Preliminary Results from the Yale Microwave Cavity Experiment

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We present the first preliminary measurements from the Yale Microwave Cavity Experiment from a search for galactic halo axion like particles at about 34 GHz. The experiment can be run in two modes, a single cavity search or a two cavity search. We give estimated sensitivities for axions and axion like particles in this experimental setup.

1 Introduction

Many of the extensions of the standard model predict the presence of new particles which can have small masses. For example, the axion [1] and other axion-like particles (ALPS) have been postulated to account for broken symmetries and should behave as weakly interacting sub-eV particles (WISPs) (see e.g. [2]). In addition there are *hidden sector* particles with very low masses that arise from supersymmetry which only rarely interact with standard model particles [3, 4]. The discovery of a new low mass particle could be a solution to the cosmological dark matter problem.

Many of the searches for new sub-eV particles have relied on their coupling to low energy photons. Many of these experiments have taken the form of a *light shining through walls* (LSW) experiment (e.g. [5, 6, 7, 8]) and resonant cavity searches for galactic halo axions [9]. These experiments have placed limits on the photon coupling constants, predominantly below 1 meV.

In this work we discuss early results from an LSW experiment designed to use two resonant cavities at 34 GHz, one driven by the high power magnicon source at Yale [10, 11].

2 Experiment

The apparatus will consist of two side by side copper cavities operating in TE_{011} mode inside the bore of a 7 T magnet. One cavity will be coupled to the magnicon, a 34.29 GHz microwave source. This cavity is a right cylinder which will be thermally tuned to the magnicon's frequency.

The second cavity is also a right cylinder whose frequency is tuned via a plunger assembly which will vary the length of the cavity. This cavity is located inside a cryostat and is cooled to liquid helium temperatures. The Q of the cavity has been seen as high as 14,000.

The electronics chain consists of a triple heterodyne receiver which mixes the central frequency of 34.29 GHz down to 0 Hz [12]. The first amplification is done by a cryogenically cooled

HEMT amplifier located in the cryostat just above the signal cavity separated by approximately 12 cm of WR28 waveguide. The remaining amplifiers, the mixers, and filters are all operated at room temperature inside a shielded room. The output of the final video amplifiers goes into an Infinium oscilloscope to digitize the waveform and then transfered to a computer for analysis.

3 Sensitivity Estimates

To calculate the sensitivity of this experiment we start with the ideal total power Dickie Radiometer equation [13] $\sigma_T = \frac{T_{sys}}{\sqrt{\Delta\nu_{RF}\tau}}$, where $\Delta\nu_{RF}$ is the measurement bandwidth of 1 MHz and τ is the integration time in seconds. For system noise temperature of 32 K and 1 s integration time a 5σ signal corresponds to a minimum detectable power of $P_{sig} = 2 \times 10^{-18}$ W.

For a galactic halo ALP search the expected signal power P_a is given by [14]

$$P_{sig} = g^2 V B_0^2 \rho_a C_{lmn} Q$$

where g is the coupling strength of the ALP to two photons, V is the volume of the cavity, B_0 is the external field strength, ρ_a is the local ALP density, and Q is the quality factor of the cavity. For a scalar ALP, the form factor C_{lmn} is the overlap integral between B_0 and the magnetic field of the TE_{011} mode of the cavity

$$C_{lmn} \equiv \int_V d^3x \hat{\mathbf{B}}_\mathbf{0} \cdot \mathbf{B_{cav}} \approx 6 \times 10^{-7}$$

where B_{cav} is normalized using $\int_V d^3x(E_{cav}^2 + B_{cav}^2) = 1$. Taking ρ_a to be $10^{13}/\text{cm}^3$ at 0.1 meV [15] gives $P_{sig} = 2.8 \times 10^{-5}$ W GeV$^2 g^2$. Using P_{sig} from above gives $g \gtrsim 2 \times 10^{-7}$ GeV^{-1}.

For the LSW experiment looking for ALPS we have two cavities with quality factors Q and Q'. The probability for a photon to convert to an ALP in the first cavity and the ALP to convert back to a photon in the second cavity is given by [2]

$$P_{trans} = (\frac{gB}{\omega_0})^4 QQ'|G|^2$$

where ω_0 in the energy of the incident photon and G is the dimensionless geometry factor for scalar ALPs. For the case where ω_0 is equal to the ALP mass, G is defined by [2]

$$G \equiv \omega_0^2 \int_{V'}\int_V d^3\mathbf{x} d^3\mathbf{x}' \frac{(E_1^2 - B_1^2)(E_2^2 - B_2^2)}{4\pi|\mathbf{x}-\mathbf{x}'|} \approx \omega_0^2 \int_{V'}\int_V d^3\mathbf{x} d^3\mathbf{x}' \frac{(\hat{\mathbf{B}}_\mathbf{0}\cdot\mathbf{B_1})(\hat{\mathbf{B}}_\mathbf{0}\cdot\mathbf{B_2})}{4\pi|\mathbf{x}-\mathbf{x}'|}$$

