Snowmass2021 - Letter of Interest

Cosmic Axion Spin Precession Experiment (CASPEr-e)

Thematic Areas:

■ (CF2) Dark Matter: Wavelike
■ (IF1) Quantum Sensors

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Abstract:

The nature of dark matter is one of the most important open problems in modern physics. Axions, originally introduced to resolve the strong CP problem in quantum chromodynamics (QCD), and axion-like particles (ALPs) are strongly motivated dark matter candidates. The CASPEr-e experiment searches for the EDM interaction g_d and the gradient interaction g_{aNN} of axion-like dark matter with nuclear spins in the mass range from 10^{-12} eV to 10^{-6} eV. These interactions give rise to spin torque that oscillates at the axion-like dark matter Compton frequency. CASPEr-e uses precision magnetic resonance sensing to detect this torque, using a macroscopic spin ensemble. Experimental sensitivity estimates show that achieving sensitivity at the level of QCD axion coupling strength is possible in the mass range from $10^{-12}\,\text{eV}$ to $5 \times 10^{-9}\,\text{eV}$.

Physics goals: The CASPEr-electric experiment is sensitive to the nuclear EDM coupling g_d and the gradient coupling g_{aNN} of axion-like dark matter. The goal is to search for axion-like dark matter in the mass range between $10^{-12}\,\mathrm{eV}$ and $\approx 10^{-6}\,\mathrm{eV}$, with sufficient sensitivity to detect the QCD axion with mass between $\approx 10^{-12}\,\mathrm{eV}$ and $\approx 5\times10^{-9}\,\mathrm{eV}$. This corresponds to the theoretically-favored range of axion decay constants f_a near the grand unified and Planck scales. CASPEr-e detection of an axion with the QCD coupling g_d would solve several cosmological and high-energy physics puzzles, including the strong-CP problem and the nature of dark matter, as well as opening a new experimental window on the early history of the universe, probing physics of the inflationary epoch.

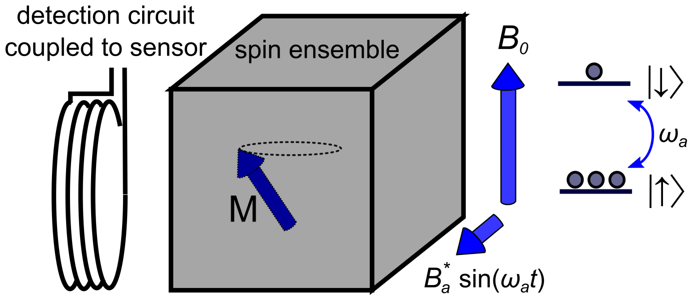

Figure 1: The CASPEr-e experimental schematic. The nuclear spin ensemble in a solid crystalline sample acts as the transducer, whose dynamical evolution is sensitive to spin interactions with axion-like dark matter.

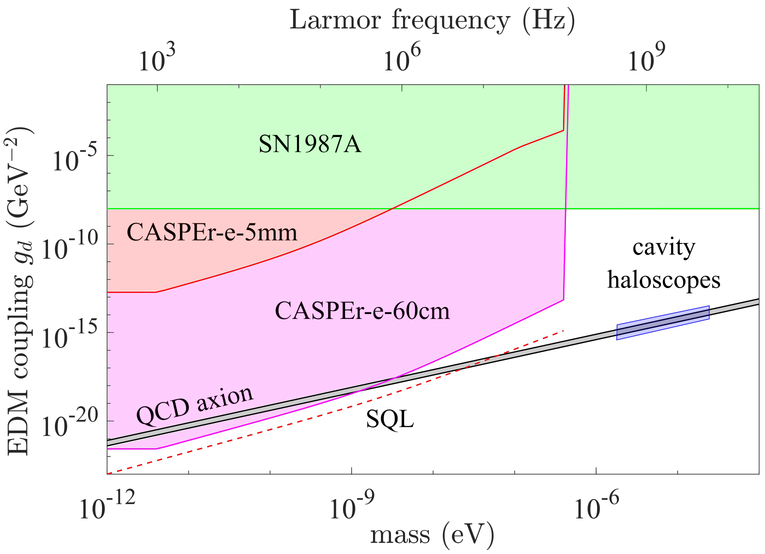

Figure 2: The projected sensitivity of CASPEr-e. The green region is excluded by constraints on excess cooling of SN1987A [1–3]. The mass range covered by the cavity haloscope experiments is shown as the blue band (we note that these experiments search for the electromagnetic coupling) [4, 5]. The QCD axion is in the grey band, whose width shows theoretical uncertainty [1]. The red line shows the projected sensitivity of the CASPEr-e experiment with a 5 mm PMN-PT sample. The purple line shows the projected sensitivity of the CASPEr-e experiment with a 60 cm PMN-PT sample. The dashed red line shows the sensitivity limited by the Standard Quantum Limit, due to nuclear spin projection noise.

