ARIADNE (Axion Resonant InterAction Detection Experiment): an NMR-based Axion Search, Snowmass LOI

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The Axion Resonant InterAction Detection Experiment (ARIADNE) is a collaborative effort to search for the QCD axion using techniques based on nuclear magnetic resonance. In the experiment, axions or axion-like particles would mediate short-range spin-dependent interactions between a laser-polarized ^{3}He gas and a rotating (unpolarized) tungsten source mass, acting as a tiny, fictitious magnetic field. The experiment has the potential to probe deep within the theoretically interesting regime for the QCD axion in the mass range of 0.1-10 meV, independently of cosmological assumptions. In this SNOWMASS LOI, we briefly describe this technique which covers a wide range of axion masses as well as discuss future prospects for improvements. Taken together with other existing and planned axion experiments, ARIADNE has the potential to completely explore the allowed parameter space for the QCD axion.

A well-motivated example of a light mass pseudoscalar boson that can mediate new interactions or a "fifth-force" is the axion. The axion is a hypothetical particle that arises as a consequence of the Peccei-Quinn (PQ) mechanism to solve the strong CP problem of quantum chromodynamics (QCD)[1]. Axions have also been well motivated as a dark matter candidatedue to their "invisible" nature[2]. Axions can couple to fundamental fermions through a scalar vertex and a pseudoscalar vertex with very weak coupling strength. Possible allowed interactions are monopole-monopole, monopole-dipole, and dipole-dipole in the sense of a multipole expansion. Monopole-dipole interactions include a scalar coupling, g_s, and a pseudo-scalar coupling, g_p, thereby violating P and T symmetry. In non-relativistic limit, this interaction is proportional to $g_s g_p \vec{\sigma} \cdot \vec{r}$ where $\vec{\sigma}$ is the spin of one particle, and $\vec{r}$ is the distance between two particles. Dipole-dipole interactions are dependent on spins of two particles, $\vec{\sigma}_1$ and $\vec{\sigma}_2$, and are proportional to $g_p^2 \vec{\sigma}_1 \cdot \vec{\sigma}_2$[3], [4], [5]. Depending on the model, the monopole and dipole couplings can occur for either electrons or nuclei. Although the couplings are extremely small for the interaction between single particles, a macroscopic object with $10^{22} \sim 10^{23}$ components would produce a coherent field which can be detectable with a sensitive laboratory experiment[6]. Many of the experimental tests of this interaction have been done with polarized gases[7]. Torsion balance experiments also have recently set new limit on both monopole-dipole interactions and dipole-dipole interactions. But laboratory constraints on possible new interactions in the "meso-scopic" range have not yet been well developed [8]. In many cases, combined laboratory measurements taken in parallel with astrophysical data have produced the most stringent constraints on the products of the coupling constants g_s and g_p [9].

ARIADNE aims to detect axion-mediated spin-dependent interactions between an unpolarized source mass and a spin-polarized ^{3}He low-temperature gas [10, 11]. Unlike other direct axion search experiments which depend on the local Dark Matter density at the earth, with the axion being the particle that constitutes Dark Matter, the signal can be modulated in a controlled way. The experiment probes QCD axion masses in the higher end of the traditionally allowed axion window of 1 μeV to 6 meV, which are not accessible by any existing experiment including dark matter haloscopes such as ADMX. Thus ARIADNE fills an important gap in the search for the QCD axion in this important region of parameter space. The axion can mediate an interaction between fermions (e.g. nucleons) with a potential given by $U_{sp}(r) = \frac{\hbar^2 g_s^N g_p^N}{8\pi m_f} \left(\frac{1}{r\lambda_a} + \frac{1}{r^2} \right) e^{-\frac{r}{\lambda_a}} (\hat{\sigma} \cdot \hat{r})$, where m_f is their mass, $\hat{\sigma}$ is the Pauli spin matrix, $\vec{r}$ is the vector between them, and $\lambda_a = h/m_A c$ is the axion Compton wavelength. For the QCD axion the scalar and dipole coupling constants g_s^N

