

Ultracold Neutron Energy Spectrum and Storage Properties from Magnetically Induced Spin Depolarization

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(Received 10 November 2025; revised 30 January 2026; accepted 14 April 2026; published 5 June 2026)

We present a novel method for extracting the energy spectrum of ultracold neutrons from magnetically induced spin depolarization measurements using the n2EDM apparatus. This method is also used to exploit sensitivity to the storage properties of the materials used to trap ultracold neutrons, specifically, whether collisions are specular or diffuse. To do so, we utilize TOMaT simulation to map storage properties to correlation times of the ultracold neutrons to induced magnetic nonuniformities. We highlight the sensitivity of this new technique by comparing the two different storage chambers of the n2EDM experiment, which host different ultracold neutron energy spectra. This method should prove to be invaluable to assess systematic effects in experiments utilizing spin-polarized systems with precise magnetic control and long spin-spin coherence time relative to the observation time, such as neutron electric dipole moment and neutron lifetime experiments worldwide.

DOI: [10.1103/hspm-dwkn](https://doi.org/10.1103/hspm-dwkn)

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Introduction—Spin decoherence due to magnetic field noise or nonuniformities is often a limitation in many precision nuclear and particle physics experiments, such as in spin gases [1,2] and ion traps [3]. However, magnetic nonuniformities can be leveraged to improve the utility of many systems: enabling nanoscale spin-imaging [4] and ultrasensitive electrometry [5], improving the manipulation of quantum gates [6,7] or continuous time crystals [8], and permitting sensitive surface probes [9,10]. They can even be used as tools of discovery, including possibly quantum gravity signatures [11]. Here, we utilize magnetic nonuniformities to extract the trapped energy spectrum of a spin-polarized ensemble of ultracold neutrons (UCNs).

UCNs are free neutrons of very low energy (less than ~ 300 neV) and can be materially, magnetically, or gravitationally trapped for measurements on the same timescale as the neutron lifetime [12–18], enabling fundamental precision physics experiments to take place, such as studying the neutron lifetime and, as discussed here, the neutron electric dipole moment (nEDM) with the n2EDM apparatus [19]. In many of these experiments, a significant limitation in assessing systematic effects is the poor knowledge of the UCN energy spectrum in the trap. In neutron lifetime experiments, UCNs that are marginally trapped can mimic shorter neutron lifetime [17,20], and thus, knowing the energy spectrum within the trap can allow better control of systematics. In storage nEDM experiments that utilize thermal atoms for comagnetometry [21], the vertical center-of-mass offset of the slow UCN ensemble and its “sagging” in the trap (with respect to the geometrical center) can lead to a sizable difference in the sensed magnetic field between UCN and atoms in the presence of a magnetic field gradient (thereby leading to resonant frequency shifts) [19,22,23]. Additionally for nEDM experiments, the motion of particles in a nonuniform magnetic field with an electric field induces a “false” EDM signal proportional to the squared velocity [24–27], and thus precise knowledge of the energy spectrum will be important to estimate this systematic effect.

Beyond the energy spectrum of UCNs in the trap, the specularity of reflections and loss-per-bounce of the material trap play substantial roles. The roughness of the trap surfaces determines the fraction of specular reflections, which influences the spin depolarization [27,28] and influences the characteristic times to fill and empty the trap volume.

Here we present a new method for extracting the UCN energy spectrum and the fraction of specular reflection of material traps using magnetically induced spin depolarization. Unlike other approaches to access the energy spectrum [29,30], which often require experimental modifications (such as changing storage materials or detector heights) or suffer from extrapolating measurements to the original setup, this Letter relies solely on magnetic gradients that are generated from coils surrounding the material trap. While similar to Refs. [23,31] in extracting the spectral information, here we can simultaneously extract the fraction

of specular reflection of the material trap for the first time. This Letter can be advantageous to other spin-polarized systems like ours, where the spin-spin coherence time is long compared to the observation time, and spin depolarization due to wall collisions is minimal (discussed later). Experiments utilizing spin-polarized UCNs (at TRIUMF, LANL, ILL, etc.) may benefit from this method to extract the spin-polarized UCN energy spectrum.

