Characterization of the new Ultracold Neutron beamline at the LANL UCN facility

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Abstract

The neutron electric dipole moment (nEDM) experiment that is currently being developed at Los Alamos National Laboratory (LANL) will use ultracold neutrons (UCNs) and Ramsey's method of separated oscillatory fields to search for a nEDM. We present measurements of UCN storage and UCN transport during the commissioning of a new beamline at the LANL UCN source and demonstrate a sufficient number of stored polarized UCNs to achieve a statistical uncertainty of $\delta d_n = 2 \times 10^{-27}\ e \cdot \mathrm{cm}$. We also present an analytical model describing data that provides a simple parameterization of the input UCN energy spectrum on the new beamline.

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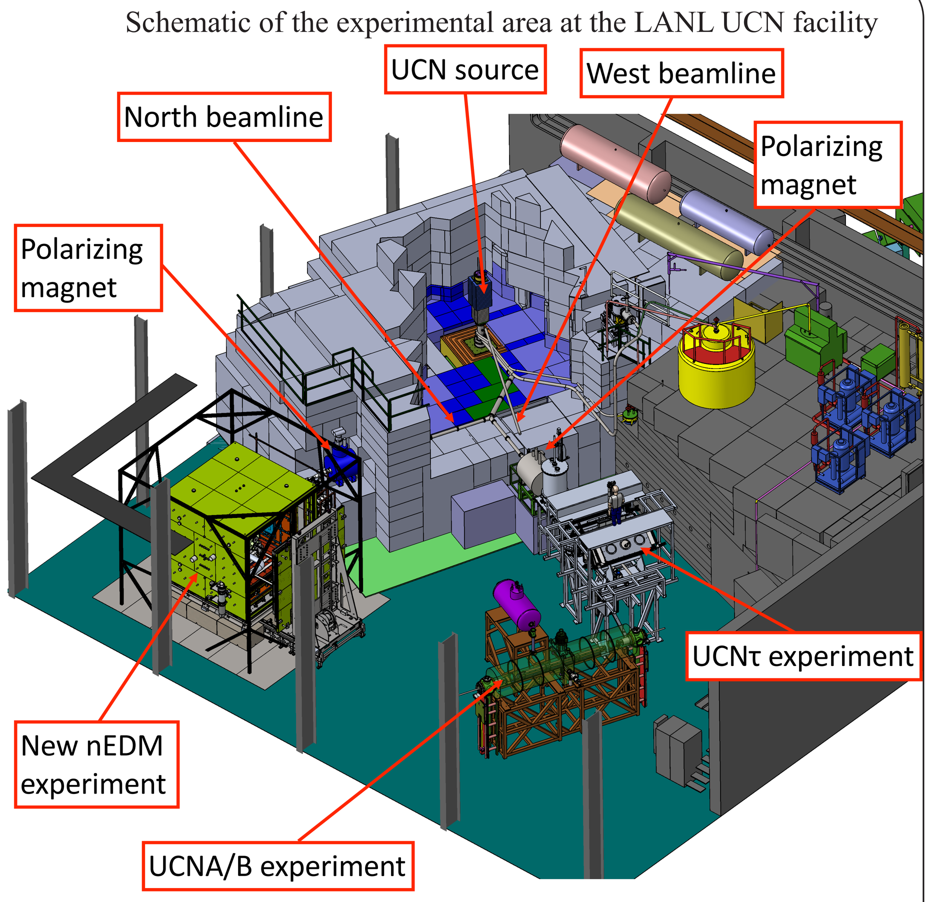
Introduction

