Snowmass2021 - Letter of Interest

Resonant Halo Axion Detectors for the Mass Range 16-41 μeV

Thematic Areas: (check all that apply ☐/■)

☐ (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
■ (IF01) Quantum Sensors

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Abstract: We present a summary of efforts to probe the mass range $16 - 41\,\mu eV$ for dark matter halo axions. Technological challenges in probes of this mass range are discussed, and some solutions outlined. Solutions to some of these challenges are also of interest to communities involved in more general quantum measurement, such as quantum information science. We outline the experimental challenges anticipated when probing this mass range and summarize experimental efforts in which the authors plan to search this mass range for axions in the next 5-10 years.

1 Introduction

Axions, representing the potential solution of the 44-year-old strong CP Problem[1], are a candidate of rapidly increasing interest in the quest to solve the 90-year-old dark matter problem[2,3]. QCD axions[4] possess very faint couplings to ordinary matter. Search experiments achieving the requisite sensitivity exploit high-Q resonators, in which photons from Primakov conversion of axions drive modes of an electromagnetic resonator of volume V threaded by a static magnetic field B[5,6]. When the frequency of a suitable cavity mode matches the axion energy, resonant enhancement boosts the otherwise undetectable signal power to of order yoctowatts, detectable with existing technology. In practice, the mode frequencies are tuned to probe a range of axion masses at a rate limited by the radiometer equation. Though the range of possible axion masses is many orders of magnitude, recent developments in lattice QCD[7,8] predict m_a in the range $16 - 41\,\mu\mathrm{eV}$. Some post-inflation production string and domain wall models claim very precise predictions of m_a also within this range[9]. This letter summarizes experimental issues relevant to searches for axions in this well-motivated range of masses.

2 Magnets and Resonators

Because the signal power is proportional to the magnetic field squared and volume, the first experiments optimized for both B^2V and cost. The ADMX experiment currently uses a single cavity in a 220-liter, 7-T solenoidal magnet. Its most recent experiments probe the DFSZ[10,11] and KSVZ[12,13] axion models in the range $2.6 - 3.3\,\mu\mathrm{eV}$[14]. The Haystac haloscope, operating a higher frequencies, uses a smaller volume, 9-T solenoidal magnet. Its first results place limits on axions at about twice the KSVZ model power level for a $23.55 - 24.0\,\mu\mathrm{eV}$ mass range. Probing much higher masses naturally leads to ever-decreasing cavity volumes, and hence less signal power. Several approaches to achieving higher sensitivity in this mass range are possible. First, arrays of small cavities power-combined can be tuned in-phase to achieve the required volume. This difficult technical task has been made tractable in the past decade through the development of cryogenic piezo crystal actuators. Second, a higher field magnet can be used at a smaller volume. Developments in magnet technologies now enable fields exceeding 30 T over suitable geometries, though such magnets are very costly[15]. An aspiration for the future would be funding for a large (order 1m bore) magnet with a high field (order 20-30 T), though such a magnet would itself be a major research and development project.

