A Ramsey Neutron-Beam Experiment to Search for Ultralight Axion Dark Matter at the ESS

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High-intensity neutron beams, such as those available at the European Spallation Source (ESS), provide new opportunities for fundamental discoveries. Here we discuss a novel Ramsey neutron-beam experiment to search for ultralight axion dark matter through its coupling to neutron spins, which would cause the neutron spins to rotate about the velocity of the neutrons relative to the dark matter halo. We estimate that experiments at the HIBEAM beamline at the ESS can improve the sensitivity to the axion-neutron coupling compared to the current best laboratory limits by up to $2-3$ orders of magnitude over the axion mass range $10^{-22}\,\mathrm{eV} - 10^{-16}\,\mathrm{eV}$.

I. INTRODUCTION

Astrophysical and cosmological observations indicate that about one-quarter of the total energy and five-sixths of the total matter content of the Universe is due to dark matter (DM) [1], the identity and microscopic properties of which remain a mystery. Traditional detection schemes have largely focused on searching for possible particle-like signatures of weakly interacting massive particles (WIMPs) with masses in the $\sim \mathrm{GeV} - \mathrm{TeV}$ range [2], whose signatures scale to the fourth power of a small interaction constant between the DM and ordinary matter. On the other hand, ultralight bosons with sub-eV masses and a high particle number density may produce distinctive wavelike signatures. One of the leading candidates for DM is the axion, which is a light pseudoscalar (spin-0, parity-odd) particle originally proposed to resolve the strong $\mathcal{CP}$ problem of quantum chromodynamics (QCD) [3–9]. Besides the canonical QCD axion, more generic axion-like particles may also exist in nature [10, 11].[12] Searches for axion DM have mainly focused on the axion's possible electromagnetic coupling to photons [13].

Neutron-beam experiments have previously been considered for fundamental physics tests, such as neutron-antineutron oscillations, electric dipole moment searches, new-boson-mediated forces and investigations of the structure of the weak interaction; see, e.g., Refs. [14–24]. With major new neutron sources, such as the European Spallation Source (ESS) [25], Spallation Neutron Source (SNS) in the U.S. [26] and China Spallation Neutron Source (CSNS) [27], providing extremely strong, pulsed neutron beams, it is imperative to maximally leverage the potential of these state-of-the-art facilities. Here we explore the sensitivity of a Ramsey experiment at such a pulsed neutron beam facility to a pseudo-magnetic field effect stemming from the coupling of an ultralight axion DM field to the neutron. The derivative coupling of axion DM to neutron spins would cause neutron spins to precess about the velocity of the neutrons relative to the DM halo. Depending on the orientation of the pseudo-magnetic field with respect to the experiment, this would cause neutrons in the beam to accumulate an additional phase as they travel along their flight path. We estimate that with the proposed HIBEAM neutron beamline [24] at the ESS, the sensitivity to the axion-neutron coupling can be improved compared to the current best laboratory limits by up to $2-3$ orders of magnitude over the axion mass range $10^{-22}\,\mathrm{eV} - 10^{-16}\,\mathrm{eV}$.

II. THEORY

Ultra-low-mass axions with very small kinetic energies can be produced efficiently via nonthermal production mechanisms, such as vacuum misalignment [28–30] shortly after the big bang, and can subsequently form a coherently oscillating classical field: $a(t) \approx a_0 \cos(\omega t)$, with the angular frequency of oscillation given by $\omega \approx m_a c^2/\hbar$, where m_a is the axion mass, $\hbar$ is the reduced Planck constant, and c is the speed of light in vacuum. The oscillating axion field carries the energy density $\rho_a \approx m_a^2 a_0^2/2$ and behaves like a cold, nearly pressureless fluid on length scales greater than the de Broglie wavelength of the field.[31] Cosmological and astrophysical observations rule out the possibility of axions with masses $m_a \lesssim 10^{-21}\,\mathrm{eV}$ comprising the dominant fraction of the DM [32–35], although such ultralight axions may still comprise a sub-dominant fraction of the DM depending on their mass. Gravitational interactions between axion DM and ordinary matter during galactic structure formation subsequently virialise galactic axions ($v_{\text{vir}} \sim 300\,\mathrm{km/s}$ locally), which gives an oscillating axion field in our local Galactic region the finite coherence time: $\tau_{\text{coh}} \sim 2\pi/(m_a v_{\text{vir}}^2) \sim 2\pi \times 10^6/m_a$; i.e., $\Delta\omega/\omega \sim 10^{-6}$ corresponding to nearly monochromatic oscillations of the field.

