A Technique to Search for High Mass Dark Matter Axions

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Axions are a well motivated dark matter candidate. Microwave cavity experiments have been shown to be sensitive to axions in the mass range 1 µeV to 40 µeV, but face challenges searching for axions with larger masses. We propose a technique using a microwave Fabry-Pérot resonator and a series of current-carrying wire planes that can be used to search for dark matter axions with masses above 40 µeV. This technique retains the advantages of the microwave cavity search technique but allows for large volumes and high Qs at higher frequencies.

INTRODUCTION

The axion is a particle predicted as a consequence to the Peccei-Quinn solution to the Strong CP problem [1–4]. Axions also could make up some or all of dark matter [5–7].

Dark matter axions may be detected using the ‘Axion Haloscope’ technique [8]. This technique consists of placing microwave cavity in a strong magnetic field. The axion-to-photon conversion in the presence of the magnetic field is enhanced when an electromagnetic resonance in the cavity is tuned to correspond to the frequency of the photons produced. Axions would be expected appear as excess power at this frequency.

The ADMX experiment has demonstrated that microwave cavity experiments can be built with the sensitivity necessary to detect axions in the mass range that has been traditionally associated with axion dark matter, 1 µeV–40 µeV [9, 10]. However, some studies of axions as dark matter have predicted masses in the range 40 µeV to 10 meV [11, 12]. There have also been some experimental anomalies that may be associated with axions in that mass range [13, 14].

Extending microwave cavity experiments to masses above 40 µeV presents several difficulties [15]. Higher frequency cavities have smaller characteristic volumes and lower Qs, which decrease the signal power from dark matter axion conversion. We present here an experimental design that overcomes these difficulties.

TECHNIQUE

The experimental design we propose builds on the technique in Ref. [16], where axion conversion occurs in a spatially varying magnetic field generated by a series of wire planes. That technique allows for axion conversion over large volumes, but sacrifices resonant conversion enhancement and detection of the resultant photons has proven difficult to implement.

We propose placing a spatially varying magnetic field within a Fabry-Pérot resonator as a dark matter axion detector. This allows conversion volumes larger than available with the traditional resonant cavity experiments while retaining the resonant enhancement of axion photon conversion with Qs higher that can be achieved with closed cavities.

A schematic diagram of this experimental design is shown in Fig. 1. It consists of two reflectors that make up the Fabry-Pérot resonator, a series of wire planes to generate the spatially varying magnetic field, and a power detector coupled to the resonator. Dark matter axions passing through the resonator can convert into photons in the TEM$_{00n}$ modes of the resonator through the $E \cdot B$ coupling of the axion Lagrangian in precisely the same manner as with a microwave cavity experiment [8]. The conversion is maximized when the volume integral of the dot product between the electric field of the resonant mode and the magnetic field produced by the wire planes is maximized.

The electric field of the TEM$_{00n}$ mode of a microwave Fabry-Pérot resonator with spherical reflectors can be approximated as a sinusoid along the axis of the resonator and a Gaussian radially [17]. There are two polarizations to the mode, but only the polarization where the E field is parallel to the B field couples to axions. In order to maximize axion-to-photon conversion, the wire planes should be placed at the nodes of the desired resonant mode so the magnetic field alternates direction every half wavelength.

The resonant mode will be most sensitive to axions that convert into photons with frequencies within one Q width of its center frequency. The center frequency of the mode, and thus the mass of axion to which it is sensitive,
can be tuned by moving the reflectors relative to one another. For maximal sensitivity, the wire planes also must be moved to remain at the nodes of the resonance.

Photons in the resonator from axion-to-photon conversion can be extracted via standard techniques such as aperture coupling, and detected either with a microwave receiver or bolometer.

The magnetic field should be made as high as possible, with 470 A/mm capable of supporting these currents available commercially. The generation of higher magnetic fields will require finer wire spacing for the same supplied current. Such small spacing is impractical to achieve with wound superconducting wire but might be possible by employing thick film micro-fabrication techniques. The critical current density of Nb3Sn films have been shown to be as high 4 × 10^4 A/mm² at 6 T [25]. This field could be supported by photolithographically patterned wires with 60 µm spacing carrying 144 A.

