Search for Hidden Photons using Microwave Cavities

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The Yale Microwave Cavity Experiment (YMCE) uses microwave cavities in a "light shining through wall" (LSW) approach to look for hidden photons, hypothesized particles that could exist in many beyond the standard model theories. By cooling one cavity and reducing the bandwidth of our receiver, we increase the sensitivity of our experiment and report first results, excluding hidden photons with a mass of 141.8 μeV for a coupling $\chi > 1.7 \times 10^{-7}$.

1 Introduction

The structure of the Standard Model is SU(3) $\times$ SU(2) $\times$ U(1); one natural question to ask is, do other symmetries exist? If one adds a local U(1) gauge symmetry then a new gauge boson appears with a wide range of possible couplings and mass (see [1] for a recent review). In the low mass limit, the dominant interaction of the new gauge boson is with the photon via kinetic mixing [2]. This gauge boson, or hidden photon, must have extremely weak couplings in order to have evaded detection. Astrophysical considerations of solar energy loss place strong constraints on possible hidden photon coupling and mass [3, 4]; however, these constraints become weaker in the 1-100 μeV range. Direct searches for hidden photons using the LSW technique nicely complement astrophysical bounds and probe new regions for physics beyond the Standard Model.

The principle behind the LSW method is that a laser shining on a wall will produce photons and via kinetic mixing, hidden photons. The wall will stop the ordinary photons but the hidden photons will pass through unimpeded because they interact very weakly with matter. On the other side of the wall, they can convert to ordinary photons again and be detected. The LSW technique extended to microwaves allows one to probe longer wavelengths and thus smaller masses for the hidden photon, precisely where astrophysical constraints are weakest. Placing resonant cavities on either side of the wall enhances the sensitivity by several orders of magnitude [6] and is the technique used by our group. In this paper we discuss our setup and first results searching for hidden photons at a higher microwave frequency than so far attempted elsewhere.

2 Sensitivity

The experiment consists of a high power microwave source driving a cavity on resonance and a second cavity, electromagnetically shielded from the first, used to look for a power excess at the frequency ω_0 of the microwave source. The expression for the power expected in the second cavity due to photon - hidden photon oscillations is given by [8]:

$$P_{det} = \chi^4 (\frac{m_{\gamma'}}{\omega_0})^8 |G|^2 Q_{drive} Q_{det} P_{drive}$$

where Q_{drive} and Q_{det} are the loaded quality factors of the drive and detection cavities, respectively, P_{drive} is the power of the microwave source, χ is the hidden photon - photon coupling, and $m_{\gamma'}$ is the unknown mass of the hidden photon. $|G|$ is a geometrical form factor that depends on the cavity modes, their separation, and the hidden photon momentum. We use natural units, where $\hbar = c = \epsilon_0 = 1$. Note that the expected power excess P_{det} should appear at one frequency: ω_0. However RF power leaking from the original microwave source will also appear at that frequency, so shielding the detection cavity (and all subsequent electronics) from the microwave source is extremely important to prevent a spurious signal. In order to reduce the background, which is a combination of electronic noise from our amplifiers and thermal noise in the cavity, we cool the detection cavity and our first stage amplifiers to 5 K using liquid helium and use a narrow resolution bandwidth of 6.7 mHz.

3 Experimental Setup

The experiment uses two cylindrical copper cavities resonant at 34.29 GHz in the TE_{011} mode. This mode has a high quality factor, is easily tunable, and has a high geometry factor. The power source used is an Anritsu MG3694C signal generator capable of putting out 22 dBm at our operating frequency. During runs, a spectrum analyzer monitors the reflected power from the driven cavity to ensure the cavity resonance is stable. The detection cavity and cryogenic amplifiers are placed in a cryostat with two waveguide lines; see Figure 1. One waveguide goes to a weakly coupled port on the detection cavity and is used with a network analyzer to determine the resonant frequency, while the second waveguide takes the signal from the strongly coupled port of the cavity and high electron mobility transistor (HEMT) amplifiers [9]. The cavity is tuned to the frequency of the drive cavity by vertically adjusting the top cap, with a slight gap between the cap and the cavity walls to break the degeneracy between the TE_{011} and TM_{111} modes. The waveguides transmit power to a shielded room housing the receiver chain and data acquisition system. The receiver chain is a triple heterodyne mixing scheme [10] that amplifies, filters, and mixes the RF signal down to baseband, where the data is then split into its in-phase (I) and quadrature (Q) components and digitized for further analysis.