Magnetic spin depolarization—In the n2EDM experiment, UCNs are spin polarized and then filled into a material trap positioned inside vertical, collinear electric and magnetic fields (also collinear with gravity). The resonance frequency in the 940 nT magnetic field and 15 kV cm^{-1} electric field is then extracted via Ramsey’s method of separated oscillating fields [32], whereby a magnetic pulse rotates the spins into a coherent superposition in the transverse plane, they freely precess for some time T , and then a second pulse converts the accumulated phase into a spin-population difference, measured by counting neutrons in their respective spin state, $N_{\uparrow}$ and $N_{\downarrow}$.

During this process, UCN spins can be depolarized through several channels. Magnetically induced depolarization can occur through wall collisions, *intrinsic* depolarization (due to magnetic field inhomogeneities), and through an energy-dependent relative dephasing of different UCN energy groups in a vertical magnetic-field gradient, referred to as gravitationally enhanced depolarization. The depolarization due to wall collisions for our precession times is negligible in n2EDM (discussed later). Intrinsic and gravitationally enhanced depolarization have been thoroughly discussed in Refs. [19,23,27,31], and can be summarized by the following equations. Gravitationally enhanced depolarization is expressed as

$$\alpha_{\text{grav}}(G_{1,0}) = \alpha_0 \int n(\epsilon) \cos(\gamma_n G_{1,0} T(\bar{z}(\epsilon) - \langle z \rangle)) d\epsilon, \quad (1)$$

where α is the final spin polarization of the UCN ensemble, $n(\epsilon)$ is the normalized energy spectrum, α_0 is the final polarization at zero gradient (see Fig. 1), $T = 180$ s is the spin precession time, γ_n is the neutron gyromagnetic ratio. To describe the magnetic field in the chamber, we use the harmonic polynomial expansion detailed in Ref. [27], where $G_{i,j}$ are harmonic expansion coefficients. $G_{1,0}$ then describes a vertical gradient ($\partial_z B_z$). The vertical center-of-mass offset of the neutron ensemble is $\langle z \rangle$, where $\bar{z}(\epsilon)$ is the offset for each energy group. See Refs. [19,23,31] for discussion on $\bar{z}(\epsilon)$.

Intrinsic depolarization is characterized by the depolarization rate $1/T_{2,\text{mag}}$, and defined as

$$\begin{aligned} \alpha_{\text{int}}(G_{i,j}) &= \alpha_0 \int n(\epsilon) \exp(-T/T_{2,\text{mag}}(\epsilon, G_{i,j})) d\epsilon \\ T_{2,\text{mag}}^{-1}(\epsilon, G_{i,j}) &= \gamma_n^2 \int \langle b_{z,[i,j]}(0) b_{z,[i,j]}(\tau) \rangle d\tau \\ &\equiv \gamma_n^2 \langle b_{z,[i,j]}^2 \rangle \tau_{i,j}(\epsilon). \end{aligned} \quad (2)$$