Microwave Fabry-Pérot devices are a well studied technology, and Qs of 5 × 10⁹ have been achieved at frequencies of 50 GHz using superconducting reflectors [26]. The intervening wire planes will decrease this somewhat, and

### Sensitivity of Technique

The ultimate sensitivity of this technique will be determined by the technology used to produce the magnetic field, the quality factor and volume of the resonator, and the noise temperature of the receiving electronics. We estimate the reasonable values of these parameters and thus the reach of experiments using this technique here.

The magnetic field should be made as high as possible, but the current carrying lines must remain transparent to the mode used for detection. In principle a plane of wires perfectly parallel to the mode is transparent, but in practice finite wire thickness and misalignment will be a loss factor in the resonator. We estimate that planes of wires with 0.4 mm spacing carrying 470 A could support a 3 T field. Power supplies and superconducting NbTi wire capable of supporting these currents are commercially available. The generation of higher magnetic fields will require finer wire spacing for the same supplied current. Such small spacing is impractical to achieve with wound superconducting wire but might be possible by employing thick film micro-fabrication techniques. The critical current density of Nb3Sn films have been shown to be as high 4 × 10^4 A/mm² at 6 T [25]. This field could be supported by photolithographically patterned wires with 60 µm spacing carrying 144 A.
the width of the axion signal is expected to correspond to a Q of $1 \times 10^6$ [27]. As higher Q cavities have a more narrower bandwidths, the speed at which a given frequency range can be explored at a fixed axion photon coupling sensitivity will increase only linearly with $Q$ [28].

The resonator length is limited fundamentally by the axion wavelength, and practically by beam alignment and reflector fabrication. The axion wavelength in a conservative cold dark matter scenario is $\lambda = 100 \text{ m} \sqrt{\frac{100 \text{ GHz}}{f}}$. We estimate the longest convenient detector is thus 10 m long up to frequencies of 100 GHz. The maximum beam width will be dependent on the fabrication of the reflectors. From current fabrication technologies we estimate the beam width will scale roughly as $(50 \text{ cm}) \sqrt{\frac{100 \text{ GHz}}{f}}$.

Assuming the resonators are kept at cryogenic temperatures, the noise temperature of the receiver will be dominated by the first stage amplifier. Josephson Parametric Amplifiers have been produced in these frequency ranges with noise temperatures near the quantum limit, roughly $50 \mu \text{K}$ [29]. Furthermore at sufficiently high frequencies the effective noise temperature of a receiver can be exponentially improved if a detector technology that counts the presence of single photons within the cavity can be implemented [30]. Such detectors based on superconducting Josephson qubits already exist at 4 GHz [31] and might be engineered to operate at higher frequencies. We estimate an axion search operating near 120 GHz and cooled to 100 mK would have an effective noise temperature of only $6 \times 10^{-10}$ mK if single photon counting techniques could be implemented. In practice the effective noise temperature of such an experiment would be dominated by stray radiation entering the reflectors resulting in a somewhat higher noise floor.

Our estimates on important experimental parameters are summarized for a number of hypothetical experiments in several frequency ranges in Table I and the potential reach of such experiments is shown in figure 2. This technique can be sensitive to even pessimistically coupled axion dark matter, or dark matter scenarios where axions do not make up all of the dark matter. Bolometer detectors, single photon detectors, and alternate resonator construction may be able to push beyond our estimates at higher frequencies.

| Experiment | Mass Target | Frequency | B Field | Q | Volume | Noise Temperature | Run Time |
|------------|-------------|-----------|---------|---|--------|------------------|----------|
| A          | 52 $\mu$eV  | 15 GHz    | 3 T     | $10^6$ | $1 \times 10^6 \text{ cm}^3$ | 750 mK | 1 Year |
| B          | 103 $\mu$eV | 30 GHz    | 3 T     | $10^6$ | $8 \times 10^5 \text{ cm}^3$ | 1.5 K  | 1 Year |
| C          | 207 $\mu$eV | 60 GHz    | 6 T     | $10^6$ | $4 \times 10^5 \text{ cm}^3$ | 3 K    | 1 Year |
| D          | 414 $\mu$eV | 120 GHz   | 6 T     | $10^6$ | $2 \times 10^5 \text{ cm}^3$ | 6 K    | 1 Year |

TABLE I. Estimated parameters for axion experiments.

CONCLUSIONS

We have presented a technique to search for dark matter axions in the mass range 40–400 $\mu$eV. Reasonable estimates on the technology available suggest that experiments using this technique could be constructed to explore the majority of theoretically allowed axion-photon couplings in scenarios where axions constitute the bulk of the dark matter over this mass range.

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