Status of the ADMX-HF Experiment

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The Axion Dark Matter eXperiment - High Frequency (ADMX-HF) was designed to address the specific challenges of the microwave cavity search at higher frequencies in an operating environment. The platform is intended to serve both as a *pathfinder* for data in the frequency range > 5 GHz, as well as an *innovation test-bed* for new cavity and amplifier technologies. ADMX-HF has recently begun operation with a 9 T magnet, a dilution refrigerator, Josephson Parametric Amplifiers, and copper cavities. It will eventually test new concepts such as squeezed-state receivers and single-quantum detectors to evade the quantum limit, and thin-film superconducting cavities to increase conversion power.

1 Introduction

Axions constituting the dark matter of our Milky Way halo may be resonantly converted to a weak RF signal in a tunable high-Q microwave cavity permeated by a strong magnetic field, under the condition that the cavity frequency equals the mass of the axion, i.e. $h\nu = mc^2$ [1] ; see Figure 1. The conversion power is given by

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

where $g_{a\gamma\gamma}^2$ is the axion-photon coupling, m_a and ρ_a the mass of the axion and its local halo density, B the magnetic field strength, and V, Q_C and C_{nml} the volume, quality factor and form factor of the microwave cavity. While the expected signal power is exceedingly small for all experiments to date, being measured in yoctowatts (10^{-24} W), the critical factor for detection is the signal-to-noise ratio,

$$SNR = \frac{P}{k\,T_S}\sqrt{\frac{t}{\Delta\nu_a}}$$

which depends not only upon the signal power, but also on the bandwidth of the signal line ($\Delta\nu_a/\nu_a \sim 10^{-6}$ for virialized axions), the integration time t , and most importantly the system noise temperature T_S. The system noise temperature is the sum of the thermal and the noise equivalent temperature contributions from the amplifier,

$$k\,T_S = h\nu\left(\frac{1}{e^{h\nu/kT}-1}+\frac{1}{2}\right) + k\,T_A$$

which for $kT \gg h\nu$, reduces to $T_S \approx T + T_A$. Linear amplifiers are subject to an irreducible noise temperature, called the Standard Quantum Limit (SQL), $kT_{SQL} = h\nu$, but there are strategies to evade this limit, which will be explored in ADMX-HF.

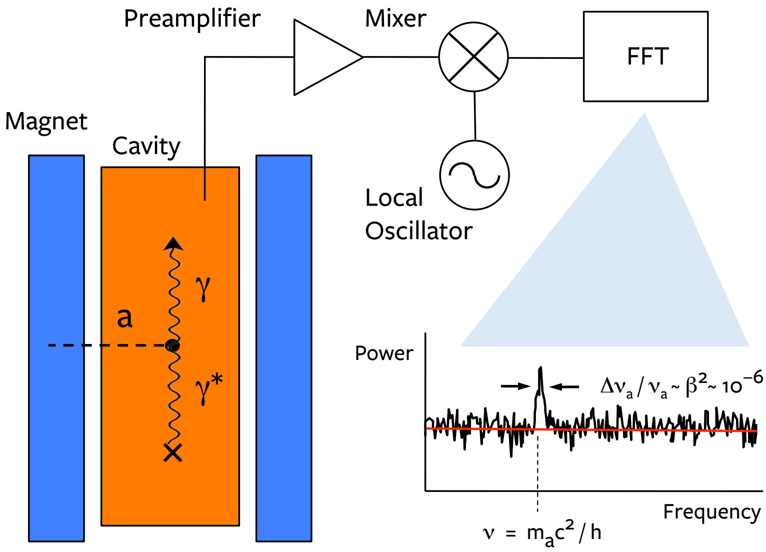

Figure 1: Schematic of the microwave cavity experiment.

Figure 2 displays the excluded range of mass and coupling (m_a, $g_{a\gamma\gamma}$) for the microwave cavity search to date, including the original Rochester-Brookhaven-Fermilab (RBF) [2, 3] and University of Florida (UF) experiments [4], along with the results from the Axion Dark Matter eXperiment (ADMX) [5]. Since 1995, approximately an octave of mass range has been covered by ADMX in the few μeV range within the band of plausible models; ultimately the microwave cavity search or other techniques must cover up to the $\sim$ 10 meV range with a sensitivity to find or exclude axions of the most pessimistic photon coupling, ideally even if they do not saturate the halo dark matter density.