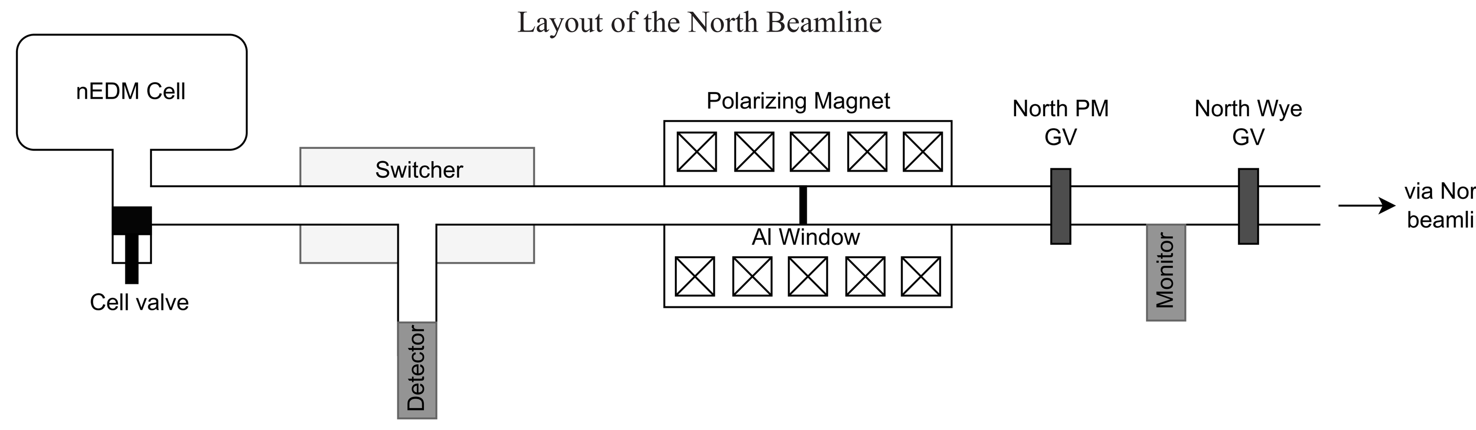
- Ultracold neutrons (UCNs) are neutrons of low kinetic energy (< 340 neV) that may be confined in material or magnetic bottles
- A nonzero neutron electric dipole moment (nEDM) signifies violation of charge conjugation (C) and parity (P) symmetries and may provide insight into the baryon asymmetry of the universe
- For a nEDM search using the Ramsey Method to achieve a statistical uncertainty of $\delta d_n = 2 \times 10^{-27}\ e \cdot \mathrm{cm}$ careful characterization of the UCN beamline is required
- Measurements were taken on the "North" UCN beamline at the LANL UCN facility to measure storage properties of the UCN precession cell, input UCN energy spectrum, and UCN density at the location of the experiment

