Axions as Dark Matter and HAYSTAC

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Abstract

Dark matter is thought to be non-baryonic by nature and composed of yet to be detected subatomic particles. Though several dark matter candidates exist, this paper will focus on the axion, whose detection would also resolve the strong charge-parity (CP) problem of quantum chromodynamics (QCD) [1]. The Haloscope at Yale Sensitive to Axion Cold Dark Matter (HAYSTAC) has made recent improvements to the microwave cavity dark matter axion experiment by circumventing quantum noise using a squeezed state reciever (SSR) and by implementing physical changes to the microwave cavities themselves. HAYSTAC is the first particle physics experiment to circumvent the Standard Quantum Limit of linear amplifiers.

1 The Axion

For many years, the leading candidate for dark matter was the Weakly Interacting Massive Particle (WIMP). However, much of its parameter space has been excluded, thus motivating the search for different dark matter particles [2–4].

The QCD axion is a hypotheical particle that was initially proposed in Peccei-Quinn theory as a solution to the strong CP problem. As WIMP detection has become increasingly difficult in recent years, the axion has become a well-motivated candidate for cold dark matter [5]. The search effort for the axion relies on the inverse Primakoff effect, which would allow an axion in the presence of a DC magnetic field to convert into a detectable photon [6]. A comprehensive review of the particle physics of the axion, its cosmological and astrophysical significance, and experimental searches for it can be found in Ref. [7].

2 The Microwave Cavity Dark Matter Axion Experiment

In the presence of a strong DC magnetic field, the hypothetical axion may convert to a photon via the inverse-Primakoff effect. In 1983, Sikivie proposed that a tuneable microwave cavity permeated by a strong magnetic field, and coupled to a low-noise readout system may be able to resonantly detect this axion-induced photon [8], with expected signal power given in natural units by

$$P_S = \left(g_\gamma^2 \frac{\alpha^2 \rho_a}{\pi^2 \Lambda^4}\right)\left(\omega_c B_0^2 V C_{mn\ell} Q_L \frac{\beta}{1+\beta}\right) \tag{1}$$

where the first term in parentheses relates the theory parameters out of the experimentalist's control: g_γ and $\rho_a \approx 0.45\ \mathrm{GeV/cm^3}$ are the dimensionless axion-photon coupling and local dark matter density, respectively, α is the fine structure constant, $\Lambda \approx 77.6\ \mathrm{MeV}$ is the QCD parameter, and $\omega_c = 2\pi m_a$ is the angular frequency associated with the axion.

Within experimental control are the frequency of the cavity's TM_{010}-like mode ω, the applied magnetic field strength B_0, the volume V, the "form factor" $C_{mn\ell}$ of the $mn\ell$ electromagnetic mode, and the loaded quality factor of the cavity Q_L with coupling β.

Because the signal power is expected to be on the order of 10^{-22} Watts [7], the cavity must have a high quality factor (Q) and be immersed in a strong magnetic field. Furthermore, operation at dilution refrigerator temperatures and use of a low noise receiver are necessary.

However, searching for the axion requires detecting a narrow band signal of unknown frequency. Therefore, the figure of merit of microwave cavities is determined by scan rate, the rate at which one may scan frequency space at a given sensitivity. For a given strength magnetic field, the scan rate depends functionally on three parameters of the microwave cavity, i.e. its volume, quality factor and form factor (to be described below) as follows:

$$R \equiv \frac{dv}{dt} \propto QC^2V^2. \tag{2}$$

This shows that the scan rate is dependant on the quality factor of the cavity (Q), the figure of merit (C), and the volume of the cavity. The form factor describes the coupling of the axion to a specific mode, and is calculated from

$$C_{nml} = \frac{(\int E_z dV)^2}{V\int \epsilon_r E^2 dV}. \tag{3}$$

where E the electric field and ϵ_r is the relative permittivity. In order to maximize the scan rate, we seek to maximize these three factors. Microwave simulations can be performed and show ideal cases; however when cavities are manufactured, the quality factor will generally be less than the simulated Q due to imperfections in manufacturing and quality of the copper coating. Typical Q values achieved are $Q_L = 3\times10^4$, where Q_L is the loaded quality factor, which accounts for the resonator's connection to an external network.

