Snowmass2021 - Letter of Interest

Search for Halo Axions with Ferromagnetic Toroids (SHAFT)

Thematic Areas:

■ (CF2) Dark Matter: Wavelike

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Abstract:

The Search for Halo Axions with Ferromagnetic Toroids (SHAFT) is a direct broadband laboratory search for the electromagnetic interaction of axion-like dark matter. The detection scheme is based on a modification of Maxwell's equations in the presence of axion-like dark matter, which mixes with a static magnetic field to produce an oscillating magnetic field. The experiment makes use of toroidal magnets with iron-nickel alloy ferromagnetic powder cores. The first generation of the experiment has reported limits on the electromagnetic interaction of axion-like dark matter in the mass range that spans three decades from 12 peV to 12 neV [1]. It improved the CAST limits on the magnitude of the axion-like dark matter electromagnetic coupling constant over part of our mass range, at 20 peV reaching 4.0×10^{-11} GeV^{-1} (95% confidence level). After a number of technical improvements, we project a sensitivity improvement of two orders of magnitude, reaching sub-10^{-12} GeV^{-1} level in the mass range between $10^{-12}\,\mathrm{eV}$ and $\approx 10^{-8}\,\mathrm{eV}$.

Physics goals: The SHAFT experiment is sensitive to the electromagnetic coupling $g_{a\gamma}$ of axion-like particles. The goal is to search for axion-like dark matter in the mass range between 10^{-12} eV and $\approx 10^{-8}$ eV, with coupling strength sensitivity down to 10^{-12} GeV^{-1}. We aim to explore the region of parameter space where ALP-photon mixing could explain the anomalous transparency of the universe to TeV gamma-rays [2–4].

Experimental technique: Our approach is based on a modification of Maxwell's equations in the presence of axion-like dark matter, which mixes with a static magnetic field B_0 to produce an oscillating magnetic field [5–9]. We use a toroidally-shaped permeable iron-nickel alloy material to enhance the magnitude of the static magnetic field B_0 by a factor of 24, and thus improve sensitivity to axion-like dark matter [1]. SHAFT contains two independent detection channels. Each channel consists of two stacked toroids, each of which can be independently magnetized by injecting a current into a superconducting magnetizing coil wound around the toroid, fig. 1(a). With azimuthal field B_0 inside the magnetized toroid, the ALP dark matter-induced effective current creates an axial magnetic field B_a. The pickup coil, wound around the inner circumference of the toroids, is coupled to a Superconducting Quantum Interference Device (SQUID) magnetometer, as shown in fig. 1(b), measuring the magnetic flux Φ_a due to B_a. The axion-like dark matter detection signature is an oscillating SQUID output signal, whose amplitude is correlated with toroid magnetization. The experiment bandwidth, and the range of axion-like dark matter mass it is sensitive to, is limited by the SQUID magnetometer bandwidth of 2 MHz.

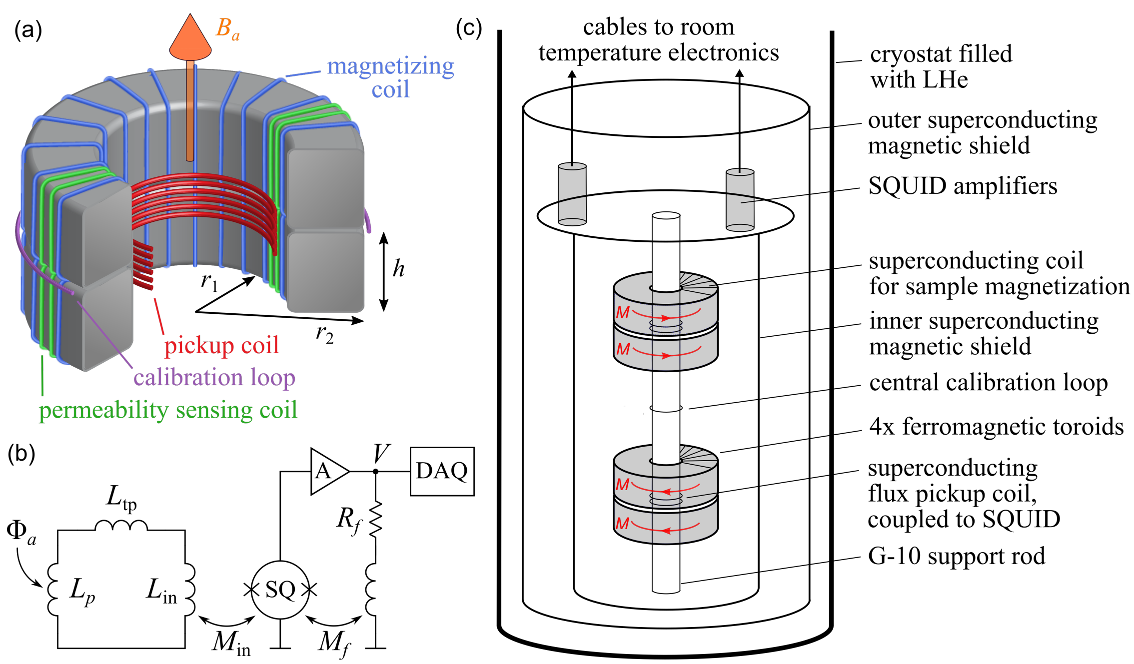

Figure 1: The SHAFT experimental approach. (a) Schematic of a single detection channel. Two permeable toroids are independently magnetized by injecting current into a magnetizing coil wrapped around each toroid. Toroid magnetization was monitored by measuring the inductance of the permeability sensing coils. Dimensions: $r_1 = 24.4$ mm, $r_2 = 39.1$ mm, $h = 16.2$ mm. (b) The circuit model that shows the axion-induced flux Φ_a coupling into the pickup coil (inductance L_p). The pickup coil is coupled to the SQUID magnetic flux sensor (SQ) via twisted pair leads (inductance $L_{\rm tp}$) and input coil (inductance $L_{\rm in}$). The SQUID is operated in the flux-locked-loop mode, with feedback resistance R_f. The feedback voltage V was digitized and recorded by the data acquisition system (DAQ). (c) The SHAFT experimental schematic. The apparatus contains four permeable toroids, shown magnetized in the $(++, --)$ configuration, which was used to collect data sensitive to axion-like dark matter. The experiment operates at 4.2 K in a liquid helium bath cryostat.