Schematic of the experimental area at the LANL UCN facility



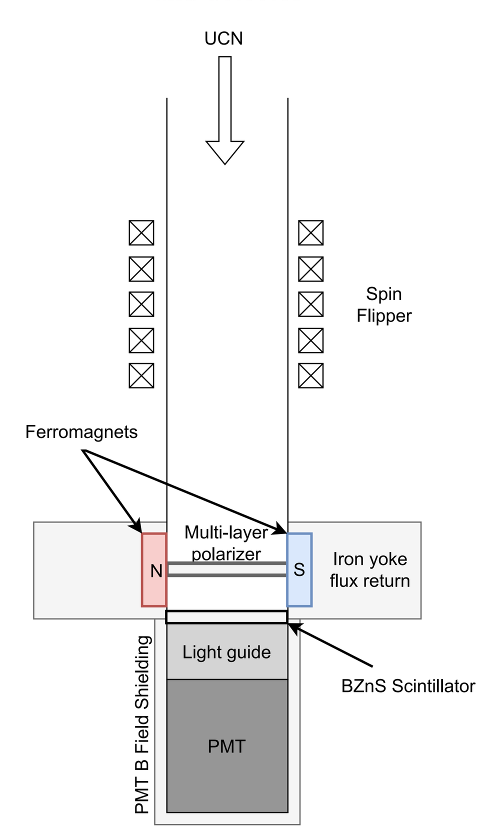
Experimental Setup & Measurement

Layout of the North Beamline

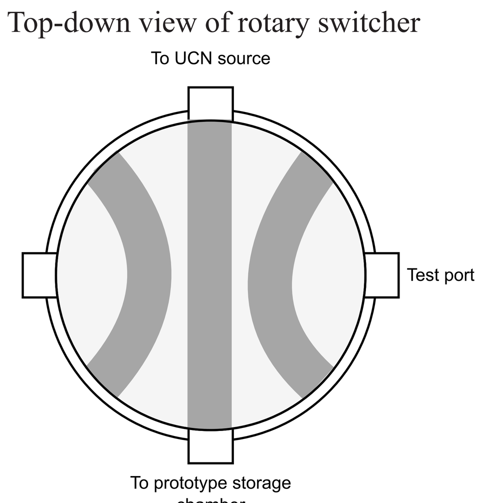


- 5 T, horizontal warm bore, superconducting magnet used as a polarizing magnet (PM). A thin ((0.0762 mm) Al foil, termed the "PM window", is located in the beamline at the center of the PM field region to separate UCN source vacuum from measurement apparatus vacuum.
- The PM field is effectively a UCN spin filter, acting as a potential barrier that rejects low-field seeking UCN below 300 neV and a potential well that passes high-field seeking UCN.
- All guide sections downstream of the PM had a 50 μm-thick electroless nickel phosphorus (NiP) coating
- A UCN switcher was located downstream of the PM to divert UCN from source to the cell, or from the cell to a UCN spin analyzer and detector
- A neutron spin analyzer that consisted of a 10 layer polarizer made of iron and silicon was located immediately above the drop detector. This polarizer was magnetized with a 10 mT field from permanent magnets and preferentially transmits high-field seeking UCN
- UCN detection achieved via ^{10}B ZnS:Ag scintillator films. UCNs were captured on the top layer of ^{10}B, and reaction products (^{4}He and/or ^{7}Li) from the ^{10}B(n, α)^{7}Li neutron capture reaction were detected in the ZnS:Ag layer. Scintillation light is then captured with a photomultiplier tube
- UCN were stored in cylindrical cell with an inner diameter of 50 cm and a height of 10 cm, giving a total volume of 19.6 L.
- Storage time measurements of UCN were performed with different precession cell walls: (i) NiP coated Al and (ii) dPS coated poly(methyl methacrylate) (PMMA). Storage curve scans were repeated with PM strengths of 0 T, 1.25 T, 2.5 T, 3.75 T and 5 T.
- Direct "flow-throw" measurements of UCN transmission through the PM were taken to provide information on the incoming UCN energy spectrum. Magnetic field of PM slowly decreased from 5 T to 0 T over 72 minutes. UCN were spin flipped by an adiabatic fast passage spin flipper above the drop detector every 70 s.

Single channel UCN spin analyzer and detector



Top-down view of rotary switcher



Analysis

UCN storage curve model (no PM window)

$$N(t) = C \int_{v_{\mathrm{low}}}^{v_{\mathrm{high}}} dv \frac{dN_1}{dv} e^{-\frac{t}{\tau(v',\bar{\mu})}}$$

$$\frac{1}{\tau(v',\bar{\mu})} = \frac{1}{\tau_\beta} + \frac{Av'}{4\ \mathrm{Vol}}\bar{\mu}$$

