PROCEEDINGS OF SCIENCE

Wave-Like Dark Matter and Axions

Chelsea Bartram[a,*]

[a] *University of Washington,*
3910 15th Ave. NE, Seattle, United States

E-mail: chelsb89@uw.edu

Despite composing 85% of the matter in the universe, the exact nature of dark matter is still unknown. The possibility of wave-like dark matter and axions is driving a surge of new experiments that are vitalized by progress in quantum amplification and optics, microwave electronics, high magnetic fields, and cryogenics. We discuss the technology that enables such searches, and break down the experiments by their reliance on different axion couplings. We explain how the Axion Dark Matter eXperiment (ADMX) has achieved sensitivity to a particularly compelling class of dark matter candidates, known as DFSZ axions, in a narrow range of axion masses. Finally, with a new fleet of experiments arriving online, we present their goals to probe as yet unexplored parts of axion parameter space in the coming years.

40th International Conference on High Energy physics - ICHEP2020
July 28 - August 6, 2020
Prague, Czech Republic (virtual meeting)

*Speaker

PoS(ICHEP2020)004

1. Introduction

Dark matter, composing 85% of the matter content of the universe, could manifest as axions, or 'wave-like' dark matter. The ΛCDM model predicts that dark matter is cold (non-relativistic), feebly-interacting, very stable, and non-baryonic. Axion dark matter is wave-like in the sense that its de Broglie wavelength is much larger than that of other particles in the Standard Model. For example, the Axion Dark Matter eXperiment (ADMX) is sensitive to axions on the order of about a tenth of a meter. The large de Broglie wavelength of the axion has some interesting implications, including high occupation numbers, prompting speculation that axions could exist in a Bose-Einstein condensate [1, 2].

There are two broadly recognized classes of axion models: the KSVZ (Kim-Shifman-Vainshtein-Zakharov), and DFSZ (Dine-Fischler-Srednicki-Zhitnitsky) [3–5]. Further, a subset of the DFSZ class consists of axion dark matter that could also solve the Strong CP problem via the Peccei-Quinn Mechanism [6, 7]. Known as QCD axions, their ability to resolve two problems at once motivates experimental searches in their mass range. The QCD axion, if it exists, could comprise all of the dark matter. This is the mass range in which the Axion Dark Matter eXperiment looks [8, 9].

The axion dark matter mass range is wide, and largely still unexplored. The lower bound on the axion mass is set by the dark matter halo size of dwarf galaxies, whereas the upper bound is set by the SN1987A and white dwarf cooling time [10].

Pierre Sikivie proposed the concept of the resonant cavity haloscope to search for axion dark matter [11, 12]. The idea has been realized in the form of Axion Dark Matter eXperiment (ADMX), as well as other cavity resonator searches such as Haystac [13], and CAPP-8T [14]. To date, the resonant cavity haloscope is the only experimental approach which has demonstrated the ability to obtain the long-sought-for DFSZ sensitivity, in the form of ADMX.

2. Axion Search Techniques

The prevailing means of searching for axion dark matter for the past several decades has been to leverage the conversion of the axion to a photon in a magnetic field, also known as the inverse Primakoff effect. This principle hinges on the axion coupling to photons, and is the underlying concept behind many axion haloscope searches. In recent years, novel techniques that use alternative couplings have emerged to search for axion dark matter. Some examples include probing for time-varying nucleon electric dipole moments induced by the axion field [10], looking for axion-mediated spin precession [15], and searching for the axioelectric effect [16]. Fig. 1 shows a number of axion experiments grouped according to the usage of various axion couplings, for reference.

2.1 Photon-based haloscope searches

The vast majority of axion searches to-date exploit the inverse Primakoff effect. Resonant cavity searches such as ADMX, Haystac, and CAPP-8TB and ORGAN [17] use a strong magnetic field accompanied by a tunable microwave cavity to search for the dark matter axion in a mass range 10^{-6}–10^{-4} eV. Resonant cavity haloscopes are capable of reaching DFSZ sensitivity, but are limited by their narrow bandwidth and performance at higher frequencies. The axion signal power is proportional to the volume of the detector, implying lower sensitivity at higher frequencies,

