Snowmass2021 - Letter of Interest

Cosmic Axion Spin Precession Experiment (CASPEr-wind)

Thematic Areas:

■ (CF2) Dark Matter: Wavelike

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Abstract: The elusiveness of dark matter is a major sign that our understanding of Nature is incomplete. This significant problem is strongly suspected to be solvable by introducing new fundamental particles [1, 2]. One such class of particles, axions and axion-like particles (ALPs), were already hypothesized to solve another issue specific to the Standard Model of particle physics, namely the observational absence of predicted violation of charge conjugation and parity symmetry (CP-symmetry) by the strong force [3, 4]. The CASPEr-wind experiment searches for a coupling between the relative momentum of the local ALP field and nuclear spins by employing well established methods from the field of nuclear magnetic resonance (NMR). In this manner, we aim at significantly improving current limits on the associated coupling strength in the ALP mass range from 10^{-6} eV down to 10^{-22} eV. It can also detect other types of dark matter, for example hidden photon dark matter [5, 6] is detectable through a nuclear dipole moment coupling [7].

Physics goals: If axion or ALP dark matter is indeed the main component of dark matter, its mass m_a is constrained by astrophysical observations to be below a milli-eV and its density is large enough that, rather than individual particles, it is convenient to treat it as a quantum field $a = a_0 \cos \omega_a t$ that oscillates at the Compton frequency $\omega_a = m_a c^2/\hbar$ and whose amplitude a_0 is related to the dark matter energy density ρ_{DM}. The CASPEr-wind experiment is searching for coupling of this field to proton and neutron spins (g_{aNN}) as described by the Lagrangian

$$\mathcal{L}_{\text{spin}} \approx g_{aNN}[\partial_\mu a(\vec{r}, t)]\overline{\Psi}_n \gamma^\mu \gamma_5 \Psi_n \; , \tag{1}$$

where Ψ_n is the nucleon wave function, and σ and γ are the standard Dirac matrices [8–10]. CASPEr-wind aims at probing a previously unexplored region of masses m_a and coupling strengths g_{aNN} spanning approximately six and three orders of magnitude respectively, c.f. Fig. 1.

Experimental technique: Unlike haloscope experiments looking for photons created by the conversion of axions in strong electromagnetic fields via the inverse Primakoff effect [11–13], the CASPEr experiments directly probe interaction between SM particles and axions and ALPs [9]. An important property of the coupling described by eq. 1 is that the interaction contains the gradient of the axion field $\partial_\mu a$ rather than the field a itself. The gradient acts as an effective magnetic field with amplitude

$$B_a \approx 10^{-3} \times \frac{g_{aNN}}{\hbar \gamma_n} \sqrt{2\hbar^3 c^3 \rho_{\text{DM}}} \tag{2}$$

which exerts a measurable torque on nucleon spins with a gyromagnetic ratio γ_N. Additional features of axion-wind experiments that we plan to exploit are the expected annual and daily modulation of the signal, as well as the dependence of the signal on the orientation of the experiment with respect to the gradient of the axion field.

In the CASPEr-wind experiment, we employ NMR techniques to probe the torque acting on a sample of nuclear spins. The most sensitive measurements will be performed with a high-density, highly spin-polarized sample placed in a magnetic field B_{ext}. As B_{ext} is scanned, the corresponding Larmor frequency changes and if the Larmor frequency is tuned to resonance with the axion oscillation frequency which would result in an oscillating magnetization of the sample that can be measured using magnetometers. First results were already obtained for the mass ranges 1.3×10^{-17} eV $\lesssim m_a \lesssim 1.3 \times 10^{-22}$ eV and $m_a = 1.8 \cdot 10^{16}$ eV $\lesssim m_a \lesssim 7.8 \times 10^{14}$ eV [14, 15] using zero- to ultralow-field (ZULF) NMR techniques.

Projected sensitivity: The magnitude of the signal detected by the setup is proportional to the number of spins in the ensemble, the degree of polarization, the coherence time of the spin ensemble or axion field itself, and the magnitude of the pseudo-magnetic field B_a. The amplitude of the axion-induced oscillating magnetization will increase for a period of time determined by the coherence time of the interaction. Transverse spin relaxation times (T_2) for liquid ^{129}Xe can be on the order of 1000 s, so for the most part, the factor limiting the integration time will be the coherence time of the axion field itself (for example, for an axion frequency of 1 MHz, the axion coherence time is 1 s). Experiment sensitivity can be limited by technical noise such as Johnson–Nyquist noise, or ultimately by fundamental quantum spin projection noise. While we we do not foresee reaching the QCD-axion line (barring unanticipated technological breakthroughs), the ALP parameter space the experiment will be sensitive to is well motivated theoretically [16].