An axion field may interact with nucleons via the derivative coupling:

$$\mathcal{L}_{\text{int}} = -\frac{C_N}{2f_a} \partial_\mu a \, \bar{N} \gamma^\mu \gamma^5 N \, , \tag{1}$$

where N and $\bar{N}$ denote the nucleon field and its Dirac adjoint, respectively, f_a is the axion decay constant, and C_N is a model-dependent dimensionless parameter. The spatial components of the derivative coupling of an oscillating axion DM field in the laboratory frame of reference, $a(t, \boldsymbol{r}) \approx a_0 \cos(m_a t - \boldsymbol{p}_a \cdot \boldsymbol{r})$, with spin-polarised nucleons in Eq. (1) simplifies as follows in the non-relativistic limit [36, 37]:

$$H_{\text{int}}(t) \approx \frac{C_N a_0}{2f_a} \sin(m_a t) \, \boldsymbol{\sigma}_N \cdot \boldsymbol{p}_a \equiv \boldsymbol{\sigma}_N \cdot \boldsymbol{B}_{\text{eff}}(t) \, , \tag{2}$$

which resembles the interaction of a nucleon spin $\boldsymbol{\sigma}_N$ (which has unity norm, $|\boldsymbol{\sigma}_N| = 1$) with a time-varying *pseudo*-magnetic field $\boldsymbol{B}_{\text{eff}}(t)$. The interaction in Eq. (2) causes nucleon spins to precess about the direction of the axion DM momentum, $\boldsymbol{p}_a$, taken in the laboratory frame. The correlation $\boldsymbol{\sigma}_N \cdot \boldsymbol{p}_a$ in Eq. (2) is modulated at the daily sidereal frequency due to the rotation of Earth and can be calculated by transforming to a nonrotating celestial coordinate system; see, e.g., [38–40] for more details. The average value of $\boldsymbol{p}_a$, sampled over many coherence times, is expected to be directed opposite to the laboratory's orbital motion about the Galactic Center. However, due to the stochastic nature of the axion DM field [41], the magnitude and direction of $\boldsymbol{p}_a$ during the course of measurements may differ from the long-term average value [42, 43].

The "axion wind" spin-precession effect described by Eq. (2) induces temporal variations in the Larmor precession frequency of a polarised nucleon spin according to:

$$\hbar\omega_L(t) = | - \gamma_N \, \boldsymbol{\sigma}_N \cdot \boldsymbol{B} + 2\boldsymbol{\sigma}_N \cdot \boldsymbol{B}_{\text{eff}}(t)| \, , \tag{3}$$

principally from the component of $\boldsymbol{B}_{\text{eff}}(t)$ directed along the applied magnetic field $\boldsymbol{B}$, with γ_N being the gyromagnetic ratio of the nucleon. A (pseudo) magnetic-field measurement using a neutron spin is based on measurement of the phase $\phi(T) = \int_0^T \omega_L(t)\, dt$, where T is the spin precession time, resulting in a measurement sensitivity that depends not only on the coupling constant C_n/f_a, but also on the axion mass: for the most sensitive scenario in an experiment when $m_a \ll \omega_L$, in which case $\boldsymbol{B}_{\text{eff}}$ is approximately constant during the free precession phase and a phase can continuously build up. Note that the axion-DM-induced change in the Larmor precession frequency scales linearly in the small interaction constant, in contrast to the quadratic scaling in searches for virtual-axion-mediated spin-dependent forces [44].

III. EXPERIMENTAL APPARATUS

To measure a change in ω_L, Ramsey's method of separated oscillating fields [45] is used. The method is based on the comparison of ω_L to an external frequency ω_1 from a stable clock. Polarized neutrons enter a spin-flipper coil, a region with a magnetic field $\boldsymbol{B}_1$, oscillating at a frequency ω_1. This closely approximates a rotating magnetic field at frequency ω_L determined by the constant background field $\boldsymbol{B}_0$. B_1 is adjusted to ultimately result in a spin rotation by $\pi/2$ radians, into the plane normal to $\boldsymbol{B}_0$, resulting in a precession at the Larmor frequency ω_L. The neutrons then precess in the constant magnetic field $\boldsymbol{B}_0$ for a time T, where a phase $\phi = \omega_L T$ is built up. At the end of the flight path, a second $\pi/2$-flip is applied by passage through a second coil, driven with the same current that also drives