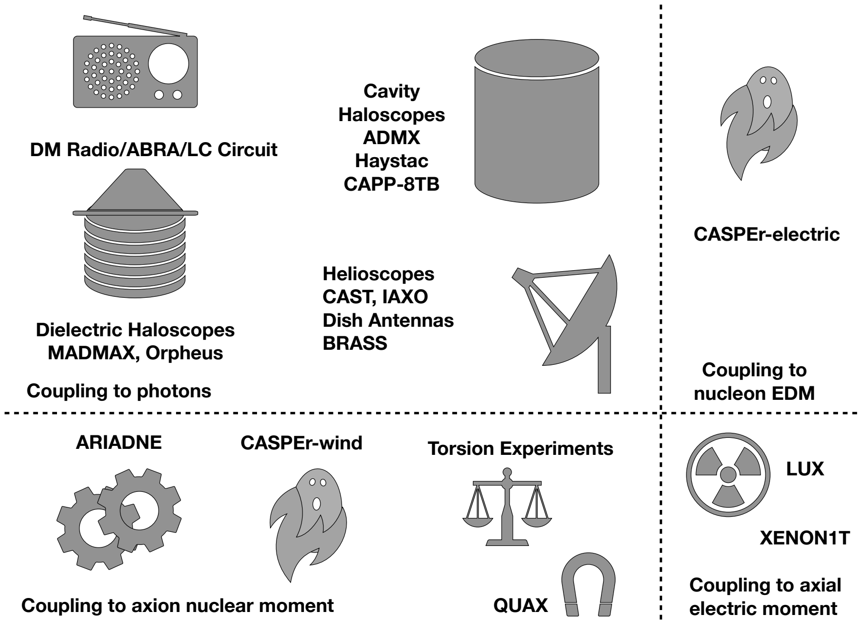

Figure 1: A variety of new and ongoing axion search experiments, grouped according to their reliance on different axion couplings.

where the cavity must shrink in size. Higher frequency (mass) axion searches such as dielectric haloscopes [18, 19] overcome this issue by using a tunable array of dielectric plats to maximize the overlap of the electric and magnetic fields, enabling the access of higher frequencies and the maintenance of reasonable detector volumes. The MAgnetized Disc and Mirror Axion eXperiment (MADMAX) will search for axion conversion to photons via the inverse Primakoff effect in the frequency range of 10^{-5}–10^{-4} eV. Lower frequency axion searches, with mass range 10^{-14}–10^{-6} eV, such as DM Radio [20], ABRACADABRA [21], and LC circuit [22] also use the axion-photon conversion in a magnetic field, but search instead for the induced magnetic field signal.

2.2 Helioscopes

Axion helioscopes also make use of the inverse Primakoff effect, but with an additional directional component. By aiming the detector at the Sun as an axion source, such experiments can achieve a boost in the sensitivity. In a strong magnetic field, axions would convert to detectable x-rays [11]. The CERN Axion Solar Telescope (CAST) [23] experiment was the first to perform such a search. The International Axion Observatory (IAXO) [24] intends to improve on the CAST limit, by using a stronger magnetic field and larger volume. By orienting the detector towards the Sun and implementing x-ray focusing optics, the signal-to-noise ratio of the axion signal is enhanced. The magnet aperture corresponds directly to a figure-of-merit for the experiment, the aspect upon which IAXO will improve.

2.3 Time-varying nucleon EDM experiments

The existence of an axion could cause time-varying electric dipole moments in nuclei, atoms, and molecules, caused by the axion-gluon coupling. Such oscillations can be detected via experiment. CASPEr-electric [25] looks for an NMR signal resulting from the QCD axion's induced nuclear electric dipole moment by placing a hyperpolarized sample in an NMR magnet and applying a static magnetic field perpendicular to the leading magnetic field. An axion-induced EDM would oscillate at the Larmor frequency when the resonance condition is satisfied. The interaction between this EDM and the static electric field causes a non-zero oscillating transverse magnetization. This creates a precession which is picked up using NMR.

2.4 Axion-induced spin precession

Axions could create spin-dependent energy shifts and spin precession in fermions. The CASPEr experiment uses this approach [15]. The CASPEr-wind experiment is designed to detect the pseudo-magnetic coupling of ALPs to nucleons. As the earth moves through the galaxy, there is an interaction between the nuclear spins and the spatial gradient of the scalar ALP field. The resulting signal is probed via NMR in the CASPEr-wind experiment.

Another search, QUAX (QUaerere AXion) [26], looks for the interaction between axions and the spin of electrons in a magnetized sample. The Larmor resonance frequency of the sample is tuned to that of the axion mass via a static magnetic field. The signal is an oscillation in the total magnetization of the sample, which is picked up by a SQUID amplifier.

In the ARIADNE experiment, the axion coupling would manifest as an effective magnetic field. This field would resonantly drive spin precession in laser polarized ^{3}He gas [10]. A small, transverse magnetization is amplified by a Superconducting Quantum Interference Device (SQUID).

2.5 Axioelectric effect

The axioelectric effect is analogous to the photoelectric effect; the axion-electron coupling implies atomic ionization. Such interactions can be investigated using high radio-purity detectors in low background, underground laboratories. A number of such experiments already exist to search for Weakly Interacting Massive Particles (WIMPs). The LUX [27] collaboration is one example of such an experiment that has undertaken a search for the axioelectric effect.

