Superconducting RF Cavity Search for a Hidden Sector Photon

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Using a pair of high-quality superconducting niobium-titanium cavities we will search for hidden sector photons with coupling $\chi < 10^{-8}$ in the 1-30 μeV range. The experiment is the radio frequency analogue of the classic "light shining through a wall" technique. We present the proposed experimental setup and discuss the anticipated physics reach.

1 Introduction

Generically, extensions of the Standard Model (SM) of particle physics contain extra $U(1)$ gauge bosons. If these have direct Yukawa couplings to SM matter they are referred to as Z' bosons. Negative collider searches have constrained the mass of these to greater than a few hundred GeV. However, in many cases (notably string based extensions), SM matter is uncharged in the additional $U(1)$ symmetry. Then the only renormalizable interaction between the additional $U(1)$ gauge boson and visible matter is via mixing between it and the photon [1]. Collider experiments are not sensitive to this, particularly if the mass of the hidden sector photon (HSP) is in the sub-eV range. In the μeV to meV range the current bounds arise from Cavendish type tests of Coulomb's law [2, 3] and from constraints on distortions in the cosmic microwave background that would be produced by resonant production of HSPs [4, 5]. In the meV to eV range bounds have recently been extended by light shining through a wall (LSW) experiments using both optical lasers [6, 7] and intense, accelerator based infrared free-electron lasers [8]. In the eV to keV range bounds arise from considerations of the solar lifetime [9] and the non-observation of photon regeneration in helioscopes such as CAST [10].

2 Proposed experimental setup

We intend to use superconducting RF cavities in a light shining through a wall configuration to extend the limits on the existence of the HSP by more than an order of magnitude. This relies on exploiting the high-quality nature of the cavities developed for the international linear collider ($Q \sim 10^8$) [11] and existing high power microwave infrastructure at Daresbury Laboratory [12]. Initially, two frequency matched cavities will be mounted in separate cryostats and cooled to 2 K. One cavity, termed the emitter, will be powered in it's first dipole transverse magnetic mode (TM110) at 3.9 GHz. From a non-observance of this power in the second, receiver cavity one can construct a bound on the mixing parameter between photon and HSPs that would mediate a transmission between the two cavities if it exists.

Figure 1 shows the existing vertical test facility cryostat that will hold the emitter cavity. This is a fully shielded experimental environment, being buried below ground level in a concrete pit. This is designed to allow high field running of cavities within the cryostat without risk of personnel exposure to field emission X-rays, but also ensures isolation from external RF interference. Cryogenic connections to an in-situ LHe dewer ensure that multi-hour running at 2K is possible. Our intention is to install a second cryostat to hold the receiver cavity next to the existing one in an underground access tunnel. At a later stage this could be replaced with a dilution refrigerator, permitting operation of the receiver cavity in the millikelvin regime. Doing this would further improve sensitivity to the coupling through the virtual elimination of thermal noise.

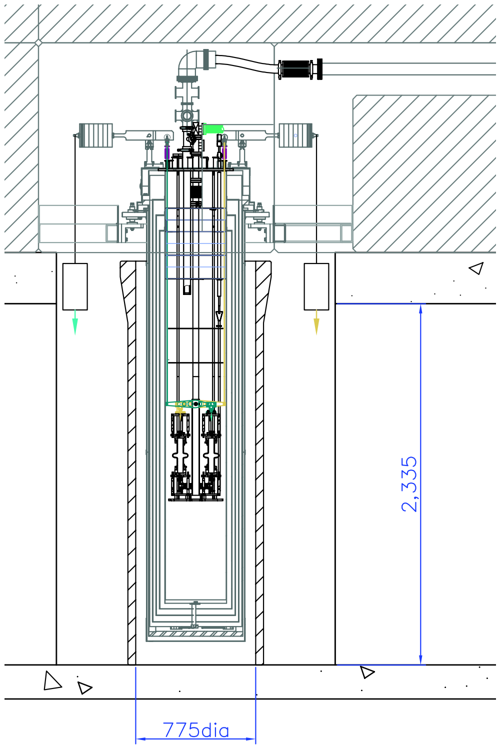

Figure 1: Vertical test facility

The sensitivity of the experiment relies on the suppression of regular microwave leakage between the cavities by many orders of magnitude (roughly an attenuation of 300dB is required). We intend to achieve this by employing a "box in a box" technique [13] that also allows leakage to be exactly quantified. This involves generating not only the fundamental driving frequency, but also a number of sidebands. One of these is mixed with the signal from the receiver cavity and FFT analysed to determine existence of the signal. The others are deliberately leaked into the outer receiver box and general external environment. These can also then be FFT analysed and compared with the signal to determine the amount of shielding achieved. Each box will have minimal RF connections to ensure a near perfect Faraday cage. The two internal boxes will be the cavities themselves, the outer boxes will be the cryostats. For the emitter, one connection is required to feed in the fundamental 3.9 GHz RF from a solid-state amplifier. For the receiver, the only RF connection allowed is that of the sideband leakage monitor. The signal output and power for the internal low noise amplifier (LNA) will be fed using electro-optic conversion equipment.