2 ADMX-HF

2.1 Technical description

The Axion Dark Matter eXperiment - High Frequency (ADMX-HF) was proposed to address the challenges of extending the microwave cavity experiment to the next higher decade in mass, i.e. $5-25$ GHz ($\sim 20-100$ μeV). The collaboration includes Yale University, where the experiment is sited, the University of Colorado, the University of California Berkeley and Lawrence Livermore National Laboratory. ADMX-HF serves both as a *pathfinder* for first data at higher masses, and as an *innovation test-bed* for R&D on new higher frequency cavity and amplifier concepts, to be validated in an operational environment.

The experimental gantry is suspended from a dilution refrigerator (VeriCold) with a base

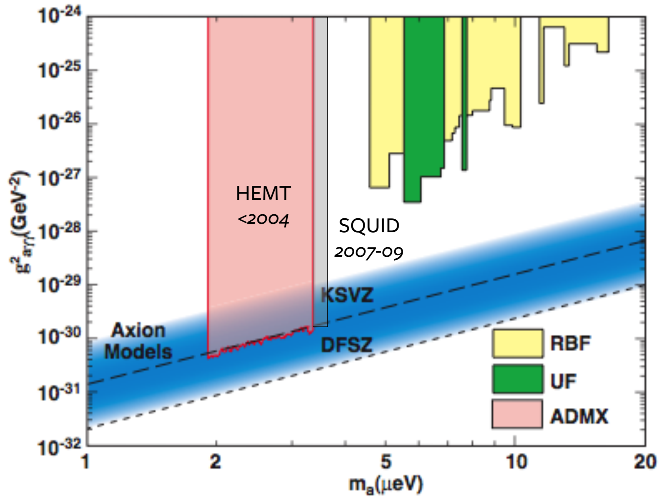

Figure 2: Exclusion region for the microwave cavity experiment.

temperature of 25 mK, and top-loaded into a 9 T superconducting solenoid (Cryomagnetics Inc.), 40 cm long x 17.5 cm diameter. The magnet was designed to provide an exceptional field uniformity ($B_r < 50$ G), anticipating the exploration of thin-film superconducting multilayers on the cylindrical surfaces of the cavity to boost the quality factor Q.

The microwave cavity for initial operation however is normal conducting, consisting of a cylindrical volume (25.4 cm long x 10.2 cm diam.), and tuned by the radial displacement of a metallic rod (5.1 cm diam.). The cavity and tuning rod are made of stainless steel, electroplated with OFHC copper and annealed. The TM_{010} is the mode of choice for the microwave cavity experiment, as its form factor is the largest by far, and can be tuned from $3.6 - 5.8$ GHz here. Berkeley and LLNL share responsibility for all cavity R&D and fabrication.

ADMX-HF represents the inaugural use of Josephson Parametric Amplifiers (JPA) for the microwave cavity axion search. JPAs are a natural technology in the $5 - 10$ GHz range, as they are intrinsically quantum-limited and broadly tunable. They require a magnetically field-free environment to operate however, requiring a “defense in depth” approach to shield out the fringe field from the main magnet. A field compensation coil was designed in the magnet cryostat to cancel out most of the fringe field; this was supplemented with 4 persistent coil packages to further reduce the fringe field and, more importantly, its gradient. Within the coils and ~ 50 cm above the cavity, it is the JPA canister, consisting of two layers of CryoPerm, and lined inside with thin lead sheets, superconducting for $T < 7.2$ K. This design has proven completely successful, and the remnant field at the JPA has been demonstrated to increase by $< 1\%$ of a flux quantum at the JPA when the field is ramped from 0 - 9 T. Figure 3 shows the experiment in various stages of assembly; a more complete description of ADMX-HF is found