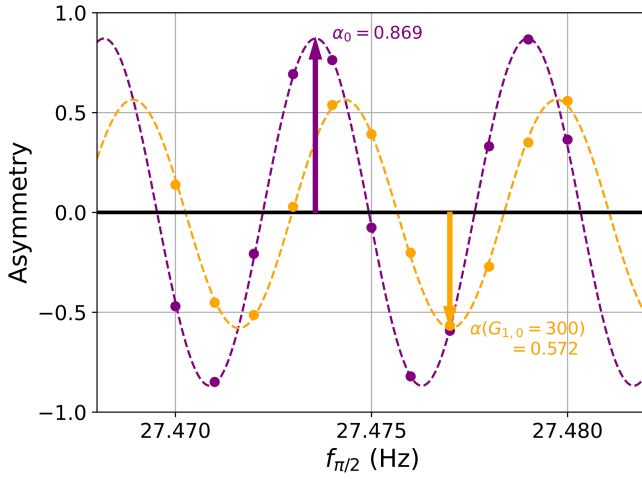


FIG. 1. Measured spin asymmetry $A = (N_{\uparrow} - N_{\downarrow}) / (N_{\uparrow} + N_{\downarrow})$ as a function of the driving frequency to induce a $\pi/2$ spin flip pulse, $f_{\pi/2}$, in two magnetic field configurations. Purple: $B = 940$ nT with no vertical gradient. Orange: $B = 940$ nT with a vertical gradient of $G_{1,0} = \partial_z B_z = 300$ pT cm $^{-1}$. Following Eq. (1), α decreases with G . The statistical uncertainty on the asymmetry is shown but not visible and on the order of 1%. In both cases, the precession time is $T = 180$ s. The asymmetry is fitted to $A(f_{\pi/2}) = -\alpha \cos[(\pi/\Delta\nu)(f_{\pi/2} - f_n)]$ in order to extract the final polarization α , where f_n is the neutron Larmor precession frequency to be extracted, $1/\Delta\nu = 2T + 8t_{\pi/2}/\pi$, and the duration of the $\pi/2$ pulse is set to $t_{\pi/2} = 2$ s. The curves shift in $f_{\pi/2}$ due to an induced frequency shift in f_n proportional to G .

Here, $\langle b_{z,[i,j]}^2 \rangle$ is the volume-averaged longitudinal magnetic perturbation. The correlation time $\tau_{i,j}(\epsilon)$ encodes properties of the material trap, such as the diffuse reflection probability of the surfaces (discussed below) [19]. The exact depolarization rate and correlation time depends on the magnetic perturbation created from the gradient $G_{i,j}$. For example, a linear- x gradient $G_{1,1} = \partial_z B_x$ would create a perturbation $\langle b_{z,[1,1]}^2 \rangle = G_{1,1}^2 R^2 / 4$ in a cylindrical volume of radius R .

The correlation time, $\tau_{i,j}(\epsilon)$, is related to the autocorrelation of the longitudinal disturbance, $\langle b_{z,[i,j]}(t)b_{z,[i,j]}(t+\tau) \rangle$, and therefore depends on the directionality of the magnetic perturbation $b_{z,[i,j]}$. To calculate the correlation functions, energy-dependent trajectories of UCNs in the trap are required. This strongly depends on how specular or diffuse the UCN scattering is on the surfaces of the trap, as this will drastically change the correlation time for different field gradients: the specularly can determine how long a UCN can stay on a given trajectory without exploring the full volume of the storage chamber and field gradient. To model this, we use TOMAt [33] to simulate trajectories $x(t)$, $y(t)$, $z(t)$ in the absence of gravity. Within TOMAt, we specify the volume of the trap and the diffuse properties of the storage walls. For n2EDM, these are the diffuseness of the electrodes (the floor and

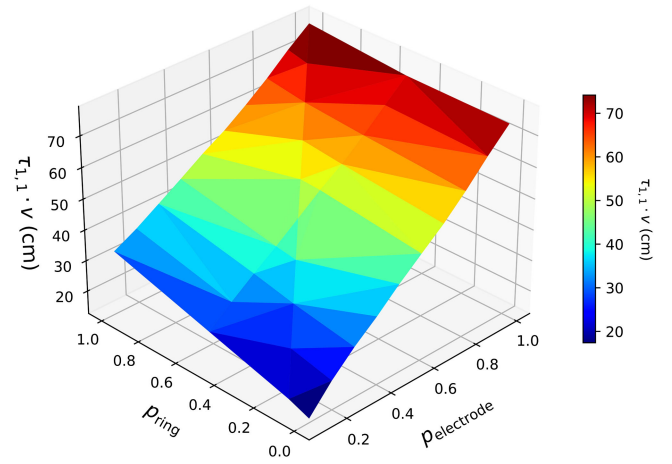


FIG. 2. Correlation time $\tau_{1,1}$ dependence on the diffuse parameters of the electrode $p_{\text{electrode}}$ and ring p_{ring} . The color scale indicates the value of the correlation time multiplied by the simulated UCN velocity v . In the absence of gravity, $\tau_{1,1} \cdot v$ is constant for all energies.

