Status of the ADMX-HF Experiment

Samantha M. Lewis,

ADMX-HF Collaboration,
University of California, Berkeley, United States

DOI: http://dx.doi.org/10.3204/DESY-PROC-2016-03/Lewis_Samantha

The axion is a leading dark matter candidate particle. Haloscope-type experiments search for the axion using its resonant conversion to a photon in the presence of a strong magnetic field, enhancing the signal through the use of resonant microwave cavities and quantum-limited amplifiers. The Axion Dark Matter eXperiment – High Frequency (ADMX-HF) is an operating experiment taking a first look at data in the 20–100 μeV ($\sim$ 4–25 GHz) range. This paper discusses the newly completed data run as well as research and development underway that will further the reach of the experiment.

1 Introduction

The axion is a hypothetical pseudoscalar that was originally proposed in the Peccei-Quinn solution to the Strong CP problem. It is also a compelling candidate particle for cold dark matter in the 1–100 μeV range (see Ref. [1]). Like the π^0, the axion can couple to two photons in an inverse Primakoff conversion, one of which can be virtual.

Axion haloscopes attempt to observe this conversion by resonantly enhancing the photon signal using a microwave cavity permeated by a strong magnetic field [2]. The resonant conversion relies on the frequency of the cavity corresponding to the axion mass via the relation $h\nu = m_a c^2 \left(1 + \frac{1}{2} O\left(\beta^2\right)\right)$, where ν is the cavity resonant frequency, m_a is the axion mass, and $\beta \approx 10^{-3}$ is the galactic virial velocity. An overview schematic of the axion haloscope detection mechanism is shown in Fig. 1.

In this process, the power of the axion signal is expected to be very weak (on the order of 10^{-23} W). Thus, various techniques are employed to enhance this signal. The conversion axion-photon conversion power is given by

$$P_{sig} = \eta g_{a\gamma\gamma}^2 \left(\frac{\rho_a}{m_a}\right) B^2 Q_L V C_{nml} \tag{1}$$

where $g_{a\gamma\gamma}$ is the axion-photon coupling constant, ρ_a is the halo axion density, B is the strength of the applied magnetic field, Q_L is the loaded quality factor of the cavity, V is the cavity volume, and C_{nml} is the mode-specific form factor. The η constant specifies the fraction of power coupled out of the cavity. The detectability of the signal depends on the signal to noise ratio, which is governed by the Dicke radiometer equation

$$\frac{S}{N} = \frac{P_{sig}}{kT_{sys}} \sqrt{\frac{t}{\Delta\nu_a}} \tag{2}$$

where k is the Boltzmann constant, t is integration time, and $\Delta\nu_a$ is the width of the axion signal. The system noise temperature T_{sys} is

$$kT_{sys} = h\nu \left(\frac{1}{e^{h\nu/kT} - 1} + \frac{1}{2} \right) + kT_A \tag{3}$$

Here, T is physical temperature of the cavity and T_A is the equivalent temperature of the intrinsic amplifier noise.