With high-Q cavities it is important to ensure that they remain mutually on tune for the duration of the experiment. For the emitter this is simple, one merely measures the reflected power continuously and re-tune periodically if required. For the receiver this will require the periodic switching in of a reference signal, correction, then re-establishing of full RF isolation. With the expected stability of the LHe, we can expect that the cavity will then remain on tune for many minutes before the process needs to be repeated. This is analogous to the Dicke procedure of eliminating electronic gain fluctuations in radio astronomy.

3 Expected physics reach

The probability for photon-HSP mixing is given by

$$P = \chi^4 Q_1 Q_2 \frac{m_{\gamma'}^8}{\omega_0^8} |G|^2 ,$$

where χ is the photon-HSP kinetic mixing fraction, Q_i are the cavity quality factors, $m_{\gamma'}$ is the HSP mass, ω_0 is the resonant frequency of the cavities and

$$G(k/\omega_0) \equiv \omega_0^2 \int_{V'} \int_{V} d^3\mathbf{x}\, d^3\mathbf{y} \frac{\exp(ik|\mathbf{x}-\mathbf{y}|)}{4\pi|\mathbf{x}-\mathbf{y}|} A_{\omega_0}(\mathbf{y}) A'_{\omega_0}(\mathbf{x})$$

is a dimensionless factor that encodes the geometrical setup of the cavities. Figure 2 shows the geometric factor for a pair of pillbox cavities in the TM110 mode with the configuration envisaged for our setup. We have also evaluated the TM310 mode at 6.4 GHz which could be excited in the emitter given a suitable solid state amplifier. The performance of the crab cavities has been measured whilst operating at 4K. Using a standard extrapolation to 2K we can expect that the cavities will exhibit $Q = 1.6 \times 10^8$ when critically coupled (i.e. a ring time of tens of milliseconds). The emitter will achieve this, however to accommodate the output coupling the receiver will have $Q = 1.0 \times 10^6$. Assuming a noise temperature for the LNA of 2K and a power gain of 17 dB, and a stored power in the emitter of 0.1 W for four hours of data taking we expect to obtain the 3σ exclusion limits indicated in Fig. 3 (green shaded regions). This is compared to the existing bounds espoused in Section 1. We consider these bounds to be conservative as there are methods of improving a number of the parameters from the values assumed in this paper. For example, signal to noise ratios can be improved by moving from a solid state LNA to a SQUID device, and through cooling the receiver to millikelvin temperatures. Additionally, more power could be stored in the emitter, and if LHe stability is as expected running could be extended over many days.

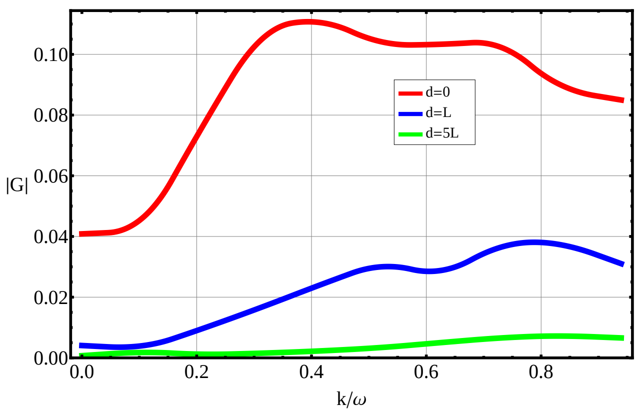

Figure 2: Geometric factor for a pair of pillbox cavities in the TM110 mode, d indicates the cavity separation in units of cavity length.

4 Conclusion

The high electric fields and quality factors attainable by the superconducting microwave cavities we propose to use in this experiment opens up a method to search for μeV particles with unprecedented sensitivity.

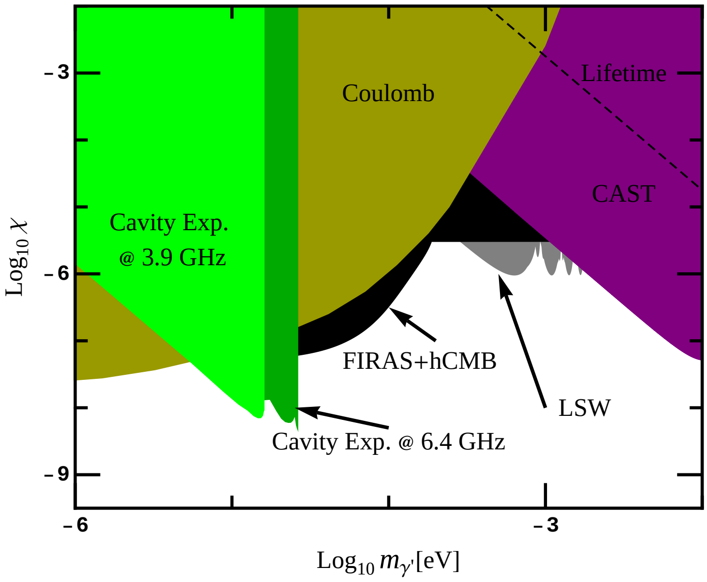

Figure 3: Anticipated SCRF cavity experiment 3σ exclusion limits on the photon-HSP kinetic mixing fraction with 4 hours running compared to existing bounds.

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