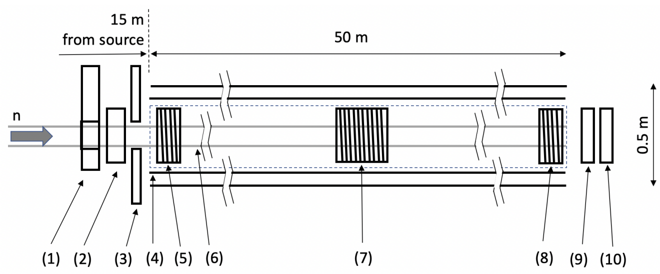

FIG. 1. Schematic setup of the experiment with components (longitudinal cut), neutrons entering from the left (see the main text for details). The flight path is 50 m.

the first coil. In the case when $\omega_L = \omega_1$, both $\pi/2$-flips add up, resulting in a downward pointing polarization of the neutron. A mismatch of the frequencies, such that a phase π is built up during the flight time relative to ω_1, results in the polarization pointing upwards. Performing many independent Ramsey experiments with different settings for ω_1 results in the well-known Ramsey fringes. An unknown magnetic-field-like effect, as well as any other magnetic field applied in addition to $\boldsymbol{B}_0$, will shift the whole pattern in frequency. Repeatedly determining the central fringe of the pattern for subsequently different $\boldsymbol{B}_0$ orientations thus reveals a slowly oscillating offset field $\boldsymbol{B}_{\text{eff}}$ or its absence within the boundaries of statistical and systematic precision. This can then be converted into the parameter space of coupling constant and axion mass. A constant magnetic field $\boldsymbol{B}_0$ is obtained with magnetic shielding around the field-generating coil and neutron flight path. However, the axion DM field is not necessarily affected by the passive magnetic shield based on a ferromagnetic alloy and a (regular) conductive shield [46]. A flight time of $\sim 50\,\text{ms}$ for a length of 50 m with high statistics and a 10 Hz repetition rate allow for a sensitive bandwidth to an oscillating field with frequency from around 3 Hz (corresponding to an axion mass of 10^{-14} eV) to below mHz.

As shown in Fig. 1, the apparatus to determine the spin precession frequency of the neutrons consists of: (1) a chopper; (2) a polarizer; (3) a collimator; at (4) the neutrons enter the magnetically controlled region, formed by a 2-layer passive magnetic shield, a vacuum chamber and a field coil to produce a magnetic field transverse to the neutron direction; (5) and (8) are the $\pi/2$-spin flippers; (6) a neutron guide; (7) an optional π-spin flipper; (9) a spin analyzer; and (10) a detector. The magnetic holding field is applied over the region denoted with the dotted rectangle. The setup is situated starting 15 meters from the moderator. The whole length of the flight path is magnetically shielded and a constant magnetic field is applied. Initial conditions for the measurement were established using the ray-tracing software McStas [47]. Collimators are utilized to reduce the beam area to 10 cm $\times$ 10 cm at the entrance to the experiment.

IV. SENSITIVITY

Statistical sensitivity. The frequency resolution of a single Ramsey experiment scales as

$$\Delta f = \frac{1}{2\pi T \alpha \sqrt{N}}\,, \tag{4}$$

with N being the number of neutrons and α the contrast in detection of the different spin states. The sensitivity then increases with the square-root of the number of repetitions, while the oscillations of the DM field remain coherent. The initial neutron flux from the moderator into the exit of the neutron extraction system is $1 \times 10^{12}\,n/\text{s}$, which is subsequently reduced by polarization ($\times 0.5$), polarization analysis ($\times 0.5$) and calibration runs ($\times 0.8$). Here we assume a quasi-perfectly fit elliptic neutron guide section with $m \sim 3$ to capture practically the whole flux. Also, the spin flippers are assumed to be perfectly efficient over the entire velocity range. Assuming only systematic errors uncorrelated with the frequency of the DM oscillation signal, the experiment is statistically limited. A frequency resolution of 10^{-8} rad/s can be reached in one year of run time for a 50-meter flight path. As the signal is measured as a time-dependent modulation of the magnetic field, the effect alternatingly adds and subtracts from the magnetic field, thus effectively doubling the precision to 5×10^{-9} rad/s. Using Eq. (2), this translates into the sensitivity estimates shown in Fig. 3, assuming that axions saturate the observed density of DM in our local Galactic region, $\rho \approx 0.4\,\text{GeV/cm}^3$ [1]. The sensitivity is also constrained by systematic issues, which is estimated by a simulation of the so-called Ramsey fringes, which is the polarization P_z along the magnetic field $\boldsymbol{B}_0$ as a function of the detuning from the resonance frequency ω_L. The parameters varied in the simulation are the spread of measurements with