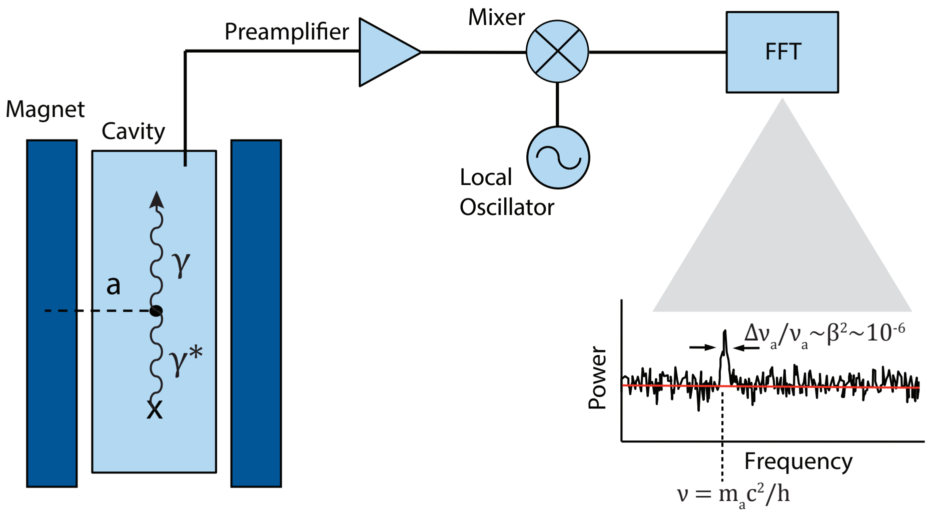

Figure 1: Block diagram of the axion haloscope detection mechanism. A microwave cavity is placed in the bore of a strong superconducting magnet. An axion entering the cavity converts to a real photon when the cavity is tuned to the frequency corresponding to m_a. This photon signal is extracted from the cavity, passing through an RF receiver chain, finally giving a peak.

2 Experiment

ADMX-HF is a collaboration of four institutions: Yale University, the University of California Berkeley, the University of Colorado Boulder, and Lawrence Livermore National Laboratory. The experiment was created to search for QCD axions at higher frequencies than existing haloscope limits and designed as a data pathfinder in the 4–25 GHz range (corresponding to 20–100 μeV in axion mass). These high frequencies can pose challenges that do not exist at lower frequencies. ADMX-HF serves as a small versatile testbed platform for new amplifier and microwave cavity technologies that address these challenges.

To enable the search for QCD axions, ADMX-HF uses state of the art technology. The superconducting magnet (0.40 m $\times$ 0.175 m $\oslash$, 9 T) is a dry system and was designed to have a large bore and long straight-field region. A copper cylindrical cavity with a large tuning rod allows for tuning from 3.5 GHz to 5.85 GHz with a loaded, critically coupled quality factor of $Q \sim 2 \times 10^4$. From the outset, the experiment has used Josephson Parametric Amplifiers (JPAs) which allow for amplification with quantum-limited noise. The current JPA has a tuning range of 4.4–6.5 GHz with $\sim$ 20 dB of gain. Magnetic shielding consisting of a bucking coil, passive coils, μ metal, and superconducting shield layers reduce the magnetic field at the JPA by a factor of 10^8, allowing for proper amplifier performance despite the presence of a strong magnetic field. A dilution refrigerator (base temperature 25 mK) cools the cavity to $\sim$ 100 mK to minimize thermal noise. Altogether, these components enable the experiment's extraordinary sensitivity in the GHz range which has not been achieved by any other experiment. Figure 2 shows a detailed view of these components.

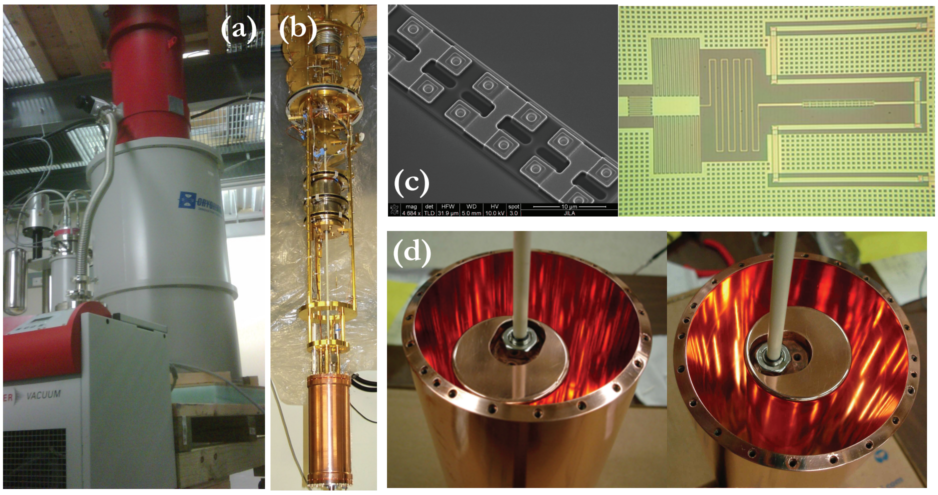

Figure 2: (a) Fully assembled experiment, showing the superconducting magnet. (b) Gantry attached to the dilution refrigerator. (c) Micrographs of a Josephson Parametric Amplifier (JPA) which allows for very low noise amplification. (d) Current microwave cavity, partially assembled, with minimum (left, 3.8 GHz) and maximum (right, 5.85 GHz) tuning positions shown.