ceiling), $p_{\text{electrode}}$, and the insulator rings p_{ring} (the cylindrical walls). Using TOMAt, we calculate a grid of $\tau_{1,1}(p_{\text{electrode}}, p_{\text{ring}})$ (for a perturbation $G_{1,1} = \partial_z B_x$) and then perform an interpolation, see Fig. 2. Here, $p = 0$ is perfectly specular reflections and $p = 1$ is perfectly diffuse. Thus, by measuring intrinsic depolarization for different gradients [Eq. (2)], we access the diffuse parameters of the storage chamber via the correlation times (Fig. 2). The dependence of $\tau_{2,0}$ is available in Supplemental Material [34], along with comparisons that show consistent correlation times as calculated from MCUCN [28,35] and starUCN [36] which includes gravity.

Energy spectrum and storage properties extraction—The work described here was performed using the n2EDM apparatus [19]. n2EDM uses two vertically stacked, cylindrical storage chambers with DLC-coated electrodes and quartz insulator rings. Each chamber is 12 cm in height and has a diameter of 80 cm. As the UCNs are filled into the two chambers differently, they have access to different UCN energy spectra. The top chamber is filled from the top, while the bottom chamber is filled from the bottom. In this Letter, the total energy ϵ is taken with respect to the floor of each chamber separately. Because of the filling of the top chamber, the minimum energy in the top chamber is approximately ~ 18 neV. Additionally, the geometric aspect ratio of the chambers results in more effective depolarization from horizontal gradients versus vertical gradients. The Paul Scherrer Institut (PSI) UCN source was conditioned (brought back to nominal solid deuterium conditions) every 8 h to avoid degradation of the UCN yield and changes to the output energy spectrum.

Surrounding the two storage chambers is a set of coils that can generate magnetic field gradients, such as vertical gradients $G_{1,0} = \partial_z B_z$ or quadratic gradients

$G_{2,0}$. The UCNs are measured by a spin-sensitive detector scheme [19,37] to construct the spin asymmetry $(N_{\uparrow} - N_{\downarrow})/(N_{\uparrow} + N_{\downarrow})$. For a given gradient $G_{i,j}$, we measure the spin asymmetry as a function of the Ramsey-pulse drive frequency, and then fit it to extract $\alpha(G_{i,j})$, as shown in Fig. 1. While the free precession time was fixed to $T = 180$ s in each dataset, the overall neutron storage time, from closing the trap to opening it again, was 200 s. This is to accommodate the spin manipulation and provide for additional buffer time. The longitudinal depolarization in n2EDM is negligible over these additional 20 s (discussed later).

We simultaneously fit four depolarization datasets [using Eqs. (1) and (2)] for the two storage chambers separately: $\alpha(G_{1,0})$, $\alpha(G_{1,1})$, $\alpha(G_{1,-1})$, $\alpha(G_{2,0})$. In each dataset, we remove random background contamination from the detected UCN counts. We parameterize the energy spectrum as $n(\epsilon) = n_0(\epsilon - \epsilon_{\min})^a(\epsilon_{\max} - \epsilon)^b$, which ensures vanishing density at $\epsilon_{\min}$ and $\epsilon_{\max}$ (such as the lowest Fermi potential of the storage chamber), and n_0 is a normalization such that $\int_{\epsilon_{\min}}^{\epsilon_{\max}} n(\epsilon) d\epsilon = 1$. We integrate Eqs. (1) and (2) between the $\epsilon_{\min}$ and $\epsilon_{\max}$. As mentioned, $\epsilon_{\min}$ in the top chamber is expected to be shifted by roughly 18 neV due to the UCNs gaining energy as they fill into the chamber from the top. In the bottom, $\epsilon_{\min} = 0$. Because of the correlation between $\epsilon_{\max}$ and b , we fix $\epsilon_{\max} = 165$ neV to be sufficiently high (above the expected Fermi potential) and let b control how quickly the energy spectrum decays. The extracted spectrum is independent of $\epsilon_{\max}$ for sufficiently high values. We allow α_0 to vary for each dataset, and allow for an inherent gradient shift in each dataset (i.e., an offset in G).