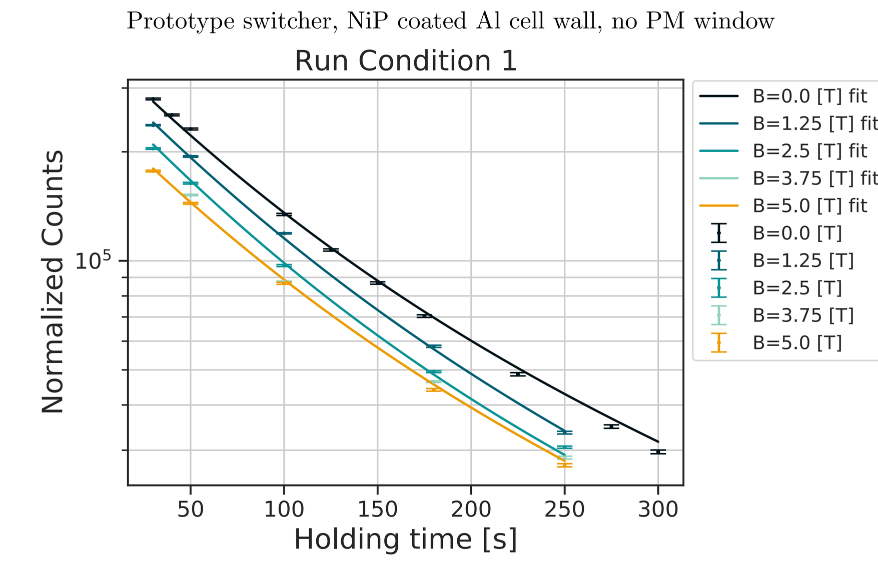
$$\bar{\mu} = 2\mu \left[\frac{V_{\mathrm{Fermi}}^{\mathrm{cell}}}{K(v')} \sin^{-1}\left(\frac{K(v')}{V_{\mathrm{Fermi}}^{\mathrm{cell}}}\right)^{1/2} - \left(\frac{V_{\mathrm{Fermi}}^{\mathrm{cell}}}{K(v')} - 1\right)^{1/2} \right]$$

$$\frac{dN_1}{dv} = \frac{1}{2} v^\alpha \left[\frac{1}{2} + f_\ell + \beta\left(\frac{1}{2} - f_\ell\right)\right]$$

$$f_\ell = \begin{cases} \frac{1}{2}\left(1 - k\left(\frac{v_\parallel^c}{v}\right)\right) & \text{for } v > v_\parallel^c \text{ where } v_\parallel^c = \sqrt{2\mu_N B/m_N} \\ 0 & \text{otherwise} \end{cases}$$

- The above model fits UCN storage curves for various PM strengths (no Al window)
- Free parameters:
  - C – Scaling constant
  - α – Velocity spectrum distribution
  - μ – Velocity dependent loss per bounce
  - k – Angular distribution. Range [0,1]
    - (Closer to 1 = more isotropic)
  - β – Depolarization probability of low field seekers upstream of the PM

Prototype switcher, NiP coated Al cell wall, no PM window



- f_L refers to the fraction of low field seekers allowed past the PM. The PM passes low field seeking neutrons if $\frac{1}{2}m_n(v_l)^2 > \mu_n B$
- With no window, the PM passes all high field seeking neutrons. (For an isotropic upstream distribution, $f_h = 1/2$)

UCN storage curve model (w/ PM window)

$$N(t) = C \int_{v_{\mathrm{low}}}^{v_{\mathrm{high}}} dv \frac{dN_1}{dv} e^{-\frac{t}{\tau(v',\bar{\mu})}}$$

$$\frac{1}{\tau(v',\bar{\mu})} = \frac{1}{\tau_\beta} + \frac{Av'}{4\ \mathrm{Vol}}\bar{\mu}$$

$$\bar{\mu} = 2\mu \left[\frac{V_{\mathrm{Fermi}}^{\mathrm{cell}}}{K(v')} \sin^{-1}\left(\frac{K(v')}{V_{\mathrm{Fermi}}^{\mathrm{cell}}}\right)^{1/2} - \left(\frac{V_{\mathrm{Fermi}}^{\mathrm{cell}}}{K(v')} - 1\right)^{1/2} \right]$$

$$\frac{dN_1}{dv} = \frac{1}{2} v^\alpha \left[f_h + f_\ell + \beta\left(f_h - f_\ell\right)\right]$$

$$f_\ell = \begin{cases} \frac{1}{2}\left(1 - k\frac{v_\parallel^c}{v}\right) & \text{for } v > v_\parallel^c \text{ where } \frac{1}{2}m\left(v_\parallel^c\right)^2 = V_{\mathrm{F}}^{\mathrm{Al}} + \mu B \\ 0 & \text{otherwise} \end{cases}$$