3. Instrumentation for Axion Searches

A number of technological advancements have made the advent of novel axion searches possible. Axion haloscopes benefit from advancements in fields such as quantum optics, cryogenics, microwave electrics and high magnetic fields. Recent iterations of ADMX have made use of Microstrip Squid Amplifiers (MSAs) and Josephson Parametric Amplifiers (JPAs) in order to achieve DFSZ sensitivity [8, 9]. Future and current axion searches look to circumvent the Standard Quantum Limit and continue to improve amplifier performances. Several experiments are looking into the application of Traveling Wave Parametric Amplifiers (TWPAs) [28], which could provide broadband gain.

4. Overview of ICHEP Axion Searches

A diverse array of axion and axion-like particle searches, covering a mass range from several μeV to the GeV range presented their progress at the ICHEP 2020 conference. Status reports and results from these experiments are summarized below.

PoS(ICHEP2020)004

4.1 CAPP-8TB

The CAPP-8TB resonant cavity search recently performed their phase 1 search for axions in a mass range 6.62–6.82 μeV at the Center for Axion and Precision Physics (CAPP). Further, a new technical paper explains their most recent efforts [29]. Their setup uses a BlueFors dilution refrigerator, microwave cavity, dielectric tuning rod, and an 8T superconducting magnet. The collaboration intends to proceed with another search over the mass range 6.2–6.62 μeV (1.5–1.6 GHz) in phase 2.

4.2 MADMAX

The MADMAX collaboration presented a status report describing recent studies and simulations, in addition to their implications on their sensitivity and longer-term goals. MADMAX is a dielectric haloscope that aims to cover the 40–400 μeV (10–100 GHz) range, using a 10 T magnetic field and about 80 dielectric disks [30, 31]. The technique involves maximizing the overlap of the electric and magnetic fields over a large volume, enabling higher frequencies to be probed. The prototype phase is currently underway using a dipole magnet located at CERN. Recent progress has involved studies on the impact of varying disc flatness, resulting in the conclusion that discs must be flat to within 10 μm. The collaboration has also been exploring various means of tuning, as well as feasibility studies of TWPAs.

4.3 IAXO

IAXO is a helioscope experiment, which will follow up on the work performed by the CAST collaboration. IAXO will use a stronger field and larger volume detector to improve the sensitivity compared to CAST. A toroidal, multi-bore configuration will be used for the superconducting magnet. IAXO will probe unexplored ALP space with couplings $g_{a\gamma} \approx 10^{-12}\,\mathrm{GeV}^{-1}$, and $g_{ae} \approx 10^{-13}\,\mathrm{GeV}^{-1}$. IAXO will be sensitive to QCD axions in the mass range of 1 meV to 1 eV. Its science capability is also multifold: IAXO will cover ranges of $g_{a\gamma}$ associated with ALP solutions to a variety of astrophysical anomalies, such as those observed in stellar system cooling. Combined with an axion detection in a haloscope, the IAXO helioscope could also break the degeneracy between $g_{a\gamma}$ and ρ_a, enabling a measurement of the local axion density. The development of an intermediate, experimental stage, called BabyIAXO, will enable the study of various detector upgrades to potentially improve upon the sensitivity the full experiment (IAXO).

4.4 Higher-mass searches

Higher mass axion-like particle searches have also been performed, though axion or axion-like particles in this mass range would only constitute a fraction of the dark matter. The Babar experiment has searched for axion-like particles in the decay of $B^{\pm}$ mesons [32]. The Belle II experiment has also searched for axion-like particles in electron-positron collisions at the SuperKEKB collider [33]. They were able to set a 95% confidence level upper limit for $g_{a\gamma\gamma}$ at the level of 10^{-3} GeV.

5. Conclusion

The discovery of wave-like dark matter in the form of axions or axion-like particles would have far-reaching implications. While well-established searches like ADMX are looking for DFSZ axions, both old and new collaborations strive to shed light on as-yet untouched mass ranges. The field of wave-like dark matter and axions is in the early stages of development, with novel experiments on the horizon and a wide parameter space to explore.

References

[1] Sikivie, Pierre, and Q. Yang. "Bose-Einstein condensation of dark matter axions." Physical Review Letters 103.11 (2009): 111301.

[2] Guth, Alan H., Mark P. Hertzberg, and Chanda Prescod-Weinstein. "Do dark matter axions form a condensate with long-range correlation?." Physical Review D 92.10 (2015): 103513.

[3] Dine, Michael, Willy Fischler, and Mark Srednicki. "A simple solution to the strong CP problem with a harmless axion." Physics letters B 104.3 (1981): 199-202.

[4] Srednicki, Mark. "Axion couplings to matter:(I). CP-conserving parts." Nuclear Physics B 260.3-4 (1985): 689-700.