Figure 3 shows the comparison between the data and the calculated theory from the minimization results. Remarkably, we can simultaneously fit all data to a few percent across extremely large gradients and across a large depolarization scale, from $\alpha \sim 1$ down to $\alpha \sim 0$. While $G_{1,0} = \partial_z B_z$ exhibits small systematic shifts at large gradients, the effect is only a few percent and is due to the coil inducing other gradients at such high currents. Figure 4 shows the resulting energy spectrum for the individual storage chambers of n2EDM and the diffuse parameters for the electrodes and rings. We emphasize that this is the extracted energy spectrum after 200 s of storage, which is relevant for the planned n2EDM data taking. This measurement procedure can be repeated for different storage times to extract how the energy spectrum evolves with storage time.

Figure 4 demonstrates the sensitivity of using spin depolarization to extract the energy spectrum and storage properties. We emphasize that UCNs with energies below 30 neV are most strongly affected by gravitational depolarization, providing the strictest constraints on $n(\epsilon)$. Since we require a continuous energy spectrum and normalization to α_0 , this constrains the high-energy tail. The larger

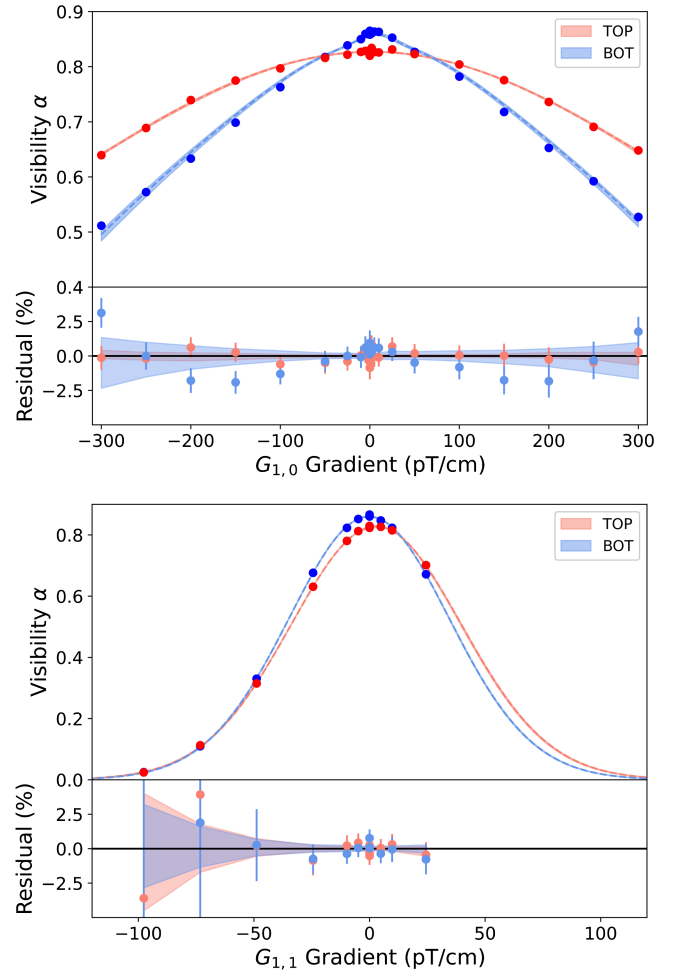


FIG. 3. Spin depolarization for different magnetic gradients in the top (red) and bottom (blue) storage chambers of n2EDM. The data points are the extracted final spin polarization from measuring the asymmetry at each gradient (see Fig. 1). The lower panel in each graph shows the percent residual between the data and theory. The error on the residual points is the normalized data statistical error, whereas the band shows the calculation $\pm 1\sigma$ normalized spread from the bootstrapped minimization. Top: gravitationally enhanced depolarization from the vertical gradient $G_{1,0} = \partial_z B_z$. Bottom: intrinsic depolarization from linear gradient $G_{1,1} = \partial_z B_x$. The fitted gradients $G_{1,-1}$, $G_{2,0}$ are not shown here for brevity, but are in Supplemental Material [34] and of similar quality.

variance in the top chamber results from a lack of UCN statistics in the lowest energy bin, and therefore a larger space of $n(\epsilon)$ is possible.