The oscillators in the receiver chain, the microwave source, and the digitizer are all frequency locked to a 10 MHz reference - this frequency locking is important to prevent the down mixed signal from smearing out over time from a relative frequency drift of the oscillators and thus degrading the sensitivity of the narrow band measurement. It is also important to know the gain of our system accurately in order to correctly calculate P_{det}; by doing a Y-factor measurement we determined the effective noise temperature of the system to be $T_{\text{noise}} = 15 \pm 5$ K and, together with the power levels we observe at the output of the receiver chain inferred the nominal gain to be 86.1±0.5 dB. Shown below in Figure 1 is a schematic of the setup, and Table 1 summarizes the experimental parameters.

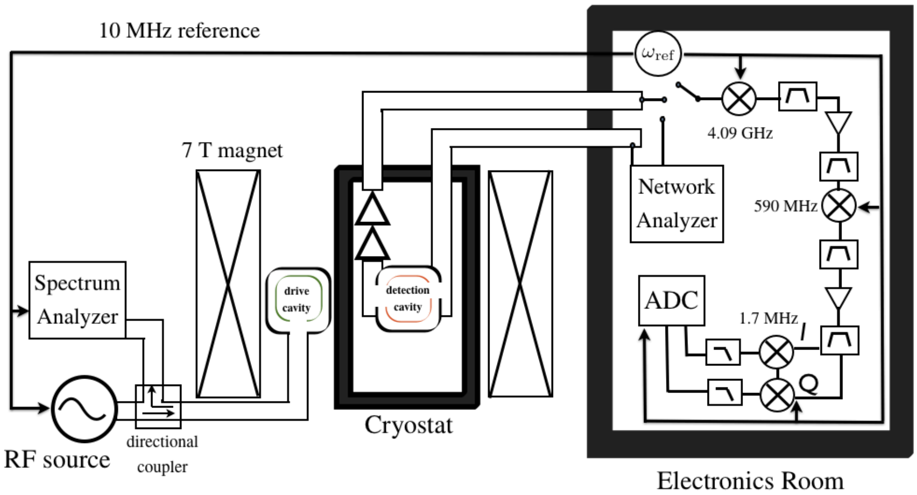

Figure 1: Schematic of the experimental set-up. The intermediate frequency at every stage of the receiver chain is shown, along with the amplifiers and filters.

Table 1: Experimental parameters for May 01 run

Q_{det}	Q_{drive}	ω_0	$\lvert G \rvert$	P_{drive}	T_{noise}	Bandwidth	Gain
9000	7000	$2\pi \times 34.29$ GHz	0.1	22 dBm	15 K	6.7 mHz	86.1 dB

Although not needed for this experiment, both the drive and detection cavities are inside the bore of a 7 Tesla superconducting magnet. We will use this magnet later on for a search for primordial axion-like particles [11].

The detection cavity and electronics are each electromagnetically shielded, but even minute levels of RF power leaking into any stage in the setup could cause a fake signal. To reduce this leakage, we covered all waveguide joints and vacuum ports with copper tape, wrapped microwave absorbing foam over the entrance of the 10 MHz cable to the electronics room, powered all the electronics in the shielded room from batteries, and surrounded the drive cavity with aluminum wool. As well, we placed the power supplies for the cryogenic amplifiers behind a wall to shield exposed wiring and reconfigured the grounds of the supplies.

4 First Results

On May 01, 2013, we recorded a two and a half minute trace with no statistically significant excess seen at ω_0, as shown in Figure 3. For comparison, Figure 2 shows a run taken with a visible leak, later attenuated by reconfiguring the grounds of the cryogenic amplifiers. From this data we exclude a hidden photon - photon coupling of $\chi > 1.7 \times 10^{-7}$ for $m_{\gamma'} = 141.8$ μeV. Figure 4 shows the limits of our experiment along with the present best limits set by astrophysical bounds and LSW experiments.