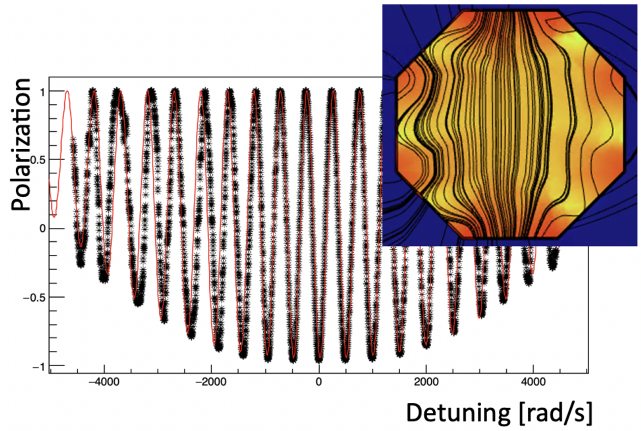

FIG. 2. Ramsey fringes for a realistic magnetic field. The inset shows a cut through the octagonal field setup with illustrated field lines.

different detuning, neutron statistics, duration of the neutron pulse, magnetic field maps, spin-flip pulses, neutron positions, momentum directions and velocities, the precession time T, the duration of a $\pi/2$-flip τ, the frequency Ω_R related to B_1 (the Rabi frequency), and the detuning $\delta\omega$ from the Larmor frequency.

Magnetic field. The phase buildup during free precession depends on the homogeneity of the magnetic field. For the magnetically controlled region, we aim for a typical homogeneity of the magnetic field over most of the volume covered by the neutron beam at the level of 10^{-3}, obtained with a field strength of $B_0 \sim 10 - 100\,\mu$T. Shielding of environmental disturbances is obtained by a two-layer octagonal passive magnetic shield with open ends and its axis approximately aligned with the neutron beam central axis; a coil made from 8 longitudinal wires produces a transverse magnetic field with strength $B_0 \sim 10 - 100\,\mu$T. Static residual fields smaller than 100 nT after degaussing do not affect the measurement and the relative inhomogeneities of the magnetic field over most of the volume covered by the neutron beam are about 10^{-3}. The actual complexity of the coil configuration inside the shield and the cross-sectional area of the shielded region occupied by the neutron beam will ultimately define the homogeneity of the field experienced by the neutrons. The inset in Fig. 2 shows a cut through the envisaged configuration, providing such a field with only a few wires. The vacuum tube, which also acts as a shield for higher frequencies, is accessed for pumping at the detector region only, as the vacuum requirement is only 10^{-5} mbar. The passive shield design is similar to that in Ref. [48].

Polarization. When the neutrons enter the shielded region, they pass through a cell containing polarised ^{3}He. Through spin-dependent nuclear absorption of neutrons on ^{3}He, an almost perfectly polarized neutron beam ($> 99\%$) can be obtained, thus hardly affecting contrast in the Ramsey measurement. Polarization analysis after the Ramsey experiment can be done in the same way. We use cells made from GE-180 glass to obtain spin life-times of the order of a day, with polarization done using the spin-exchange optical pumping technique with a similar setup as in [49] with a length of several cm, a diameter of 0.1 m and a pressure of up to 10 bar. Cell designs are conceptually based on [50]. The product of polarization and analysis power determines the contrast parameter α in Eq. (4). Spin-flipper coils are composed of approximately 50 turns of wire wound around a nonmetallic support inside the vacuum chamber to minimize coupling to the chamber and shields; both spin-flipper coils are serially connected and fed by a function generator, stabilized by a GPS-locked frequency standard. While the $\pi/2$ condition is only perfectly valid for a single velocity, the analysis works for a range of velocities but with reduced contrast. With a B_1 amplitude of $\sim 100\,\mu$T, corresponding to 3000 spin rotations per second, and for a $\pi/2$-flip at 1200 m/s, the corresponding coil length is 0.1 m. Placed along the flight path, a π-flipper is installed, which can be deployed. In particular, it can reduce wash-out of the phase measurement due to geometry; e.g., in the form of parity-symmetric magnetic-field deformations along the shield for a centered beam. A further interesting feature is that it can recover the flip angles for velocities that do not match the $\pi/2$-flip conditions and thus massively broaden the velocity acceptance of the Ramsey setup. However, for our new physics search, a symmetric placement in a constant field also strongly suppresses sensitivity to the new-physics signal in the most interesting frequency range and thus will only be used for instrument characterization. It should be noted that the magnitude of $\boldsymbol{B}_0$ does not change the new physics reach. However, a smaller field makes the experiment more sensitive to background gradients. The second spin flip and the polarization analysis are similar to the first spin flip and polarizer, respectively.