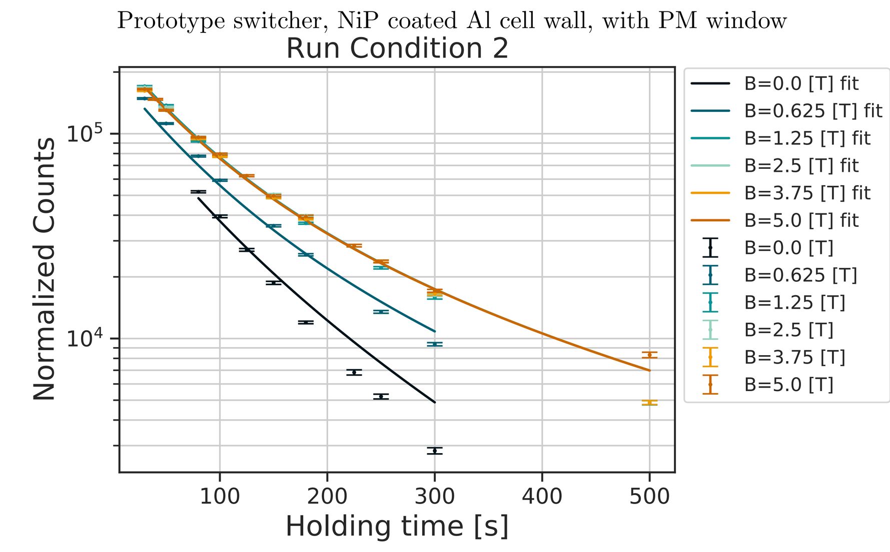
$$f_h = \begin{cases} \frac{1}{2}\left(1 - k\frac{v_\parallel^c}{v}\right) & \text{for } v > v_\parallel^c \text{ where } \frac{1}{2}m\left(v_\parallel^c\right)^2 = V_{\mathrm{F}}^{\mathrm{Al}} - \mu B \\ & \text{and } V_{\mathrm{F}}^{\mathrm{Al}} > \mu B \\ 0 & \text{for } v \le v_\parallel^c \text{ where } \frac{1}{2}m\left(v_\parallel^c\right)^2 = V_{\mathrm{F}}^{\mathrm{Al}} - \mu B \\ & \text{and } V_{\mathrm{F}}^{\mathrm{Al}} > \mu B \\ \frac{1}{2} & \text{for } V_{\mathrm{F}}^{\mathrm{Al}} \le \mu B \end{cases}$$

