 1 UCN
  - Much faster counting time as well

Data-Driven systematic uncertainty:
  - Heated UCN: $\Delta\tau_{heat} = 0 + 0.08$ s
  - Uncleaned UCN: $\Delta\tau_{heat} = 0 + 0.11$ s
  - Only applies in 1 direction

Over-threshold Neutrons suppressed to 1.8×10^{-5}!

Dagger Counting





Holley, A.T. Personal Communication 10/2/2019

Depolarization

- Neutrons are polarized
  - Recall: $V = -\vec{\mu} \cdot \vec{B}$
  - Want only low-field seeking UCN
  - High-field seeking UCN get pulled towards the Halbach array and lost

Magnetic field zeros can cause depolarization

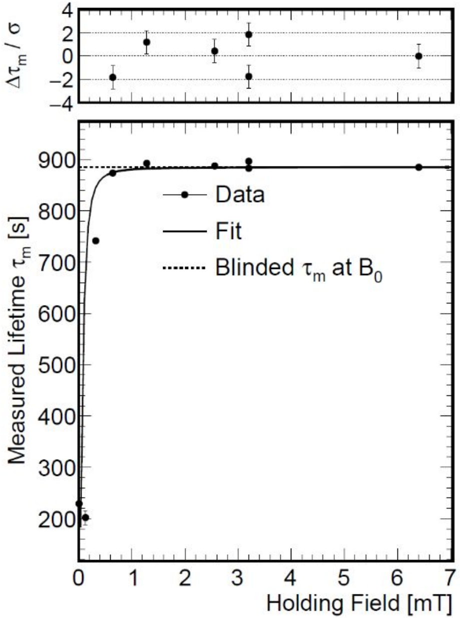
High magnetic field gradients can cause depolarization or heating

Accounting for these:
- Holding Field Scans:
  - $\tau_{depol} = 1.1 \times 10^7$s
  - $\Delta\tau_{meas} = 0 \pm 0.07$ s
- Magnetic field mapping program to identify field zeros

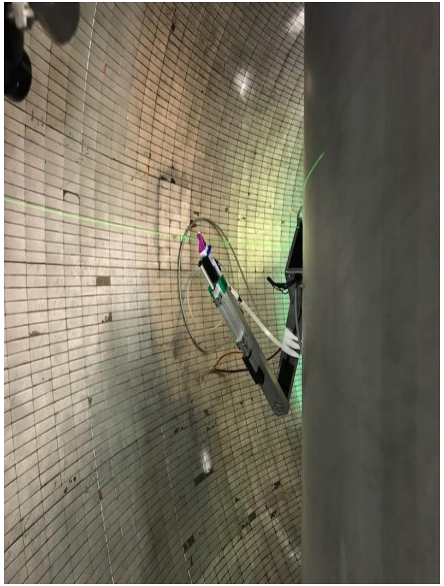
No additional work since last result

Shift in measured lifetime as a function of holding field, fitted to:

$$\frac{1}{\tau_{meas}} = \frac{1}{\tau_n} + \left(\frac{B_{\perp 0}}{B_\perp}\right)^2 \frac{1}{\tau_{depol}}$$



Magnetic Field Mapper



A. Steyerl, *et. al.*, Spin flip loss in magnetic confinement of ultracold neutrons for neutron lifetime experiments. Phys. Rev. C Nucl. Phys. 95, 035502 (2017).

BONUS

Residual gas interactions

- Trap vacuum is $\sim 2 \times 10^{-7}$ torr during holding times, improving by a factor of 3 over 2016/2017

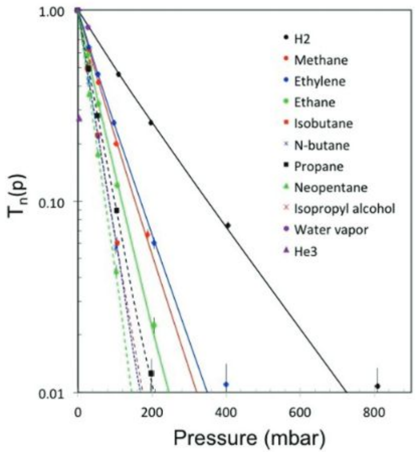
RGA scans measure concentration of gasses, and CC monitors measure pressures in the experiment

- Main contaminants include H_2O, N_2, O_2

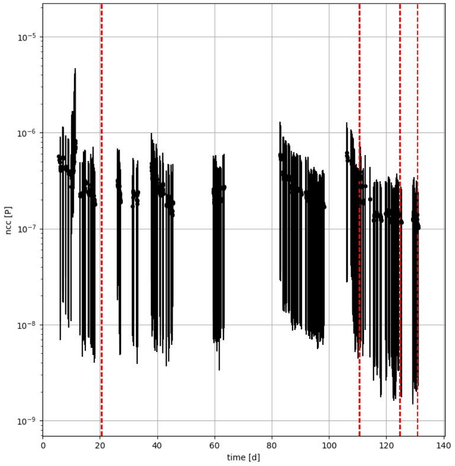
No correlation between trap pressures and yield

Lifetime Shift: $\Delta\tau_{gas} = 0.11 \pm 0.06$ s

Transmission Measurements Through a Gas-Filled Neutron Guide



Range of Pressures During Holds



Seestrom, S. J., *et al.*, Total cross sections for ultracold neutrons scattered from gases. Phys. Rev. C Nucl. Phys. 95, 015501 (2017).