where E_1, E_2, B_1, and B_2 are the electric and magnetic fields associated with the TE_{011} mode of cavities 1 and 2 and are normalized as before. For our apparatus G is approximately 7×10^{-9}. Using 1 MW as the magnicon's input power, the expected output power is $P_{sig} = P_{mag}P_{trans} = 5 \times 10^{-8}$ W GeV$^4 g^4$. Using the minimum detectable power in 1 s of integration time yields a sensitivity of $g \gtrsim 2 \times 10^{-3}$ Gev^{-1}.

For the HSP case the probability for a photon to convert to an HSP, pass through the shielding, and reconvert back to a photon in the second cavity is given by [2]

$$P_{trans} = \chi^4 QQ' \frac{m_{\gamma'}^8}{\omega_0^8} |G_{HSP}|^2.$$

For the case where $\omega_0 = m_{\gamma'}$, G_{HSP} is given by

$$G_{HSP} \equiv \omega_0^2 \int_{V'} \int_{V} d^3\mathbf{x} d^3\mathbf{x}' \frac{A(\mathbf{x}')A(\mathbf{x})}{4\pi|\mathbf{x}-\mathbf{x}'|},$$

where $A(\mathbf{x})$ and $A(\mathbf{x}')$ are the vector potentials in the two cavities. For our cavities and spacing G_{HSP} integrates to 0.02. Taking the magnicon's power to be 1 MW, the signal power is given by $P_{sig} = P_{mag}P_{trans} = 2.4 \times 10^{10}\mathrm{W}\chi^4$. Using P_{sig} as before gives a sensitivity of $\chi \gtrsim 8 \times 10^{-8}$.

4 Measurements

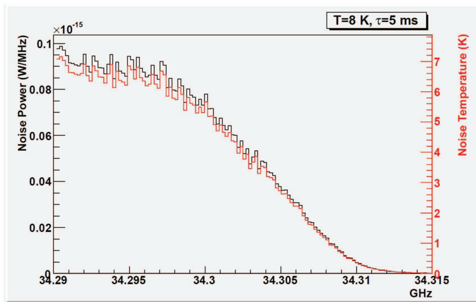

Figure 1: Noise power (top line) and noise temperature (bottom line) of the signal cavity.

We have taken data with a 50 Ω terminator at the input to the HEMT. The result is shown in Fig. 1 where the time domain data has been Fourier transformed and converted to temperature. For this run the temperature of the HEMT was 7 K which agrees very well with the temperature given in the analysis. The rolloff as a function of frequency is due to the bandpass filters used in the receiver.

We have taken our first set of data runs looking for scalar ALPS with the cavity tuned to frequencies between 34.2775 and 34.3025 GHz with a step size of 2.5 MHz. For these runs the temperature of the cavity was 4.5 ± 0.5 K and the static magnetic field strength was 7 T.

The raw time domain data was Fourier transformed and then the power versus frequency spectrum is calculated. The left side of Fig. 2 show an example of the raw power spectrum when the cavity is tuned to 34.285 GHz. Note that the narrow spike seen at 34.3 GHz is an image of the 10 MHz master oscillator in the waveform after the final mixer. A baseline spectra is generated by the same procedure with the cavity has been tuned outside the bandpass of the receiver. The right side of Fig. 2 is the result of subtracting the baseline spectra from the raw spectra. The dip seen in this plot is related to the temperature difference between the cavity and the HEMT amplifier. The spike at 34.3 GHz was essentially eliminated by this procedure.

5 Outlook

These data have shown us that our receiver is working well and we have used it to take data using it for the scalar halo ALP search. We expect to be able to extend our data taking to the LSW type experiments soon. We are looking at ways to construct a similar sized signal cavity

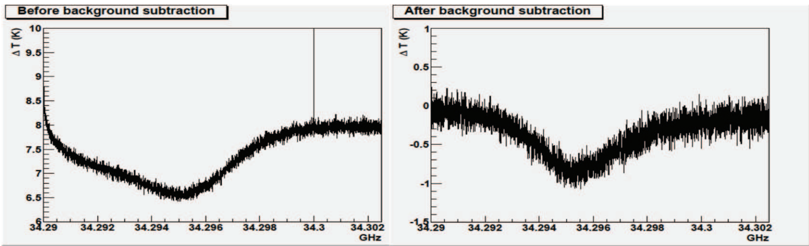

Figure 2: Raw data with cavity tuned to 34.285 GHz before background subtraction on left and after on right.

which will operate in TM_{010} mode which will enable us to improve our search capability for scalar ALPs and make searches for pseudoscalar ALPS possible.

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