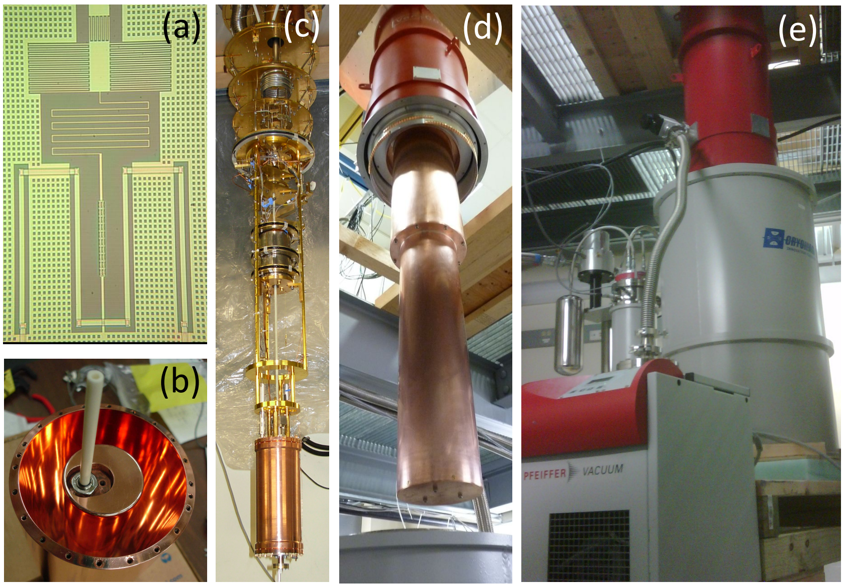

Figure 3: (a) Microphotograph of the JPA. (b) Microwave cavity. (c) Gantry. Dilution refrigerator (top); JPA canister (middle); cavity (bottom). (d) Gantry with thermal shields installed being lowered into the magnet. (e) Fully assembled experiment. Magnet cryostat (gray); dilution refrigerator (red). Floor level for the DAQ and computer is at the top of the photo.

in Reference [6].

2.2 Status

The experiment was completed and commissioned in mid-2015, and has undergone its first short data-taking runs. The system noise temperature was measured to be $k\,T_{SYS} \approx 800$ mK, about 2.9 times the Standard Quantum Limit. The additional noise source was imputed to the thermal contribution of the tuning rod, which is connected to the rest of the experiment only by a thin ceramic axle. A long data run is planned is planned once an improved thermal link between the rod and the cavity is implemented, and final data acquisition software written.

3 Future developments

ADMX-HF has already proven its utility identifying and addressing the mundane 'low-tech' issues that can impede the experiment from operating in a robust, high duty factor manner at higher frequencies. These include e.g. the proportionately more stringent specifications on machining and alignment tolerances for the cavity, and minimizing the rod-endcap gap (even $< 250\,\mu m$) to avoid mode-localization and thus keeping the form factor C_{010} as high as possible.

That being said, ADMX-HF was primarily conceived as a test-bed for beyond-state-of-art innovations in both cavities and amplifiers, or photon detection schemes more generally, that could radically advance the sensitivity and mass reach of the experiment. Below we briefly summarize near-term plans in both areas.

3.1 Microwave cavity R&D

Currently, the quality factor of the ADMX-HF cavity critically coupled is $Q_C \sim 20,000$. Compared with the intrinsic line width of the axion signal, $Q_a \sim 10^6$, it is seen that there is a potentially factor of 50 in signal power to be gained, that could improve both the sensitivity and speed up the search rate of the experiment. There is a further imperative to seek an improvement in Q, as on basic scaling grounds, Q will deteriorate as $\nu^{-2/3}$, largely as a consequence of the increasing surface to volume ratio for higher frequency structures.

Recently, Xi et al. have demonstrated that very thin films ($\sim$ 10 nm) of the Type-II superconductor $\mathrm{Nb_xTi_{1-x}N}$ exhibits a lossless microwave response, to $>$ 100 GHz, in a high magnetic field oriented perfectly parallel to the surface, $B_{\|} = 10$ T [7]. This suggests the possibility of improving the Q of the cavity by an order of magnitude, by deposition of a multilayer thin superconducting film on all cylindrical surfaces of the cavity and tuning rods. A multilayer will be required, as the required thinness of an individual layer to ensure flux vortices are expelled from the film, $\sim$ 10 nm, is still much less than the penetration depth, of order 100 nm; calculations are underway to determine the optimal design of such a multilayer.

