Snowmass2021 - Letter of Interest

ADMX-SLIC search for low-mass axions and axion-like particles

Thematic Areas:

☐ (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) *[Please specify frontier/topical group]*

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Abstract:

We propose to search for axion dark matter in the frequency range 10–200 MHz ($0.04 < m_a < 0.8\,\mu$eV) using a reentrant resonator haloscope. We call this haloscope ADMX-SLIC (Superconducting Lc-circuit Investigating Cold axions). First, a small prototype will be built and tested in data-taking mode inside the 8 T magnet of the 1980's University of Florida Axion pilot experiment. Based on this experience, a larger reentrant resonator haloscope will be built for the ADMX site at the University of Washington and operated there. The ADMX magnet has a dilution refrigerator and a zero-field region, allowing operation of SQUID amplifiers. The detector should have quantum-limited sensitivity and reach the DFSZ limit at the upper limit of the search range.

ADMX has presently achieved sensitivity to dark matter axions having the small DFSZ coupling of the axion to two photons and a local (on Earth) axion density of 0.45 GeV/cm^3.[1, 2] The frequency range covered so far is approximately 625–825 MHz, corresponding to the axion mass range 2.6–3.3 μeV. A large well-motivated effort is underway to expand the ADMX frequency upward using multi-cavity arrays, qubit electronics, and possibly a much stronger magnet. However, lower frequencies are also well-motivated. From a theoretical viewpoint, the most relevant issue is whether cosmological inflation happens before or after the Peccei-Quinn (PQ) phase transition. If before, the higher axion masses are better motivated. If after, the lower masses. The PQ phase transition occurs at a temperature of order the axion decay constant $f_a \sim 10^{12}$ GeV. The reheat temperature at the end of inflation is model-dependent but can not exceed the scale Λ_I of inflation [3]. The non-observation of tensor perturbations requires $\Lambda_I \lesssim 1.5 \cdot 10^{16}$ GeV. So, there is limited room in (Λ_I, f_a) parameter space for inflation to occur before the PQ phase transition. On the other hand, Λ_I and the reheat temperature may be very low compared to f_a. There appears to be more room in parameter space for inflation to occur after the PQ phase transition, motivating searches for axions with lower masses.

If hollow resonant cavities, such are used by ADMX, are used for low-mass axion searches, they must be very large. A cavity optimized for 0.4 μeV would resonate at just under 100 MHz. Its diameter would be 2.4 meters, requiring a really huge magnet. For 40 neV, the cavity (and magnet) would be 24 meters in diameter. The good news is that a lumped circuit, an LC resonator, can have at these frequencies very high quality factors and efficient coupling for conversion of axions to photons.[4] The LC circuit resonant frequency is (almost) independent of the dimensions of the magnet in which it goes, decoupling axion mass search range from magnet and resonator dimensions.

ADMX SLIC (Superconducting Lc-circuit Investigating Cold axions) recently reported a search for axions with masses in narrow ranges around 0.18 μeV.[5] The experiment used a single-turn inductor and parallel-plate capacitor, both made from NbTi, as a 43 MHz resonator with $Q > 10,000$. The sensitivity limit using a semiconducting first-stage amplifier was $g_{a\gamma\gamma} > 10^{-12}$ GeV^{-1}. The limit is about 30,000 times above the KSVZ and DFSZ values but is 100 times below the CAST limit. Other LC circuit experiments are taking place at MIT [6] and Stanford [7].

Instead of a simple loop, a reentrant resonator or coaxial resonator has advantages. This resonator, sketched in Fig. 1, has a coaxial section, with a metal rod in the center and a surrounding cylindrical casing. The inductance is determined by the length h and the ratio of rod diameter a to casing diameter b as $L = h\mu_0 \ln(b/a)/2\pi$. There is a capacitance between center rod and casing, which is in parallel with the parallel-plate capacitor shown. This capacitor is tuned by changing the plate separation using pressure to move a bellows. A 45 cm diameter and 100 cm long reentrant resonator can tune 10–50 MHz. Decreasing the length to 22 cm allows tuning 40–200 MHz. Reentrant resonators have applications in various fields of physics and engineering. There is extensive experience building and operating them.

