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Status of the ADMX-HF Dark Matter Axion Search

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Axions are a leading dark matter candidate, and may be detected by their resonant conversion to a monochromatic RF signal in a tunable microwave cavity permeated by a strong magnetic field. The Axion Dark Matter eXperiment - High Frequency (ADMX-HF) serves both as a innovation platform for cavity and amplifier technologies for the microwave cavity axion experiment, and as a pathfinder for a first look at data in the 20 - 100 μeV ($\sim$ 4 - 25 GHz) range. ADMX-HF is a small but highly capable platform where advanced concepts can be developed and vetted in an operational environment. The experiment is built on a superconducting solenoidal magnet (9 T, 17.5 cm $\times$ 56 cm) of high field uniformity, and a dilution refrigerator capable of cooling the cavity and amplifier to 25 mK. In its initial configuration, the microwave cavity is made of high purity electroformed copper, tunable between 3.6 - 5.8 GHz. The cavity is coupled to a Josephson parametric amplifier; JPAs are ideally suited for the 5 GHz range, being broadly tunable and exhibiting near-quantum-limited noise temperature. Construction of the experiment was completed in 2015, and its first data production run was carried out January - August 2016. Technologies to be deployed in the near future include a squeezed-vacuum state receiver, superconducting thin-film cavities, and photonic band-gap resonators.

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1. Introduction

The axion is a compelling dark matter candidate in the 1-100 μeV range that arises from the Peccei-Quinn mechanism to solve the strong charge-parity problem in the Standard Model of Particle Physics [1]. It is a pseudoscalar goldstone boson that can resonantly convert its full energy to a photon in the presence of a strong magnetic field via the Primakoff effect [2]. Our experiment takes advantage of this interaction and searches for the axion by scanning over a range of frequencies with a resonant microwave cavity. The axion conversion power is

$$P \sim g_{a\gamma\gamma}^2 (\rho_a/m_a) B^2 Q_C V C_{nml}, \tag{1.1}$$

where $g_{a\gamma\gamma}^2$ is the axion-photon coupling, ρ_a and m_a are the local halo density of the axion and its mass, B is the magnetic field strength, and Q_C, V, and C_{nml} are the quality factor, volume, and form factor of the microwave cavity. The signal to noise ratio is governed by the Dicke radiometer equation

$$SNR = \frac{P}{kT_S}\sqrt{\frac{t}{\Delta\nu_a}}, \tag{1.2}$$

where k is the Boltzmann constant, T_S is the system noise temperature, t is the integration time at each frequency step, and $\Delta\nu_a$ is the axion bandwidth. The system noise temperature is a sum of contributions from thermal noise and receiver noise equivalent temperature

$$kT_S = h\nu\left(\frac{1}{e^{h\nu/kT}-1}+\frac{1}{2}\right)+kT_A, \tag{1.3}$$

where T is the physical temperature of the cavity and T_A is the equivalent amplifier noise temperature.

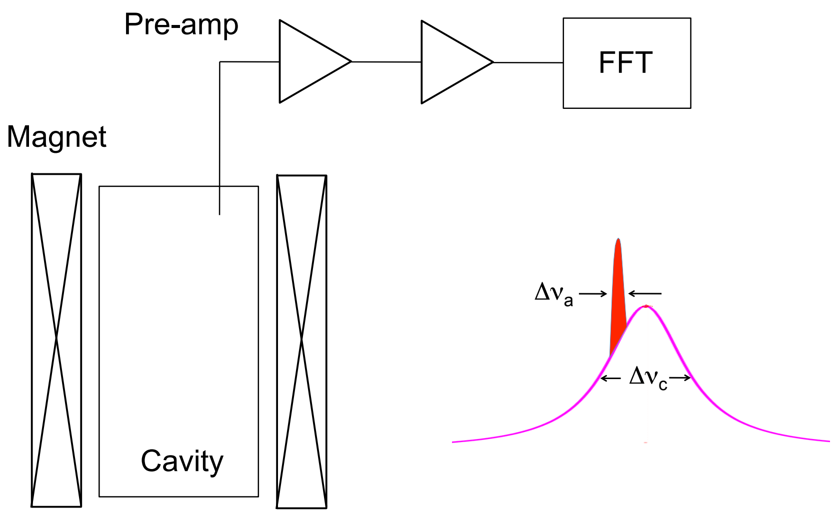

Figure 1: Schematic of the microwave cavity search for dark matter axions. The axion signal is designated by the narrow peak (red) within the bandpass of the cavity (pink).