3 Low Noise Receivers

Improvements in low noise amplifier technology may mitigate some of the limitations of axion searches in this mass range. The advent of the Josephson Parametric Amplifier (JPA) has already enabled higher frequency axion searches[14]. The HAYSTAC experiment used a JPA in its 23.55–24.0 μeV run[16]. The most recent ADMX run also used a JPA to reach DFSZ[10,11] sensitivity[14]. Traveling wave parametric amplifiers (TWPAs) may also prove beneficial in this frequency regime[17]. A major advantage of TWPAs is that they do not rely on a resonant structure and therefore provide gain over a wide bandwidth, reducing the need to tune the amplifier. They are also less sensitive to perturbations in the magnetic field. These features could help reduce some of the complexity that is inherent to multi-cavity systems that may be necessary in this frequency range. Such devices can provide a power gain of 20 dB over a bandwidth of 3 GHz[17,18]. Quantum linear amplifiers such as JPAs and TWPAs can achieve exceedingly low noise levels, but are constrained to operate above the standard quantum limit. HAYSTAC has recently used the enhancement from a squeezed state receiver to double their search rate, setting a new limit in the region from 16.96–17.12 and 17.14–17.28 μeV[19]. Single photon counters, if feasible in this frequency range, would provide an alternative to quantum linear amplifiers that could radically change the landscape of possible experiments. In fact, there is reason to believe that for a least part of the $16 - 41\,\mu\mathrm{eV}$ mass range, single photon detectors would be preferable to linear amplifiers[20]. There is some evidence that suggests this may be possible in the near future[21]. Single photon counters using Josephson Junctions have shown some promise[22], but further studies are necessary before this technology can be fully implemented. An approach pioneered by the CARRACK collaboration[23,24] coupled single photon detectors in the form of rubidium Rydberg atoms[23,24] to an axion haloscope, excluding axions of mass $\sim 1.006 \times 10^{-5}\,\mathrm{eV}$ at the level of the DFSZ model band. The continued investigation of Rydberg atoms as single-photon detectors is being undertaken at Johns Hopkins.

4 Experiments and New Target Technologies

Current and near-future ADMX operations will cover the mass range from $4.1\,\mu\mathrm{eV}$ to $16\,\mu\mathrm{eV}$ using multi-cavity arrays that fit within the confines of the existing ADMX magnet bore, or other readily available options. Going to higher masses requires either the use of a large number of smaller cavities, or a higher magnetic field, or both. A UK-based group collaborating with ADMX is now in a position to develop a two-pronged approach to cover this frequency range. First, they will collaborate with ADMX to append an additional receiver chain to the existing insert RF electronics. Second, it will also build a new UK-based high-field, high-volume, low-temperature facility for further axion and hidden sector searches in this mass range, in collaboration with ADMX. Another possibility means of scanning this regime is to run a cavity array without attempting to synchronize the resonant frequencies of all the cavities, instead combining the data from all the cavities running at different resonant frequencies to achieve equivalent sensitivity overall. This is the approach adopted in ORGAN[25]. A similar idea aims to fabricate cavities of varying dimensions coated in superconducting film operated high magnetic fields. Although operating superconducting cavities in high fields is a known technological challenge, there is a strong incentive to develop such technology for Quantum Information Science (QIS). Another recently proposed alternative approach is to use an external feedback loop incorporating a resonant circuit to induce artificial high Q resonances in an electromagnetic structure[26]. A potential advantage of this technique is that many resonances could be induced in parallel, resulting in a speed-up in the coverage of mass range by a factor of the number of resonances. Early tests of this approach are underway at ADMX. Above $41\,\mu\mathrm{eV}$ alternative detection schemes such as phased arrays of mirror reflectors as proposed by MADMAX[27] or through coupling of higher mass QCD axions to fermionic spin as in QUAX[28]. However, between $16\,\mu\mathrm{eV}$ and $41\,\mu\mathrm{eV}$, resonant structures in magnetic fields remain the only viable technology.

5 Conclusion

Axions remain one of the most compelling solutions to the dark matter and strong CP problem, with the $16 - 41\,\mu\mathrm{eV}$ mass range well-motivated by current theory. The outstanding experimental issue in this mass range is combining a large volume and $10 - 40\,\mathrm{GHz}$ resonant frequencies. We believe that this issue will be the prime focus of the experimental efforts in probing the $16 - 41\,\mu\mathrm{eV}$ mass range. This work will also act as a catalyst for the additional development of quantum electronics at higher frequencies. Further advancements in JPAs and TWPAs will be accompanied by new detectors based on QUBIT arrays. Modern mechanically pre-cooled dilution refrigerators should greatly simplify the cryogenics of new apparatus. We look forward to the ever more sensitive searches, and to the long awaited discovery of axion dark matter.

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