Table 2: Multi-parameter fits of UCN storage curves

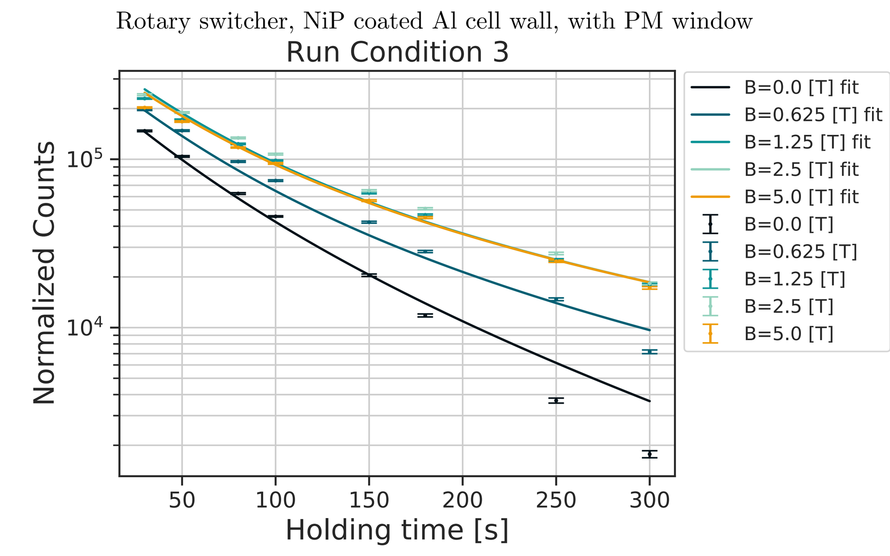
Run	1	2	3	4	3 & 4	
$C/10^3$	2(1)	3(1)	5(3)	5(3)	4(1)	7(2)
α	3.0(3)	2.5(2)	2.5(3)	2.7(2)	2.6(2)	
β	0.30(2)	0.8(2)	0.6(3)	0.8(2)	0.77(17)	
k	0.3(1)	0.6(1)	0.7(1)	0.5(1)	0.6(1)	
$\mu/10^{-4}$	2.0(1)	2.6(2)	3.5(4)	3.1(2)	3.4(2)	
Corr(C,α)	−1	−0.94	−0.96	−0.96	−0.97	−0.96
Corr(C,β)	−0.2	−0.32	−0.4	−0.5	−0.49	−0.53
Corr(C,k)	−0.7	−0.14	−0.14	0.02	−0.16	−0.12
Corr(C,μ)	0.9	0.85	0.77	0.79	0.78	0.76
Corr(α,β)	−0.2	0.01	0.15	0.27	0.23	
Corr(α,k)	0.71	0.44	0.37	0.22	0.41	
Corr(α,μ)	−0.97	−0.92	−0.84	−0.83	−0.82	
Corr(β,k)	−0.33	−0.86	−0.81	−0.83	−0.72	
Corr(β,μ)	0.21	0.14	0.16	−0.03	0.01	
Corr(k,μ)	−0.6	−0.56	−0.63	−0.41	−0.57	
Corr(C_3,C_4)					1	

- The same set of free parameters may be fit to a situation when there is a PM window present (Run Conditions 2 - 4).
- Low-field seekers must now have a high enough velocity to overcome both the PM field potential and the Al window step potential
- High-field seekers must also have a high enough velocity to overcome the window step potential, but receive the benefit of being accelerated by the PM field

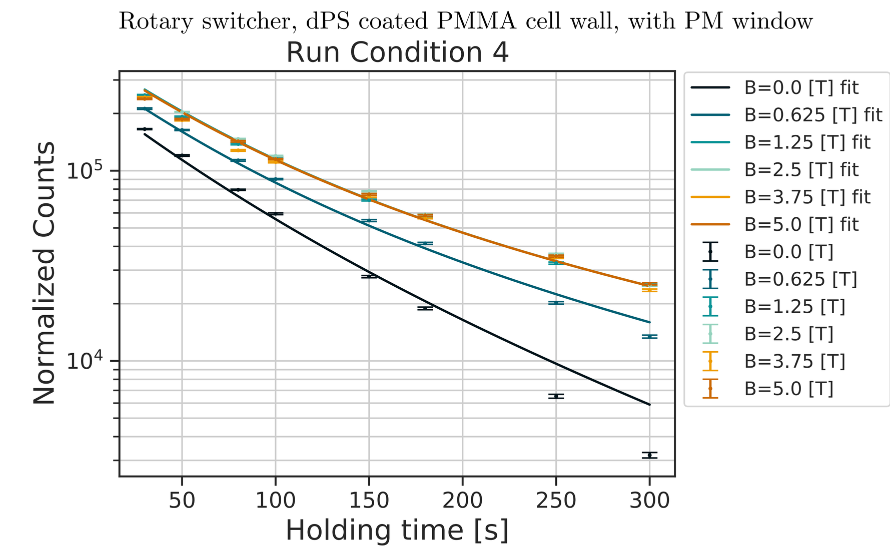
Prototype switcher, NiP coated Al cell wall, with PM window