A R&D program is underway at Berkeley, LLNL and Yale to fabricate and characterize NbTiN thin films made by RF plasma deposition; see Figure 4. Films exhibiting DC superconductivity with high critical temperatures ($T_C \sim 14\,\mathrm{K}$) were readily produced, so long as care was taken to prevent oxidation during the plasma deposition process. Film thickness and stoichiometry have been measured by Rutherford Backscattering, and more recently by X-Ray Fluorescence. The next phase of the R&D program will involve measuring the RF performance of the films in small 10 GHz cavity prototypes, along with their magnetic field dependence. Finally, multilayer structures will be modeled, fabricated and characterized; pursuant to successful prototype tests, a full-scale hybrid cavity will be produced, tested and used in ADMX-HF operational conditions.

Other cavity innovations that will be investigated within the next year will be the applicability of Photonic Band Gap structures, i.e. a lattice array of metallic posts but without the boundary condition imposed by an external cylindrical conducting surface [8]. With one or more of the posts removed in the center of the array, a judicious choice of geometry can result in the desired $\mathrm{TM_{010}}$ mode being trapped, but the myriad of confounding TE and TEM modes being propagated away. Eliminating the forest of mode crossings would greatly simplify and accelerate covering the mass range in an unbroken manner, by obviating the need for difficult and time-consuming procedures for shifting mode crossings away from an obscured notch in frequency and rescanning.

3.2 Amplifier and single-quantum detector R&D

The other major frontier will be a further reduction in total system noise temperature, circumventing the irreducible noise temperature of linear amplifiers set by quantum mechanics. Two

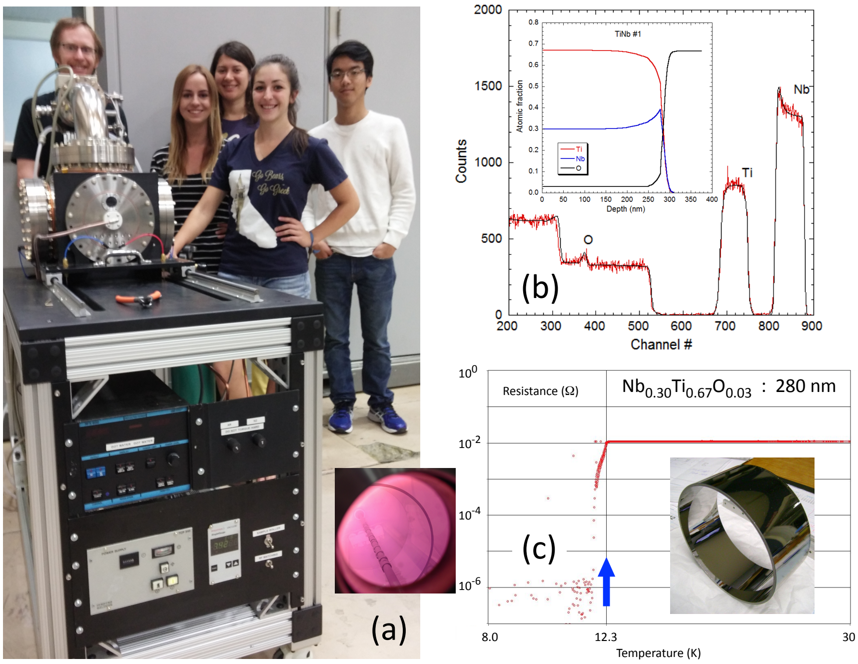

Figure 4: (a) RF plasma deposition unit at UC Berkeley. Inset: RF antenna (NbTi tube) in the plasma during deposition. (b) Rutherford Backscattering profile of a test sample. (c) Test of a planar sample, exhibiting DC superconductivity at $T_C = 12.3$ K. Inset: NbTiN coating on the inside of a 10 cm diameter quartz tube.

strategies will be pursued. In the near term, the JILA/Colorado group will deploy a receiver based on squeezed-vacuum states, by which one JPA prepares and injects a squeezed state into the cavity, and a second one measures the output of the cavity. Noise reduction below T_{SQL} by a factor of 4 has already been demonstrated on the bench by this group; successful deployment in ADMX-HF will however require proper care to eliminate all sources of signal loss (e.g. eliminating couplers, replacing coaxial cables with rigid waveguides, etc.).

Second, the Colorado group is investigating the applicability of single-quantum detection schemes (qubits, etc.) for the axion experiment as well [10, 11, 12], for which there is a significant experience base in the quantum information world to build on.

Acknowledgments

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