Figure 4 (bottom) also shows the sensitivity to the average diffuse parameters describing the surfaces of the storage chamber. We emphasize that the dependencies of α_{int} on $G_{1,1}$ and $G_{2,0}$ allow the disentanglement of $p_{\text{electrode}}$ and p_{ring} . This is due to the different types of trajectories that contribute to the correlation times $\tau_{1,1}$ and $\tau_{2,0}$ that sample the storage volume differently. As mentioned, the bottom chamber has the best sensitivity and tightly

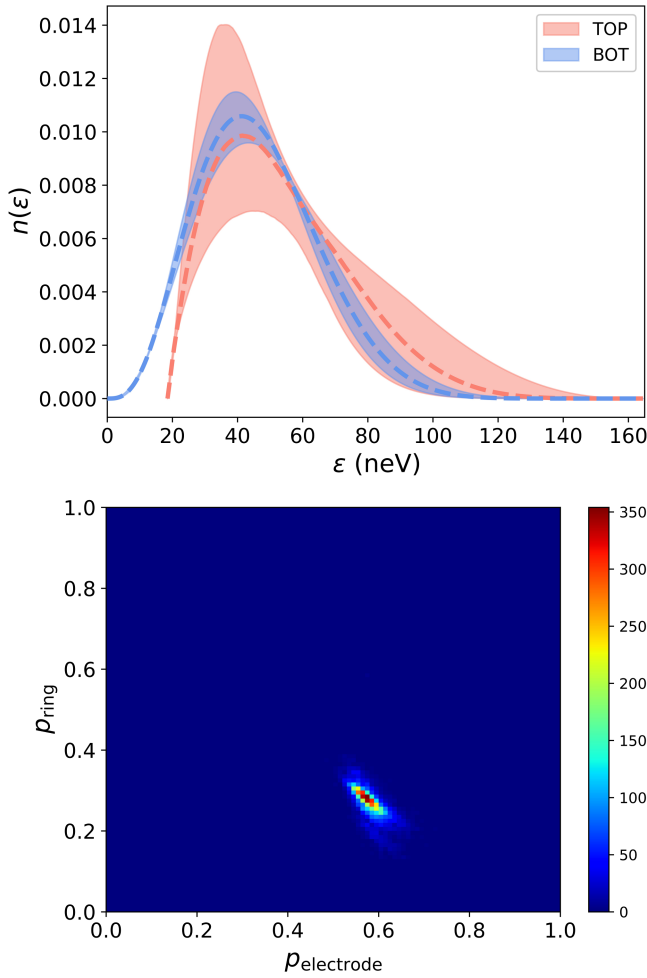


FIG. 4. Top: extracted energy spectrum for the top (red) storage chamber and bottom (blue) storage chamber. The extracted parameters are: $(a, b)^{\text{Bot}} = (3.4 \pm 0.5, 10.4 \pm 2.2)$ and $(a, b)^{\text{Top}} = (1.1 \pm 0.4, 7.5 \pm 5.9)$. The dashed line is the 50th percentile and bands demonstrate 16–84 percentile spread from the bootstrapped minimization. Bottom: correlation of the diffuse parameters for the electrode and ring surfaces of the bottom storage chamber. The color scale indicates the number of solutions from the bootstrapped minimization in a given bin. Here, $p = 0$ would be perfectly specular reflections, while $p = 1$ is perfectly diffuse. See text for discussion.

constrains $p_{\text{electrode}}$ and p_{ring} . The top chamber has a larger spread and is consistent.