UF / RBF	**ADMX @ LLNL**	**ADMX @ UW**	**CAPP**	**HAYSTAC I**	**HAYSTAC II**
1985 - 1990	1995 - 2010	2016 - present	2019 - present	2015 - 2018	2019 - present
HEMT	HEMT, SQUID	SQUID	HEMT	JPA	SSR
f $\sim$ 2.5 GHz	$\sim$ 0.6 GHz	$\sim$ 0.7 GHz	$\sim$ 1.6 GHz	$\sim$ 6 GHz	$\sim$ 4 GHz
V $\sim$ 5 L	$\sim$ 200 L	$\sim$ 150 L	$\sim$ 3.5 L	$\sim$ 1.5 L	$\sim$ 1.5 L
T_{SYS} $\sim$ 5 - 20 K	$\sim$ 3 K	$\sim$ 350 mK	$\sim$ 1K	$\sim$ 300 mK	G_{SQ} = -4 dB
T_{SYS}/T_{SQL} $\sim$ 100 - 200	$\sim$ 50 - 100	$\sim$ 10	$\sim$ 12	$\sim$ 2	<1

Table 1: Summary of past and current microwave cavity experiments. Temperatures listed in the HAYSTAC column reflect those when Squeezed-vacuum State Reciever (SSR) is used.

3 HAYSTAC

3.1 The Experiment

HAYSTAC (Haloscope At Yale Sensitive To Axion Cold dark matter) was conceived to serve both as a data pathfinder in the 3-12 GHz (12.5 - 50 μeV) mass range, and an agile innovation testbed for new technologies in resonators and quantum-limited receivers. The HAYSTAC collaboration began operations in 2015 and is composed of three groups: UC Berkeley, CU Boulder/JILA, and Yale. Berkeley is responsible for the cavities, CU Boulder/JILA for the receiver, and Yale for the magnet, dilution

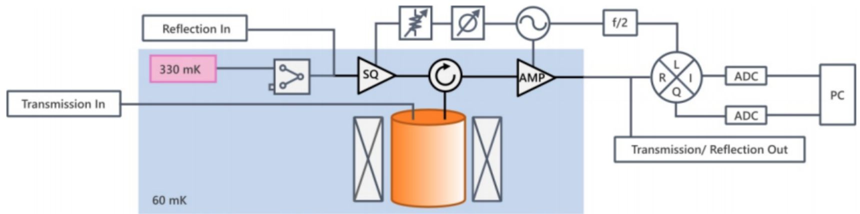

Figure 1: Block diagram of the experiment in Phase II Run 1. The Squeezed State Receiver components are shown in black.

refrigerator, balance of infrastructure and operations. The experiment is composed of the following parts:

1. The CMI magnet, NbTi-superconducting solenoid with a 9.4 T maximum field, 55 cm long, 14.5 cm cold bore.
2. The Blue Fors dilution refrigerator, which has a base temperature 25 mK, although we have run deliberately around 100 mK.
3. Microwave cavity, open volume V = 1.5 L, stainless steel electroplated with OFHC copper and annealed.
4. A receiver, originally using a single JPA (Josphson Parametric Amplifier), whose system noise temperature was 2-3 times the Standard Quantum Limit, more recently with a 2-JPA Squeezed State Reciever.

A block diagram of the experimental setup is shown in Figure 1.

The TM-like modes of the cylindrical cavity may be tuned by the rotation of a copper-plated rod which takes up 25% of the cavity volume. Rotating this rod about an off-center axle provides a continuous tuning range of 3.6-5.8 GHz for the TM_{010}-like mode, which corresponds to the axion mass range 15-24 μeV.

Various potential axion masses can be explored by changing the resonant frequency of the cavity. Only a very small range of axion masses can be explored at a time for each frequency, so the frequency must be manipulated in very small steps, on the order of 10 kHz, to collect data for different masses.

3.2 Phase I

Phase I of HAYSTAC consisted of two runs. Run 1 covered the 5.7-5.8 GHz frequency range and completed in August 2016. Run 2, completed in July 2017, covered the 5.6-5.7 GHz frequency range and featured improved thermal noise reduction over Run 1. The T_{SYS} in Run 1 was about three times T_{SQL}, but only two times T_{SQL} in Run 2, which is consistent with losses in the cables and circulator.

Fig. 3 shows the 90% exclusion limit for g_γ based on the two axion search data runs 1 and 2, labeled "HAYSTAC 2018" [9, 10]. This sensitivity is 2.7 times greater than KSVZ model couplings, a benchmark model for microwave cavity axion searches [11]. This result was the first cosmologically relevant exclusion of a QCD axion of $m_a > 20$ μeV [9].

3.3 Phase II

After a successful Phase I, HAYSTAC improved upon the experiment by implementing quantum squeezing with a squeezed state receiver (SSR) [12]. The SSR is a system of two flux pumped JPAs [13]: the first JPA, called the "squeezer," prepares a the cavity in a squeezed vacuum state and the second, or "amplifier" JPA, amplifies the signal noiselessly.