Projected timeline: Due to the significantly different B_{ext} fields and the associated technical constraints for the low and high axion mass regions, developments run allow two major lines. At the ZULF experiment we are currently investigating parahydrogen-induced polarization (PHIP), with a projected 10^5 enhancement factor allowing us to improve on our previously set bounds [14, 18]. For the high mass region, the work plan is as follows:

CASPEr-wind low field thermal (phase I-LF), 1 year. The setup for this phase is currently being assembled at the Helmholtz Institute Mainz (Germany). Here, a thermally polarized sample placed in a tunable

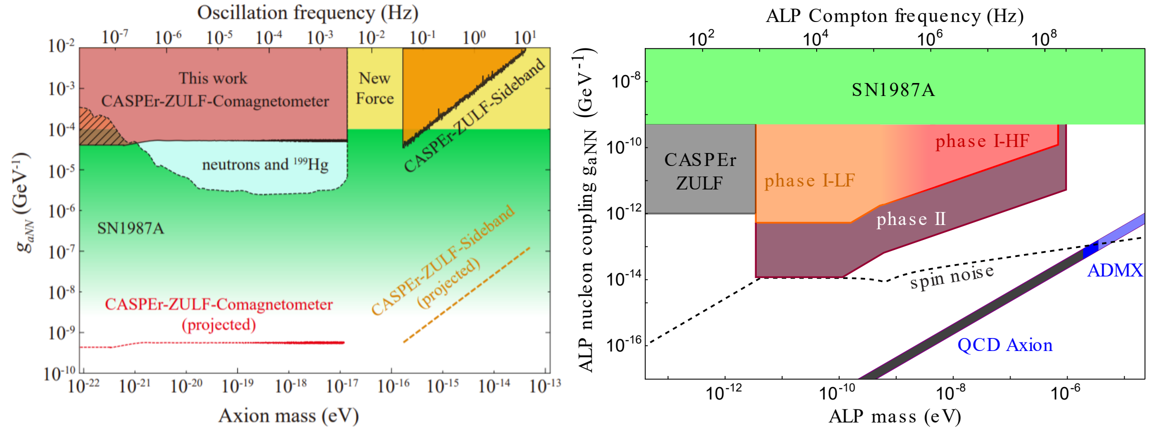

Figure 1: Axion and ALP parameter space probed by various phases and variations of the CASPEr-wind experiment. Bounds already set by ZULF experiments are shown to the left in red and orange, with projected ones as dashed lines [14, 15]. The projected bounds on high ALP masses are shown to the right. Current most stringent bounds are set by observations and modeling of the supernove SN1987A [16] (green), for lower ALP masses partially by the PSI neutron EDM experiment [17] (light blue), and for higher ALP masses by the ADMX experiment [13] (dark blue).

magnetic field of $B_{\text{ext}} \leq 0.15$ T will be employed, superconducting quantum interference devices (SQUIDs) will serve as magnetometers.

CASPEr-wind low field hyper-polarized, (phase I-LF), 1 year. After commissioning the setup with a thermal sample, the sample will be replaced by hyperpolarized ^{129}Xe. We are currently developing a source based on the spin-exchange optical pumping technique []. This will allow us to exclude the parameter space indicated in orange in Fig. 1.

CASPEr-wind high field hyper-polarized, (phase I-HF), 2 years. In order to extent the detectable axion and ALP mass range, a new magnet tunable in the range $B_{\text{ext}} \leq 14.4$ T will be installed. An inductive pickup system instead of SQUIDs will allow for efficient probing of the associated higher ALP Compton frequencies.

CASPEr-wind phase II, 3 years. Increase the reach to even weaker couplings g_{aNN} by (1) increasing the degree of nuclear polarization by using optical pumping and other hyperpolarization techniques; (2) increasing the nuclear spin relaxation time T_2 by using decoupling protocols; (3) implementing a resonant circuit detection scheme in collaboration with the Stanford DM Radio group; (4) increasing sample size.

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