2. Experiment Description

Our collaboration is composed of groups at Yale University (where the detector is sited), University of California at Berkeley, University of Colorado at Boulder, and Lawrence Livermore National Laboratory. A visual presentation of our axion detector is shown in Figure 2. The microwave cavity and Josephson parametric amplifier (JPA) are cooled by a dilution refrigerator to an operating temperature of 100 mK. A magnetic field is applied to the cavity by a superconducting magnet with a maximum field of 9.4 T made by Cryomagnetics, Inc. The JPA requires a magnetic field-free environment to operate, thus a sophisticated magnetic shielding system was designed to cancel out the fringe field from the main magnet less than 75 cm away.

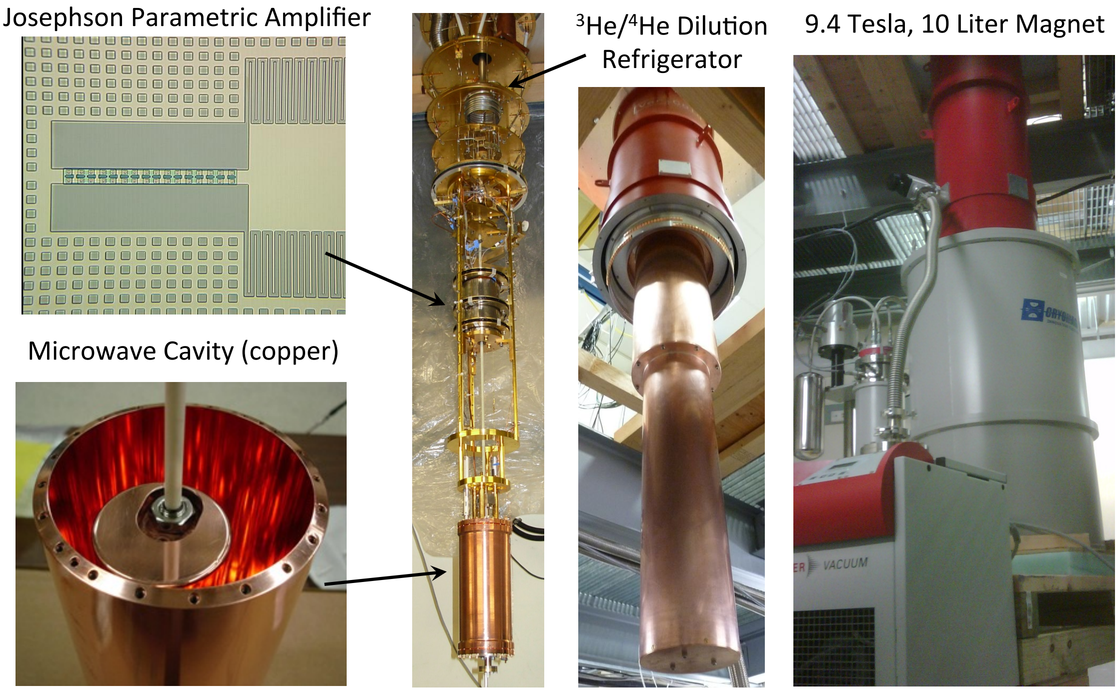

Figure 2: Top left is a microphotograph of the JPA. Bottom left is a photo of the copper-coated, stainless steel resonant microwave cavity with tuning rod inside. To the right of these is a photo of the integrated experiment with the JPA in its magnetic shielding and the cavity on the bottom of the gantry. Next on the right is the same integrated setup covered by thermal shields. Finally, rightmost photo is of the magnet.