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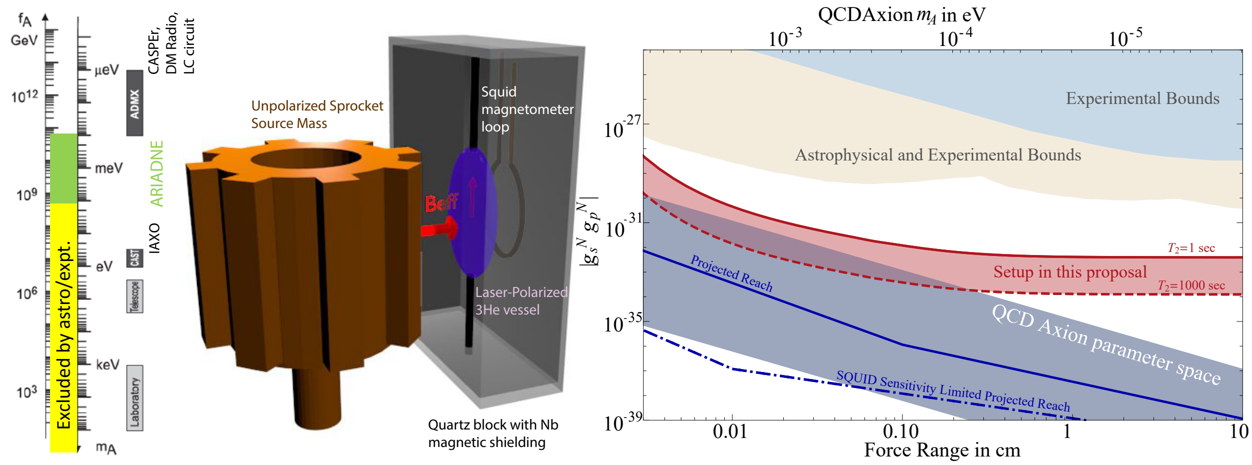

FIG. 1. (left) Constraints and experiments searching for the QCD axion, adapted from Ref. [12]. (middle) Setup: a sprocket-shaped source mass is rotated so its "teeth" pass near an NMR sample at its resonant frequency. (right) Projected reach for monopole-dipole axion mediated interactions. The band bounded by the red (dark) solid line and dashed line denotes the limit set by transverse magnetization noise, depending on achieved T_2. Current constraints and expectations for the QCD axion also are shown, adapted from Ref. [10]. Note the recent results of Ref. [13] improve constraints at the 10 cm range by approximately an order of magnitude from what is plotted here

and g_p^N are correlated to the axion mass. Since it couples to $\hat{\sigma}$ which is proportional to the nuclear magnetic moment, the axion coupling can be treated as a fictitious magnetic field B_{eff}. This fictitious field is used to resonantly drive spin precession in a laser-polarized cold ^{3}He gas. This is accomplished by spinning an unpolarized tungsten mass sprocket near the ^{3}He vessel. As the teeth of the sprocket pass by the sample at the nuclear larmor precession frequency, the magnetization in the longitudinally polarized He gas begins to precess about the axis of an applied field. This precessing transverse magnetization is detected with a superconducting quantum interference device (SQUID). The ^{3}He sample acts as an amplifier to transduce the small fictitious magnetic field into a larger real magnetic field detectable by the SQUID. Superconducting shielding is needed around the sample to screen it from ordinary magnetic field noise which would otherwise limit the sensitivity of the measurement. The experiment sources the axion in the lab, and can explore all mass ranges in our sensitivity band simultaneously, unlike experiments which must scan over the allowed axion oscillation frequencies (masses) by tuning a cavity or magnetic field. Distinct from other magnetometry experiments [13–15], the experiment uses a resonant enhancement technique. Assuming sources of systematic error and noise can be mitigated, the approach is expected to be spin-projection noise limited [10], and in principle allows several orders of magnitude improvement, yielding sufficient sensitivity to detect the QCD axion (Fig. 1).

Future prospects for improvements in the search for novel spin dependent interactions could include investigations with a spin polarized source mass, or improved sensitivity with new cryogenic or quantum technologies. Spin squeezing or coherent collective modes in ^{3}He could offer prospects for improved sensitivity beyond the Standard quantum limit of spin projection noise in experiments such as ARIADNE, potentially allowing sensitivity all the way down to the SQUID-limited sensitivity (dashed-dotted line in Fig. 1). This would allow one to rule out the axion over a wide range of masses, and when combined with other promising techniques [16–18], and existing experiments [19, 20] already at QCD axion sensitivity, could allow in principle the QCD axion to be searched for over its entire allowed mass range.

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