The two-channel, four-toroid design enables a systematic rejection scheme that allows for discrimination between an axion-like dark mater signal and electromagnetic interference. For collecting data sensitive to axion-like dark matter, the top two toroids are magnetized counter-clockwise (channel A: $++$), and the bottom two toroids clockwise (channel B: $--$), viewed from the top, fig. 1(c). An axion-like dark matter signal would then appear in the two detector channels with opposite sign (180° out of phase). Electromagnetic interference, uncorrelated with toroid magnetization, would not have such a phase relationship and could be distinguished from an axion-like dark matter signal by forming symmetric and antisymmetric combinations of the two detector channels. The toroids and pickup coils are inside an enclosure formed by two nested coaxial cylinders immersed in liquid helium. Lead foil, affixed to the inner surfaces of the cylinders and their caps, forms a double-layer superconducting magnetic shield, suppressing electromagnetic interference and ambient magnetic field noise.

Projected sensitivity: The SHAFT first-generation experiment has reported limits on the electromagnetic interaction of axion-like dark matter in the mass range that spans three decades from 12 peV to 12 neV [1]. It improved the CAST limits on the magnitude of the axion-like dark matter electromagnetic coupling constant over part of our mass range, at 20 peV reaching 4.0×10^{-11} GeV^{-1} (95% confidence level), fig. 2. We plan to implement a number of technical improvements, including mounting the experiment in a dilution refrigerator, and scaling the toroid volume by a factor of 5. With these upgrades, we project a sensitivity improvement of two orders of magnitude, reaching sub-10^{-12} GeV^{-1} level in the mass range between 10^{-12} eV and $\approx 10^{-8}$ eV.

Projected timeline: The 2019 experimental run has produced limits shown in fig. 2. We envision a 3-4 year timeline for implementing the technical improvements needed to achieve the sensitivity goal stated above.

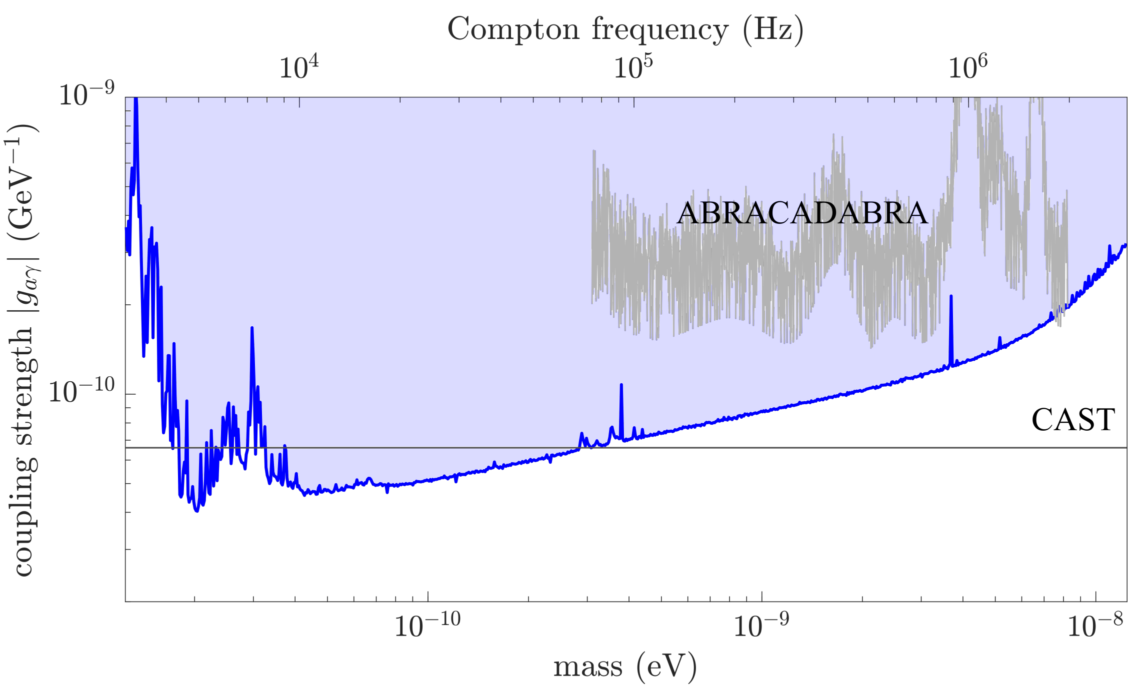

Figure 2: Current limits on the electromagnetic coupling strength of axion-like dark matter in the mass range from 12 peV to 12 neV, assuming the standard halo model. The blue shaded region is excluded by 2019 data run at 95% confidence level [1]. The horizontal black line shows the limit from the CAST helioscope [10], and the grey line shows the ABRACADABRA limits on axion-like dark matter [9].

References:

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