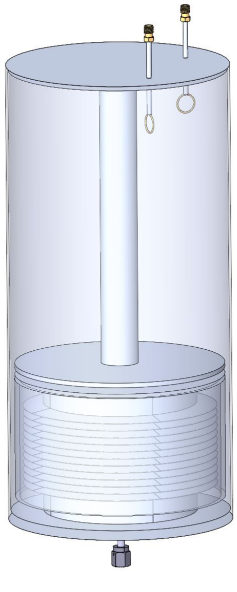

Fig. 1. A reentrant resonator, tuned by pressure in the bellows shown.

A drawback of reentrant resonators for the purpose of axion dark matter searches is that their form factor decreases with decreasing frequency f, approximately as f^2. For this reason, an ADMX-size reentrant resonator will only be sensitive to axion dark matter for some range of frequencies below where ADMX has searched already. However, it is entirely possible that this range is increased because the local axion density is much larger than the standard 0.3 GeV/cm^3. This value is obtained by fitting a spherically symmetric halo model to the Galactic rotation curve. It is indeed a good estimate of the local dark matter density but only when averaged on a scale of 1 kpc $\simeq 3 \cdot 10^{21}$ cm. The ADMX detector operates on a scale of 100 cm, i.e. 19 orders of magnitude smaller.

Because axions are cold and collisionless one should not expect the axion density on Earth to be the same as the average density on a kpc scale. A halo made of cold collisionless particles is dominated by cold unthermalized flows. Cold flows form caustics which are locations in physical space where the density is very large. The caustics have observational consequences. A recent paper [8] concludes, on the basis of GAIA and IRAS observations, that we on Earth are close to a caustic in the Milky Way halo. If so the local dark matter density is dominated by four cold flows. A lower bound on the largest of the four flows, called the Big Flow, is 6 GeV/cm^3 [8]. Two other flows, called Up and Down, have minimum densities of order 3 GeV/cm^3 each. The flows produce very narrow lines in the energy spectrum of axions on Earth. We estimate that an ADMX size reentrant resonator operating at the low noise levels already achieved by ADMX, and searching for narrow lines in its HiRes channel, would be able to discover axions with the stated densities over a frequency range from approximately 100 to 625 MHz. Below 100 MHz, the form factor is too small to find DFSZ coupled axions even at these high densities. If axions are not found, a useful limit will be set. Also, we will have developed a new technology that is suitable for axion searches at frequencies intermediate between those accessible by standard cavities and those accessible by ordinary LC circuit detectors.

A reentrant resonator can be thought of as an LC circuit resonator whose inductance and capacitance are properties of the resonator itself. LC circuits were analyzed as axion dark matter detectors in ref. [4], which provides formulas for calculating the signal to noise ratio in a LC circuit axion dark matter detector. It is on the basis of these formulas that we have obtained preliminary estimates of the sensitivity of a reentrant resonator, as stated above. However the formulas in [4] are valid only in the quasi-static regime where the size of the LC circuit is much smaller than $\hbar c/m_a$. This condition is only barely satisfied for the proposed reentrant resonator detector. However, the sensitivity of a reentrant resonator detector to axion dark matter can be calculated using numerical simulations. Such calculations have in fact already been carried out and have been validated by measurement on an actual resonator [9]. An optimization of the resonator's design for maximum form factor has not yet been done.

Our first task is to carry out numerical simulations that optimize the design of the resonator. The deliverable of such simulations is a table showing resonant frequency and optimum form factor as a function of the depth of insertion of the longitudinal tuning post.

The next step is the mechanical design of the resonator. Figure 1 shows the design we have in mind at the moment. One capacitor plate is moved by the bellows, which allows the resonator to be tuned without much heating so that very low temperatures can be achieved. We will build a prototype and test it in data-taking mode at UF. Its length will be 45 cm, and diameter 15 cm. We expect that the physical temperature will be 0.3 K, the quality factor 10^4 and the electronic noise temperature 0.7 K.

We will then build a reentrant resonator for the ADMX site at UW, with length 100 cm and diameter 40 cm. We then will build four 25 cm length resonators for he ADMX site, with output combined in phase and sent to the receiver. The low noise receiver will use “conventional” SQUID amplifiers[10] below 100 MHz and microstrip amplifiers[11] above this frequency. We expect to operate in data-taking mode at a physical temperature of 0.03 K, quality factor $2 \cdot 10^4$, and electronic noise temperature of 0.015 K.

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