BONUS

JA.00003

Quantifying an Accidental New Systematic

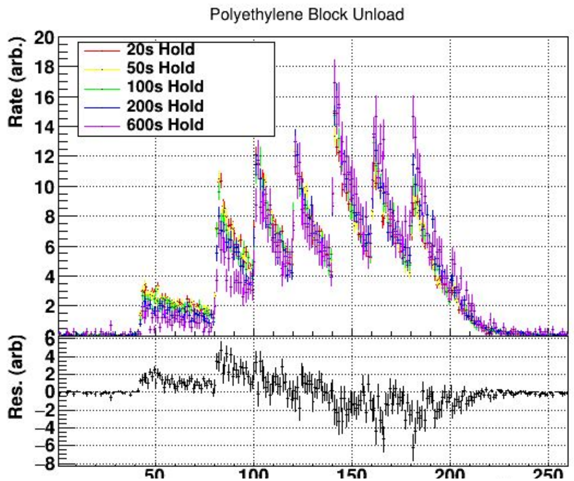
- Causes phase space evolution!

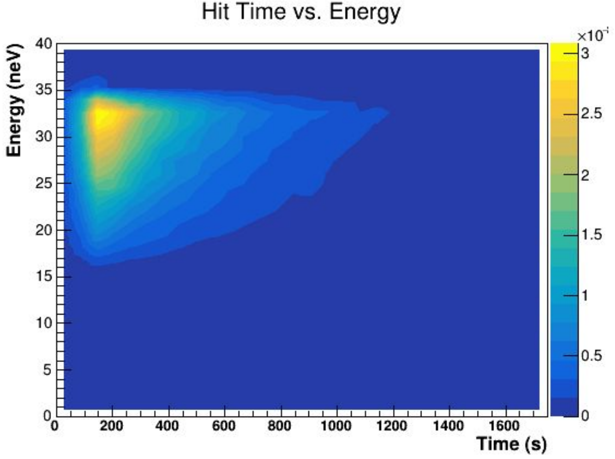
Aluminum block from top of trap could upscatter UCN during the hold
- Low loss per bounce on Aluminum: $\sim 10^{-4}$
- Shielded by $\sim$0.25 T field, minimum energy around 15 neV

Combination of methods:
- Use high-loss material to find lifetime of block
- Use trajectory simulations

$\Delta\tau_{Al} = 0.14 \pm 0.10$ s in contaminated data

Becomes $\Delta\tau_{Al} = 0.06 \pm 0.05$ s over all data

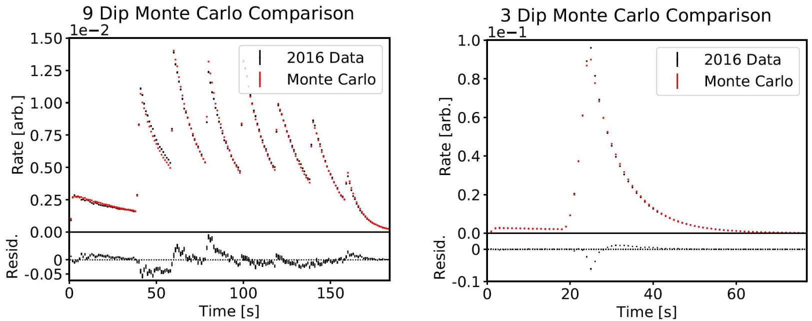


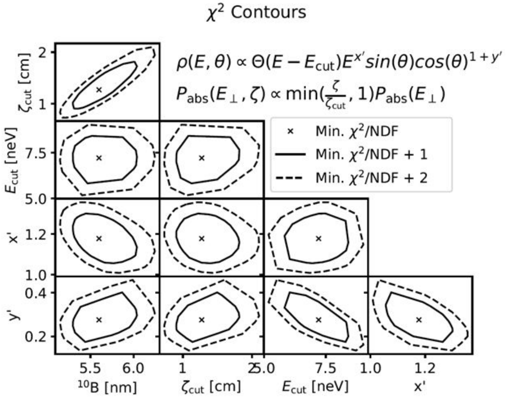


BONUS

Simulations to Tackle Systematics

- Use neutron trajectory simulations on IU's Big Red 3 supercomputer
  - Symplectic integrator
  - Idealized magnetic field
- Fit Monte Carlo to 9-dip unload data
  - Tune Monte Carlo initial neutron energy, initial angular distribution, and detector parameters
  - Optimized fit works with 3-dip data as well





Callahan, N. *et al.* Monte Carlo Simulations of Trapped Ultracold Neutron Trajectories in the UCNτ Experiment. Physical Review C. 100, 015501 (2019)

BONUS

Overthreshold Simulations

- Can also benchmark loss rates with simulations
  - Heating MC predicts:

$$\Delta\tau_{heat,MC} = 0.031 \pm 0.005\ \text{s}$$

  - Uncleaned MC predicts:

$$\Delta\tau_{unc,MC} = 0.034 \pm 0.006\ \text{s}$$

Investigate these by looking at data taken without cleaning

- Simulate what we expect to happen