Snowmass2021 - Letter of Interest

Exploring Axion Dark Matter with Ultrasensitive Optical Quantum Sensors

Topical Group(s):

☐ (CF1) Dark Matter: Particle Like
☑ (CF2) Dark Matter: Wavelike
☐ (CF3) Dark Matter: Cosmic Probes
☐ (CF4) Dark Energy and Cosmic Acceleration: The Modern Universe
☐ (CF5) Dark Energy and Cosmic Acceleration: Cosmic Dawn and Before
☐ (CF6) Dark Energy and Cosmic Acceleration: Complementarity of Probes and New Facilities
☐ (CF7) Cosmic Probes of Fundamental Physics
☑ (Other) (IF1) Quantum Sensors

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Abstract:
We aim to construct the most sensitive high-frequency optical quantum sensor (OQS) with sensitivity meeting the fundamental quantum limit on the order of 10 attoTesla, surpassing the sensitivity of superconducting quantum interference device (SQUID) as the leading magnetic-field sensor over the past decades. This work is based on unique Los Alamos National Laboratory (LANL) capability in the development and analysis of OQSs and existing LANL resources. We anticipate that achieving this unprecedented sensor sensitivity could significantly improve existing wavelike dark matter searches, targeting extremely small magnetic signals induced by dark matter particles. Furthermore, it could lead to diverse new sensitive dark matter experiments. As an example, we investigate a lumped-circuit-based axion dark matter experiment using LANL infrastructure, and we estimate that this experiment can achieve a sensitivity up to seven orders of magnitude greater than the current best limit.

1. Objective

One of the key challenges in wavelike dark matter (DM) experiments, mainly targeting minute magnetic signals as the DM observable, is to overcome the sensitivity limitation of the existing sensor technology. The sensor sensitivity limitation problem motivates us to develop the most sensitive high-frequency optical quantum sensors (OQS) with sensitivity meeting the fundamental quantum limit, beyond the capability of current magnetic sensor technology. The OQS manipulates the spins of electrons for magnetic sensing based on lasers, alkali-metal vapor cells, and optical components [1], and operates at ambient temperatures without the need for expensive cryogens. While superconducting quantum interference devices (SQUIDs) have played an important role in development of most sensitive magnetic-field measurements, OQSs can outperform SQUIDs in terms of cost, operational convenience and simplicity, and sensitivity. Table 1 summarizes an overall comparison between OQSs and SQUIDs. Importantly, OQSs are potentially capable of a sensitivity of 10 aT/Hz$^{1/2}$ at the OQS fundamental quantum limit [2], surpassing the sensitivity of a SQUID with more than 100 times improvement over the best commercial sensors. Achieving this unprecedented OQS sensitivity will be accomplished by improving and optimizing the design and operation of the OQS using unique LANL expertise in the development and theoretical analysis of OQSs [2−10]. For example, we will construct a gradiometer to cancel residual ambient noise; heat the OQS vapor cell with the coldest spot away from the measurement cell area to minimize Johnson noise from alkali-metal condensation; and employ a low-noise ferrite shield for the innermost shield layer. (LANL investment is providing initial funding for the OQS development.) We anticipate that the enhanced OQS technology can advance detector capabilities for exploring wavelike DM such as axions in the sub-eV mass range [11,12].

Table 1: Overall comparison between OQSs and SQUIDs.

Specification	OQS	SQUID
Physics principles	Atomic, optical	Bose-Einstein condensate
Operation	Completely cryogen-free, simple turn-key operation	Cryogenic
Other properties	Flexible position, Three sensitive directions	Fixed inside Dewar, One sensitive direction
Novelty	Microscopic/macroscopic detection with novel sensors	Macroscopic/bulk detection, traditional sensors (>30 years)
Magnetic field sensitivity	Best experimental sensitivity: **240 aT/Hz$^{1/2}$** with a 96 cm^3 vapor cell at 423 kHz [13] Fundamental quantum limit: **10 aT/Hz$^{1/2}$** with a 100 cm^3 vapor cell at frequencies > 10 kHz (limited by shot noise of alkali-metal vapor [2])	Best experimental sensitivity[a]: **150 aT/Hz$^{1/2}$** with a 4.5 cm-diameter pickup coil at 4.2 K and 100 kHz region [14] (fundamentally limited by Johnson noise in the junction shunt resistors)

2. Possible Axion DM Search with the Most Sensitive OQS

As an example of possible DM searches based on the most sensitive OQS, we investigate an experiment using the direct axion detection concept of an inductor-capacitor (LC) circuit [15,16] based on LANL resources. The modification of the Maxwell equations caused by the axion-photon coupling, $g_{a\gamma\gamma}$, results in a minute magnetic field, $\boldsymbol{B}_{\mathbf{a}}$, oscillating at a frequency equal to the axion mass, m_{a}, in the presence of a static magnetic field, $\boldsymbol{B}_{\mathbf{0}}$. This experiment detects the $\boldsymbol{B}_{\mathbf{a}}$ using an LC circuit comprised of an input gradiometer and an output coil, the two connected in series with a capacitor to amplify the signal, and the OQS with 10 aT/Hz$^{1/2}$ sensitivity to detect the amplified signal, $\boldsymbol{B}_{\mathbf{d}}$, as illustrated in Fig. 1. The large-bore LANL 2-T superconducting magnet can generate $B_0 = 2$ T. In order to take advantage of the enhanced OQS sensitivity, the Johnson noise caused by the LC circuit is reduced by cooling the LC circuit to 4 K using a cryogen-free closed cycle refrigerator. Currently LANL investment is supporting the development of a prototype setup using an LC circuit at room temperature and a commercial OQS with 10 fT/Hz$^{1/2}$ sensitivity.