This result is not yet competitive with the bounds placed by astrophysical limits and ana-

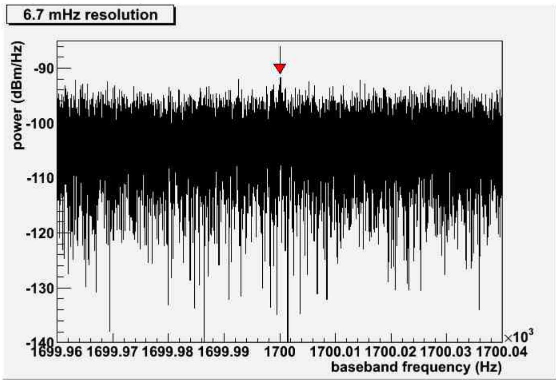

Figure 2: Power related to the signal source can be seen at ω_0. This leak was reduced by reconfiguring the grounds of the cryogenic amplifiers.

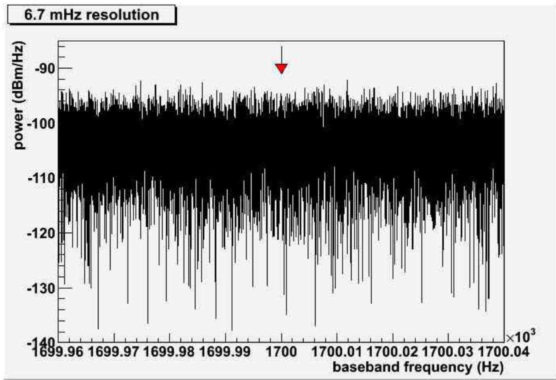

Figure 3: No power is seen at the frequency of the signal source after reconfiguring the grounds of the cryogenic amplifiers.

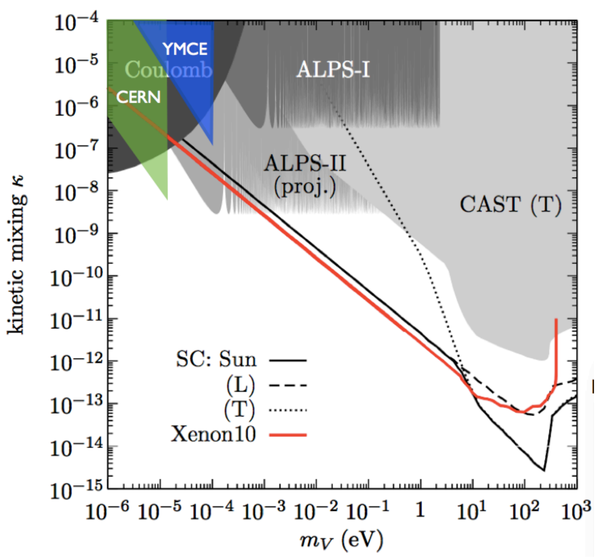

Figure 4: Updated from [13]. The filled in region labeled YMCE denotes the exclusion set by our experiment. This result and the limit from the CERN experiment (Ref. [7]) are the first microwave cavity LSW experiments to surpass the Coulomb limit; the region labeled ALPS-II [5] is the projected sensitivity of future optical LSW experiments.

lyzing XENON10 data [12]; however, in our first run to demonstrate the operation of the experiment, we have placed limits comparable in sensitivity to the first ALPS-I exclusion bound with only a modest amount of data.

5 Outlook

Much work up until this point has gone into calibrating our system, which was non-trivial due to the cryogenic setup, and understanding the various paths for RF leakage. Now that we have established the exact gain of the system and improved the shielding, the exclusion limit reported here can be improved by longer integration times and a more powerful microwave source. We also plan to do a measurement with a microwave cavity operating in the TM_{020} mode; with the strong magnetic field, this cavity will be sensitive to axion-like particles if they form part of the galactic dark matter. Finally, we can use this measurement to simultaneously place constraints on hidden photon dark matter [14, 15].

Acknowledgments

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