Experimental technique: CASPEr-electric uses precision magnetic resonance to search for an oscillating spin torque induced by interaction of axion-like dark matter with nuclear spins, fig. 1. Such an interaction can be represented by a pseudo-magnetic field $B_a^* \sin(\omega_a t)$, which oscillates at the axion Compton frequency $\omega_a = m_a c^2/\hbar$, with the amplitude B_a^* proportional to the axion-spin coupling strength: $B_a^* \propto g_d$ or $B_a^* \propto g_{aNN}$ [1, 6]. A solid sample is chosen to maximize the magnitude of this interaction. For the nuclear EDM coupling, CASPEr-e uses poled ferroelectric crystals, such as $\mathrm{PbTiO_3}$ or PMN-PT, leveraging the enhanced effective electric field $E^* \approx 3\times10^8$ V/cm [6–9]. The ^{207}Pb nuclear spins inside the crystal are pre-polarized in an applied magnetic field $\approx 9\,\mathrm{T}$; ongoing work explores how to speed up and/or increase this polarization using light-induced paramagnetic centers. The long spin relaxation time $T_1 \approx 15\,\mathrm{min}$ allows the bias magnetic field B_0 to be swept to lower values without losing polarization. If B_0 is chosen so that the spin Larmor frequency matches the axion Compton frequency ω_a, then the pseudo-magnetic field drives the spins on resonance, the magnetization vector tilts and precesses around the bias field. This precession is detected by a pickup coil, wound around the crystal, and coupled to a sensitive amplifier. The search for axion-like dark matter is performed by sweeping the bias field B_0.

Projected sensitivity: The magnitude of the signal detected by the sensor is proportional to the number of spins in the ensemble, the degree of polarization, the coherence time of the spin ensemble, and the magnitude of the pseudo-magnetic field B_a^*. Experiment sensitivity can be limited by the amplifier that detects oscillating transverse magnetization component, by thermal noise in the circuit that couples to this amplifier, or by fundamental quantum spin projection noise. Sensitivity projections for the axion EDM coupling using ferroelectric PMN-PT crystals are shown in fig. 2. An experiment with a 5 mm sample, with sensitivity limited by SQUID amplifier with $1\,\mu\Phi_0/\sqrt{\mathrm{Hz}}$ noise floor, is projected to probe beyond the astrophysical SN1987A constraints. An experiment with a 60 cm sample is projected to reach the QCD axion sensitivity in the mass range $\approx 10^{-12}\,\mathrm{eV}$ to $\approx 5 \times 10^{-9}\,\mathrm{eV}$. An experiment limited only by spin projection noise (standard quantum limit) is projected to reach QCD axion sensitivity up to masses $\approx 5 \times 10^{-8}\,\mathrm{eV}$.

Projected timeline: Experimental measurements are ongoing with a 5 mm ferroelectric PMN-PT sample, and first limits have been placed in the mass range $162\,\mathrm{neV} - 166\,\mathrm{neV}$. The sweep down to the lower mass range is projected to be completed on a 1-year timeline. Studies of light-induced paramagnetic centers in PMN-PT have demonstrated the feasibility of leveraging engineered electronic spins in the CASPEr-e experiment. The collaboration envisions the following timeline for future research activities, continuing to proceed in parallel:

(1) optimization of spin ensemble parameters, such as polarization and coherence time (2-3 years);
(2) scalable synthesis and characterization of sample materials with properties favorable for achieving CASPEr-e physics goals (3-4 years);
(3) studies of experimental sensitivity scaling with spin ensemble size (2-3 years);
(4) integration with sensitive readout sensors, such as optimized DC SQUIDs and Radiofrequency Quantum Upconverter (RQU) sensors (3-5 years);
(5) measurements at the level of quantum spin projection noise (3-5 years).

The first measurements have confirmed the feasibility of the CASPEr-e concept, and achieved experimental limits are consistent with fig. 2. The collaboration envisions that taking the experiment to the scale necessary to achieve QCD axion sensitivity can be achieved on a 5-7 year timeline.

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