Pulse duration and velocity spread. The pulse duration of a pulse at the ESS is ~ 3 ms at a 10 Hz repetition rate. Although the phase information is washed out, a fit of the central fringes of the Ramsey experiment can in principle

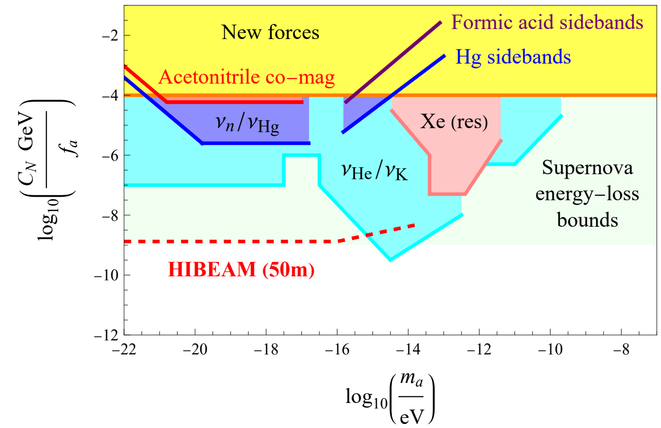

FIG. 3. Projected sensitivity of a 50 m scale Ramsey neutron-beam experiment using the HIBEAM neutron beamline at the ESS (denoted by dashed red line) to the coupling strength of axion dark matter with a neutron, defined in Eq. (1), as a function of the axion mass m_a, assuming one year of run time and that axions saturate the observed density of dark matter in our local Galactic region, $\rho \approx 0.4\,\text{GeV/cm}^3$ [1]. The cyan, blue, pink, red and purple regions indicate regions of parameter space already probed by magnetometry-based searches for time-varying spin-precession effects induced by axion dark matter [39, 52–59]. The yellow region denotes the region of parameter space ruled out by a magnetometry-based search for spin-dependent forces mediated by the exchange of virtual axions [44]. The pale green region denotes bounds from astrophysical observations of supernovae [60], which are subject to model-dependent assumptions and may be evaded altogether [61].

resolve the phase information. However a chopper can be used to refine the pulse.

Neutron detection. When 2×10^{10} neutrons per pulse arrive within $\mathcal{O}(100)$ ms at the detector, the count rate is $\sim 10^{11}\,\text{s}^{-1}$. For a detector with 1000 pixels, the rate becomes ~ 100 MHz. In this project, we will use a 2D-position-sensitive segmented ion chamber using ^{3}He as the absorber in the gas. Similar detectors have been successfully used in several sensitive polarized neutron transmission experiments conducted at both pulsed and continuous neutron sources to search for parity-odd neutron interactions with nuclei and for possible exotic spin-dependent neutron interactions [51].

V. DISCUSSION AND CONCLUSIONS

Neutron physics offers the potential to probe new physics in ultralight axion DM searches. As shown in Fig. 3, our proposed experiment at the HIBEAM neutron beamline at the ESS has significant discovery potential, offering up to $2-3$ orders of magnitude improvement in sensitivity compared to the current best laboratory limits. Using free neutrons as a probe of the "axion-wind" spin-precession effect in Eq. (2) provides a clean probe of the neutron interaction parameter C_n/f_a, which is complementary to the magnetometry approaches in Refs. [39, 52–59] that involve nuclei and hence probe linear combinations of proton and neutron interaction parameters [62]. Our proposed experiment is expected to be competitive with bounds from astrophysical observations of supernovae [60], whilst also offering the advantage of a much cleaner and better controlled environment. On the other hand, the interpretation of rare astrophysical phenomena, such as supernova explosions, which take place in conditions drastically different from those in the laboratory, require additional model-dependent assumptions that may not be valid [61].

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Spallation Source'.

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