[5] Zhitnitskij, A. R. "On possible suppression of the axion-hadron interactions." Yadernaya Fizika 31.2 (1980): 497-504.

[6] Peccei, Roberto D., and Helen R. Quinn. "Constraints imposed by CP conservation in the presence of pseudoparticles." Physical Review D 16.6 (1977): 1791.

[7] Peccei, Roberto D., and Helen R. Quinn. "CP conservation in the presence of pseudoparticles." Physical Review Letters 38.25 (1977): 1440.

[8] Du, N., et al. "Search for invisible axion dark matter with the axion dark matter experiment." Physical review letters 120.15 (2018): 151301.

[9] Braine, T., et al. "Extended search for the invisible axion with the axion dark matter experiment." Physical Review Letters 124.10 (2020): 101303.

[10] Fosbinder-Elkins, H., et al. "Progress on the ARIADNE axion experiment." Microwave Cavities and Detectors for Axion Research. Springer, Cham, 2018. 151-161.

[11] Sikivie, P. "Experimental Tests of the" Invisible" Axion." Physical Review Letters 52.8 (1984): 695.

[12] Sikivie, Pierre. "Detection rates for “invisible”-axion searches." Physical Review D 32.11 (1985): 2988.

[13] Zhong, L., et al. "Results from phase 1 of the HAYSTAC microwave cavity axion experiment." Physical Review D 97.9 (2018): 092001.

[14] Lee, Soohyung, et al. "Axion dark matter search around 6.7 μeV." Physical review letters 124.10 (2020): 101802.

[15] Budker, Dmitry, et al. "Proposal for a cosmic axion spin precession experiment (CASPEr)." Physical Review X 4.2 (2014): 021030.

[16] Graham, Peter W., and Surjeet Rajendran. "New observables for direct detection of axion dark matter." Physical Review D 88.3 (2013): 035023.

[17] McAllister, Ben T., et al. "The ORGAN experiment: An axion haloscope above 15 GHz." Physics of the dark universe 18 (2017): 67-72.

[18] Beurthey, S., et al. "MADMAX Status Report." arXiv preprint arXiv:2003.10894 (2020).

[19] Rybka, Gray, et al. "Search for dark matter axions with the Orpheus experiment." Physical Review D 91.1 (2015): 011701.

[20] Silva-Feaver, Maximiliano, et al. "Design overview of DM radio pathfinder experiment." IEEE Transactions on Applied Superconductivity 27.4 (2016): 1-4.

[21] Ouellet, Jonathan L., et al. "First results from ABRACADABRA-10 cm: A search for sub-μ eV axion dark matter." Physical review letters 122.12 (2019): 121802.

[22] Sikivie, P., N. Sullivan, and Dylan B. Tanner. "Proposal for Axion Dark Matter Detection Using an L C Circuit." Physical review letters 112.13 (2014): 131301.

[23] Andriamonje, S., et al. "An improved limit on the axion–photon coupling from the CAST experiment." Journal of Cosmology and Astroparticle Physics 2007.04 (2007): 010.

[24] Armengaud, E., et al. "Physics potential of the international axion observatory (IAXO)." Journal of Cosmology and Astroparticle Physics 2019.06 (2019): 047.

[25] Garcon, Antoine, et al. "The Cosmic Axion Spin Precession Experiment (CASPEr): a dark-matter search with nuclear magnetic resonance." Quantum Science and Technology 3.1 (2017): 014008.

[26] Ruoso, Giuseppe, et al. "The QUAX proposal: a search of galactic axion with magnetic materials." Journal of Physics: Conference Series. Vol. 718. No. 4. IOP Publishing, 2016.

[27] Akerib, D. S., et al. "First searches for axions and axionlike particles with the LUX experiment." Physical Review Letters 118.26 (2017): 261301.

[28] Macklin, Chris, et al. "A near–quantum-limited Josephson traveling-wave parametric amplifier." Science 350.6258 (2015): 307-310.

[29] Choi, J., et al. "CAPP-8TB: Axion Dark Matter Search Experiment around 6.7μ eV." arXiv preprint arXiv:2007.07468 (2020).

[30] Majorovits, Béla, and Javier Redondo. "MADMAX: A new dark matter axion search using a dielectric haloscope." arXiv preprint arXiv:1611.04549 (2016).

[31] Brun, P., et al. "A new experimental approach to probe QCD axion dark matter in the mass range above 40 μeV." The European Physical Journal C 79.3 (2019): 1-16.

[32] Izaguirre, Eder, Tongyan Lin, and Brian Shuve. "Searching for axionlike particles in flavor-changing neutral current processes." Physical Review Letters 118.11 (2017): 111802.

[33] Belle II collaboration. "Search for Axion-Like Particles produced in e^+e^- collisions at Belle II." arXiv preprint arXiv:2007.13071 (2020).