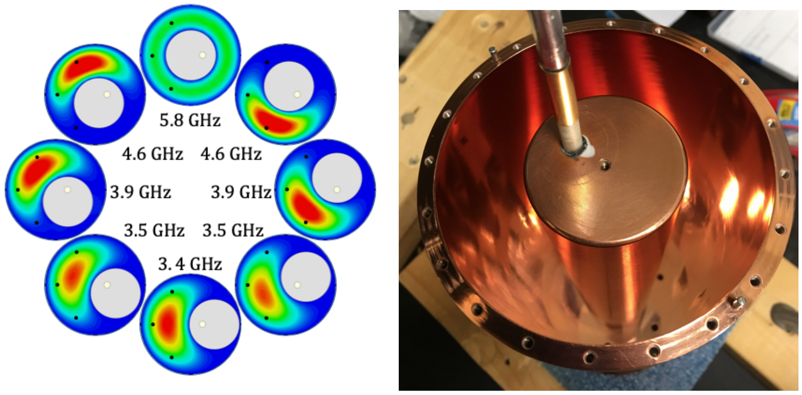

Figure 2: Left: Top view false-color plots of the magnitude of the TM010 electric field of the HAYSTAC cavity for runs I and II. Right: Top view photograph of the HAYSTAC cavity used for runs I and II with the endcap removed to show the tuning rod.

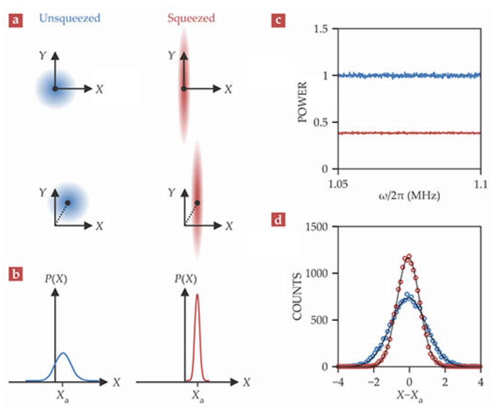

Figure 3: (a) The cavity's field can be described by its cosine (X) and sine (Y) components. These variables define the its phase space. The cavity can be prepared in either an unsqueezed state (blue) or squeezed state (red). The presence of an axion in the cavity will displace this state (represented by the dotted line). (b) Measuring the X component yields a probability density $P(x)$. Because the noise has been squeezed from the X to the Y component, the axion signal is enhanced in the squeezed case. (c) Noise power with (red) and without (blue) squeezing. (d) Measured values of X with (red) and without (blue) squeezing.

The improvement due to the SSR may be understood by considering the three sources of noise which degrade sensitivity. The first source of noise is Johnson-Nyquist sourced by internal losses in the microwave cavity, N_c. The second source of noise is amplifier added noise, which historically dominates over the other two noise sources on resonance. However, this source of noise is eliminated in one quadrature by using the JPAs in phase-sensitive mode. The third source of noise is Johnson-Nyquist noise incident on and reflected from the cavity, N_r, which dominates off cavity resonance. The SSR reduces this third source of noise by preparing the cavity in a squeezed state in one quadrature and reading out the other quadrature, therefore reducing N_r to below the quantum limit for Johnson-Nyquist noise. This technique makes N_c dominant over N_r and increases the bandwidth over which the experiment is sensitive to the axion [14]. The advantage of the SSR is shown schematically in Fig. 4.

The Phase II experiment ran in 2019, and data analysis and rescans were performed in early 2020.

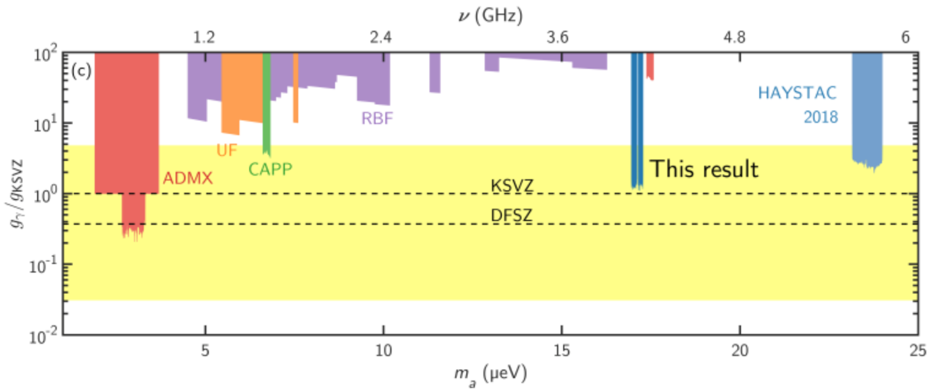

Figure 4: Exclusion plot with results from Phase II Run 1 shown by "this result" as well as results from other axion dark matter searches [8, 16–25]. KSVZ [11, 26] and DFSZ [27, 28] are shown with dotted lines.