2.1 Cavity

The cavity is a copper-coated, stainless-steel cylinder (25.4 cm long, 10.2 cm diameter) with an off-center tuning rod (5.1 cm diameter). By moving the tuning rod with stepping motors and Kevlar lines, the TM_{010}-like mode frequency can be scanned over its dynamic range of $3.6-5.8$ GHz. The cavity quality factor of the TM_{010}-like mode of interest is around $Q_C \sim 20,000$ when critically coupled.

2.2 Josephson Parametric Amplifier

The receiver is a JPA that is tunable over $4.4-6.5$ GHz with 20 dB of gain. The magnetic field-free environment required by the JPA is achieved by an actively excited bucking coil, four persistent 100-turn coils of superconductor, two layers of Amumetal, a thin lead sheet, and a thin niobium sheet in the JPA canister (both lead and niobium sheets are superconducting at the experiment's operating temperature).These multiple layers of field cancellation provide an operable environment for the JPA where the field changes by less than 0.01 of a flux quantum as the magnetic field is ramped to 9 T.

3. Status of Experiment

We began construction in early 2012 and began to integrate the different parts of the experiment in mid-2014. A year later we performed a commissioning run and finally began taking data in January 2016. Although interrupted by a magnet quench in early March, we concluded taking data for our first run in late August. For a detailed discussion of our first results, see Ref. [3].

3.1 Operations

In the current run, we predict to have achieved a sensitivity of 2.3∗KSVZ over a range of approximately $5.7-5.8$ GHz, where KSVZ is the benchmark axion model. The system noise temperature $T_S \sim 1100$ mK is higher than expected due to poor thermal contact between the rod and the cavity. An improved thermal link is currently being designed and tested.

In the near future, we plan to perform higher frequency run with a new thermal link discussed above, switch to a more stable dilution refrigerator (Blue Fors), and deploy a squeezed-vacuum state receiver that pushes the limits of sensitivity even further.

3.2 Research and Development

Aside from operating the detector, we are also developing new technologies for improving searches at higher frequencies. As seen in Equations 1.1 and 1.2, improving the Q_C and C_{nml} will increase our power and signal-to-noise ratio. Also, while scanning, we encounter frequency ranges in which our TM_{010}-like mode of interest crosses and interacts with other resonant cavity modes. At these mode crossings, we cannot have a good understanding of the conversion power of the axion and therefore of our sensitivity. These mode crossings prevent smooth scanning and leave gaps in possible exclusion areas. We are working to improve Q_C, C_{nml} and spectral cleanliness of the cavity.

One way to improve spectral cleanliness is to apply photonic band gap (PBG) concepts to the cavity design. A PBG structure is an open lattice with a defect that trap, for example, the TM_{010}-like mode of interest while allowing TE modes to radiate out [4]. Without a forest of TE modes to scan through, we can accelerate the scan rate of the experiment dramatically and take data without missing frequency ranges.

Another R&D effort is to improve the Q_C and C_{nml} by considering distributed Bragg resonator (DBR) concepts. Strategically-placed sapphire inserts have been used to achieve room temperature $Q \sim 650,000$ of a TE mode at 9.0 GHz [5]. We are looking into applying these concepts by exploring the effect of inserting dielectric shells at natural nodes of a TM_{0m0} mode to confine the mode away from the lossy metal wall.

To increase Q, we are looking into replacing the copper inner surface of the cavity with superconducting thin films. A rough estimate gives a factor of six improvement of signal power in our current cavity. For characterization, we use X-ray fluorescence and Rutherford backscattering data to study composition throughout the thickness of the film, and we use four wire measurements to determine the transition temperature of the superconducting thin films.

Finally, our collaborators at the University of Colorado / JILA are developing and testing a squeezed-vacuum state receiver that we hope to deploy within the next year. This squeezed-state receiver uses a JPA to initialize the cavity in a squeezed state and reads it out with another JPA [6]. To our knowledge, this would be the first data production experiment of any kind to employ squeezed states of the vacuum.

4. Acknowledgements

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