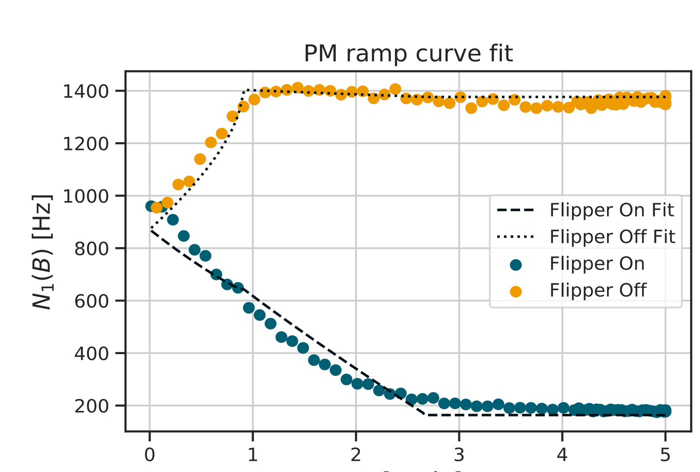


Rotary switcher, NiP coated Al cell wall, with PM window



Rotary switcher, dPS coated PMMA cell wall, with PM window





Run condition	α	β	k
With Al window, UCN-flow throw mode	1.0(1)	0.00(5)	0.30(2)

$$\frac{dN_{1,\ell}}{dv} = \frac{1}{2}v^\alpha f_\ell = \frac{1}{2}v^\alpha f_{\ell D}$$

$$\frac{dN_{1,h}}{dv} = \frac{1}{2}v^\alpha \left[f_h + \beta\left(f_h - f_\ell\right)\right] = \frac{1}{2}v^\alpha f_{hD}$$

$$\frac{dN_{\mathrm{off}}}{dv} = \frac{1}{2}v^\alpha \left[A\, f_{hD} + (1-A) f_{\ell D}\right]$$

$$\frac{dN_{\mathrm{on}}}{dv} = \frac{1}{2}v^\alpha \big[A\, S\, f_{\ell D} + A(1-S) f_{hD} + (1-A)S\, f_{hD} + (1-A)(1-S)\, f_{\ell D}\big]$$

- Holding curve model may be adapted to fit a "flow-through" UCN transmission measurement for finite spin flipper flipping power S and finite spin analyzer efficiency A

Discussion

- As measured in run condition 4, $B = 5$, a storage time of 180 s in a single cell yields a UCN count of ~60,000 UCN, well in excess of number required to reach desired nEDM statistical uncertainty in terms of UCN density
- UCN storage curve model describes both window-in and window-out storage configurations with the same input parameters.
- Value of C in run condition 3 and 4 is larger than in run condition 2, showing that the rotary switcher transports a larger number of UCN than an old prototype switcher.
- k ranging from 0.3(1) to 0.7(1)) across all run conditions indicates that the angular distribution of the input UCN velocity spectrum on the beamline is relatively forward directed.
- β is ~ 0.7 for run conditions with the Al window and is ~ 0.3 for the run condition without the window. This is consistent with the idea that the presence of the Al window reduces the number of low-field seeking UCN that pass the PM region, increasing the chance for a low-field seeker to see a depolarizing region upstream of the PM
- In some cases there are large parameter correlations in the multi-parameter fits. Special care was taken in the least-squares fitting process to choose initial parameter guesses for α and μ that were based on previous measurements along the West Beamline (see 10.1016/j.nima.2017.07.051 and 10.1103/PhysRevC.97.012501) because of these correlations
- The holding curve model may be adapted to a UCN flow-through measurement through a PM with an Al window, while the PM slowly ramps up or down. We observe that the model is able to reproduce the major features of the data