The run excluded $g_\gamma \geq 1.38 g_\gamma^{KSVZ}$ for the mass range $16.96 < m_a < 17.12$ and $17.14 < m_a < 17.28$ $\mu eV/c^2$ [15]. This corresponds to the frequency ranges 4.100–4.140 and 4.145–4.178 GHz. These results are shown in Fig. 3, labeled "This result."

3.4 Future Plans

Recent theoretical predictions for the axion mass which would account for the dark matter density of the universe (under the scenario of Peccei-Quinn symmetry breaking after inflation) are converging on the 15-35 μeV mass range [29, 30], well within HAYSTAC's range, and running in the near term will focus on covering as much of this range as possible, with a sensitivity in axion-photon coupling $g_{a\gamma\gamma}$ at or slightly greater than the KSVZ model. Our first run with a squeezed-state receiver already resulted in an improvement in scan rate of 3.6; our next run should provide an additional acceleration of a factor of 4. Half of this is expected by a cavity built by Berkeley of the same design as in Figure 2, but of electroplated copper on aluminum, rather than the stainless steel substrate as has been used to date. Owing to the lower density, much lower specific heat and much greater thermal conductivity of aluminum relative to steel, it is hoped that the last quantum of thermal noise will be eliminated that plagued the first SSR run. The other x2 contribution to the increased rate is due to elimination of dead-time in reading out the data.

Subsequent runs will employ another Berkeley cavity designed for higher frequency operation; it incorporates a tuning mechanism which preserves discrete rotational symmetry, which has been shown to be critical to preserve good figure-of-merit (i.e. maximizes scan rate) over a broad dynamic range in frequency. This multirod cavity has one fixed central rod, and six rods which pivot outward in unison. Figure 4 shows a photograph of the cavity, and plots of the magnitude of the electric field as a function of rotation, or equivalently frequency.

Collaborators from the University of Colorado Joint Institute for Laboratory Astrophysics, and currently designing a much more powerful receiver based on two-mode squeezing (entangling) and state-swapping, which could produce factors of 20-25x greater scan rate for the experiment, the CEASEFIRE project.

4 Conclusions

The QCD axion is an attractive dark matter candidate, and its discovery would solve both the strong CP problem and the identity of 85% of the universe's matter density. HAYSTAC is the first dark

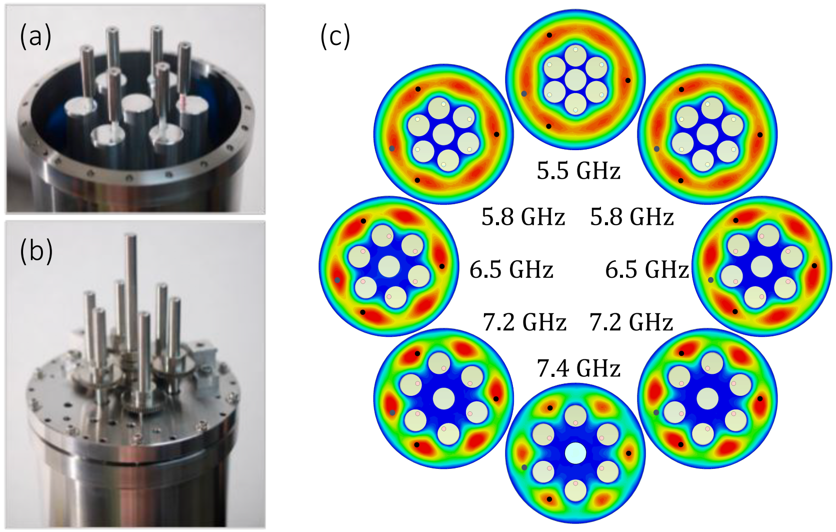

Figure 5: (a) and (b) Photographs of the symmetric tuner multirod cavity, partially disassembled. (c) False-color plots of the magnitude of the electric field of the TM_{010}-like mode [24]. Preserving discrete rotational symmetry maximizes the microwave cavity figure-of-merit over a wide dynamic range of frequencies. [31]

matter experiment to utilize squeezed states to circumvent the Standard Quantum Limit, and along with LIGO are the only experiments to have done so in fundamental physics. With the squeezed-state receiver, we have excluded $g_\gamma \geq 1.38 g_\gamma^{KSVZ}$ in the mass range $16.96 < m_a < 17.12$ and $17.14 < m_a < 17.28$ $\mu\mathrm{eV/c}^2$, which correspond to the frequencies 4.100–4.140 and 4.145–4.178 GHz. Future HAYSTAC runs will deploy new cavity geometries to probe higher mass ranges, and new quantum-enhanced receivers to both improve experimental sensitivity and further accelerate the search.

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