Additional systematic studies were performed to validate the robustness of our method and results. We varied the parameterization of the energy spectrum and found consistent energy spectra and diffuse parameters. As mentioned earlier, we compared the TOMAt correlation times to those simulated by MCUCN and starUCN (includes gravity) and found consistency. We also used our extracted energy spectrum to compare to an independent measurement in which neutrons up to different energies were polarized (using a magnetic filter) and then stored in our material trap. All of these studies are found in Supplemental

Material [34]. Detailed also there are all parameter correlations and central values, tabulated data points utilized in our fit, treatment of background, explanations on our measurement procedure, depolarization from wall collisions, and the full gradient data that was fitted but not shown here for brevity.

Conclusions—In this Letter, we described a new technique for leveraging spin depolarization mechanisms to extract the UCN energy spectrum and, simultaneously, storage chamber properties. We emphasized the sensitivity of this result by comparing the two identical storage chambers at different heights and different orientations for filling of the n2EDM experiment [19].

We additionally can utilize our Letter to predict an important systematic effect for n2EDM, the center-of-mass offset of the neutrons in the material trap: $\langle z \rangle^{\text{Top}} = -0.16(1)$ cm, $\langle z \rangle^{\text{Bot}} = -0.22(1)$ cm. This will in the future be compared to an independent measurement that is extremely sensitive to this offset but not the full energy spectrum.

Acknowledgments—We appreciate the ongoing excellent technical support by Michael Meier. Specific technical support by L. Noorda and N. Kohler is acknowledged. We acknowledge the excellent support by the BSQ group running the UCN source, the HIPA accelerator operating crew, and various PSI support groups. Support by the Swiss National Science Foundation Projects No. 188700 (PSI), No. 163413 (PSI), No. 178951 (PSI), No. 204118 (PSI), No. 172626 (PSI), No. 213222 (PSI), No. 212754 (PSI), No. 10001566 (PSI), No. 169596 (PSI), No. 181996 (Bern), No. 236419 (ETH), No. 200441 (ETH), No. 10003932 (ETH), and FLARE No. 186179, No. 201473, No. 216603, and No. 232701 is gratefully acknowledged. This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Grant Agreement No. 884104. This work is supported by the DFG (DE) by the funding of the PTB core facility center of ultralow magnetic field No. KO 5321/3-1 and No. TR 408/11-1. The LPC Caen and the LPSC Grenoble acknowledge the support of the French Agence Nationale de la Recherche (ANR) under reference No. ANR-14-CE33-0007 and the ERC Project No. 716651-NEDM. University of Bern acknowledges the support via the European Research Council under the ERC Grant Agreement No. 715031-Beam-EDM. The Polish collaborators wish to acknowledge support from the National Science Center, Poland, under Grants No. 2018/30/M/ST2/00319, No. 2020/37/B/ST2/02349, and No. 2016/23/D/ST2/00715, as well as by the Minister of Education and Science under the Agreement No. 2022/WK/07. Support by the Cluster of Excellence “Precision Physics, Fundamental Interactions, and Structure of Matter” (PRISMA+ EXC 2118/1) funded by the German

Research Foundation (DFG) within the German Excellence Strategy (Project No. 39083149) is acknowledged. Collaborators at the University of Sussex wish to acknowledge support from the School of Mathematical and Physical Sciences, as well as from the STFC under Grants No. ST/S000798/1 and No. ST/W000512/1, as well as from the STFC under Grants No. ST/S000798/1 and No. ST/W000512/1. This work was partly supported by the Fund for Scientific Research Flanders (FWO), and Project No. GOA/2010/10 of the KU Leuven. Researchers from the University of Belgrade acknowledge institutional funding provided by the Institute of Physics Belgrade through a grant by the Ministry of Education, Science and Technological Development of the Republic of Serbia. University of Kentucky also acknowledges support by U.S. Department of Energy under Contract No. DE-SC0014622.

Data availability—The data that support the findings of this article are openly available [38].

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