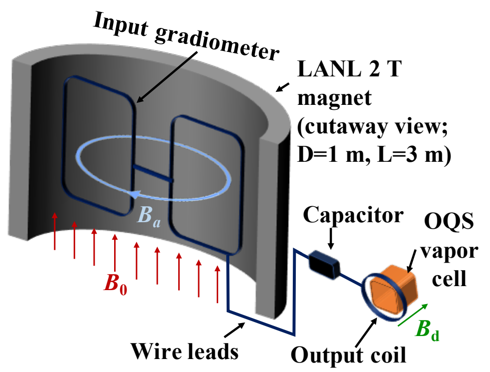

Figure 1: Schematic drawing of the experiment layout.

Figure 2 shows our expected sensitivity of the experiment to the $g_{a\gamma\gamma}$ (blue dotted line labeled "This experiment"), based on the local density, and axion signal coherence time, of the isothermal halo model [17]. This search can set a new limit on a mass range between 10^{-11} and 10^{-7} eV in particular by up to 7 orders of magnitude beyond the CAST limit [18]. The magenta band indicates a broad range of $g_{a\gamma\gamma}$ for QCD axion predicted by various axion models [24,25]. As benchmark examples, the KSVZ [26,27] and DFSZ [28,29] models are shown. Most importantly, the search can potentially access compelling targets below the KSVZ QCD axion band at $m_a \sim 10^{-8}$ eV and probe a chunk of the QCD axion parameter space.

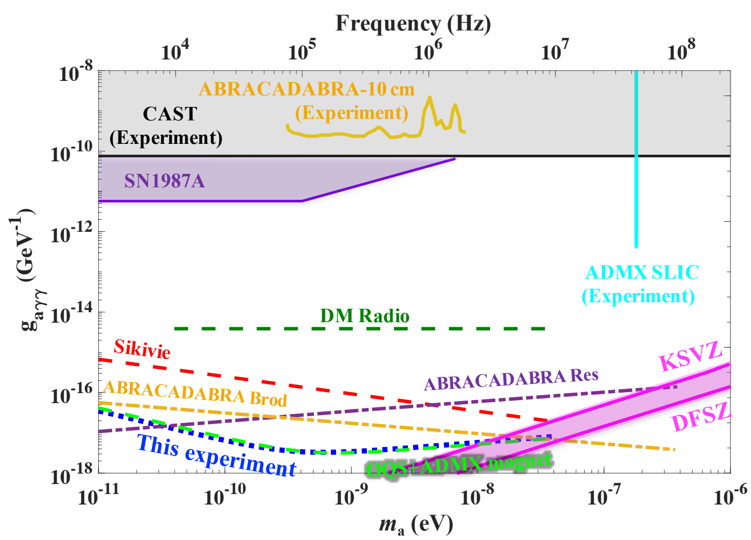

Figure 2: Projected sensitivity of the experiment based on a 4 K LC circuit and the OQS with 10 aT/Hz$^{1/2}$ sensitivity with the integration time t_{int} = 72 h on the axion mass range (blue dotted line). The experiment will improve the CAST limit [18] (gray region), specifically by 7 orders of magnitude at $m_a \sim 10^{-9}$ eV. The purple region is constrained by the astrophysical source of supernova SN1987A [19]. Also, the figure shows projected sensitivities of other experiments such as ABRACADABRA using the broadband (Broad) and resonant (Res) strategies [20] with B_0 = 5 T and t_{int} = 1 yr; DM radio [21] with B_0 = 0.1 T and t_{int} = 1.5 yr; and Sikivie's Proposal [15] with B_0 = 8 T and t_{int} = 1000 s. The yellow curve above the CAST limit shows the first result from the experiments of ABRACADABRA-10 cm [22]. The light blue curve shows the experimental results from the ADMX SLIC [23].

The improved sensor capability will lead to diverse new sensitive wavelike DM experiments, which opens collaborative possibilities. For example, the green dotted line labeled "OQS+ADMX magnet" shows the sensitivity that could be achieved with the OQS and the ADMX magnet [15].

3. Timeline

It is expected that we need at least two years for constructing an OQS for a possible DM experiment and improving its sensitivity to the fundamental quantum limit. Based on the OQS, we need at least a half year to integrate the OQS with an experimental setup; and we need many years to collect data to scan the wavelike DM mass range.

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