ADMX-HF began construction in April of 2012. Integration and commissioning took place from July 2014 to January of 2016. The first data run began in January of 2016 and was recently completed in August of 2016. The next section details the operating characteristics and scope of this first data run.

3 Data run

The first data run of ADMX-HF scanned 100 MHz ($\sim$ 0.4 μeV) near the top of the cavity tuning range, 5.8 GHz (24 μeV). In this run, $g_{a\gamma\gamma} \sim 2.3 \times$ KSVZ over the entire range. No exclusion plot appears here as the final exclusion plot with full details will be published soon.

The achieved sensitivity was limited by the physical temperature of the tuning rod. The ceramic axle of the tuning rod limited the thermal link between the rod and the rest of the system. This resulted in a noise temperature on the order of $T_{sys} \sim 1100$ mK, which is roughly 3.5 times the standard quantum limit (SQL) for noise at in this frequency range.

4 Ongoing research and planned upgrades

There are multiple upgrades planned for the near future that will allow the experiment to reach further into the QCD axion model band. A simple solution to improve the thermal linkage of the tuning rod has been identified and will be implemented on all future tuning rods used in the experiment. This will reduce the thermal noise contribution to the originally planned value. Reducing the system noise temperature allows for a shorter integration time, speeding up the possible scan rate for future data runs.

A new dilution refrigerator is ready to be installed on the experiment. It has a lower possible base temperature and should reduce vibrations, which could allow for a lower operating temperature. This switch will likely be made after other upgrades are implemented.

The University of Colorado/JILA group has developed a receiver based on a squeezed state of vacuum that will be implemented on the experiment within the next year. This will allow for amplification with a total system noise temperature below the SQL. As of the time of writing, this would be the first use of a squeezed vacuum device on an operating experiment. Amplification with sub-quantum-limited noise will reduce the system noise temperature and could allow for a large increase in the scan rate.

At the University of California, Berkeley, new cavity designs are being developed to enhance the signal power and move the experiment to new frequency ranges. Efforts are underway to develop cavities with superconducting thin film multilayers that could greatly increase the cavity Q value. The use of Distributed Bragg Reflectors (DBR) is also being studied for use in increasing the Q value as well as the form factor for higher-order TM modes.

Photonic band gap (PBG) devices are being studied for use in creating a resonator at high frequencies that would clear the mode spectrum of TE modes. PBG structures allow for the confinement of modes of interest while other excited modes are allowed to propagate out [3]. In standard cylindrical cavities and the existing ADMX-HF cavity, TE modes undergo avoided crossing with the TM_{010} mode of interest as it is tuned, making the frequency range of the crossing unusable. This is a severe limitation in the operation of existing cavity experiments; eliminating the mode crossing problem would allow for faster scan rates and a larger available tuning range with a single device.

Acknowledgments

This work was supported under the auspices of the National Science Foundation, under grants PHY-1067242, and PHY-1306729, the Heising-Simons Foundation under grant 2014-182, and the U.S. Department of Energy by Lawrence Livermore National Security, LLC, Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344.

References

[1] P. W. Graham *et al.*, "Experimental Searches for the Axion and Axion-Like Particles," Annu. Rev. Nucl. Part. S. **65**, 485–514 (2015). doi:10.1146/annurev-nucl-102014-022120

[2] P. Sikivie, "Experimental Tests of the 'Invisible' Axion," Phys. Rev. Lett. **51**, no. 16, 1415 (1983). doi:10.1103/PhysRevLett.51.1415

[3] E. Yablonovitch, "Photonic Band-Gap Structures," J. Opt. Soc. Am. B **10**, no. 2, 283–295 (1993). doi:10.1364/JOSAB.10.000283