CASCADE: A CAVITY BASED DARK MATTER EXPERIMENT

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Abstract

An experiment is proposed that uses a pair of RF cavities as a source and detector of hidden sector photons (HSP). HSP's are hypothetical low-mass dark matter candidates with coupling to ordinary photons. SRF cavities are favoured in this experiment as they are able to store a high number of photons for a given input power due to the high Q available. When powered, such a cavity will act as a source of HSP's, while an empty cavity will be able to capture any HSP's decaying back into RF photons. Such an experiment (CASCADE) is being developed at the Cockcroft Institute using single cell 1.3 GHz cavities previously utilised for manufacturing and BCP (Buffered Chemical Polishing) studies. The aims of the CASCADE project are detailed, along with the system specification.

INTRODUCTION

Many extensions of the Standard Model (SM) predict the existence of a hidden sector. The particles in the hidden sector interact only very weakly with the particles of the SM. Because of this, the detection of these particles is very difficult [1].

In one model a hidden sector photon (HSP) is hypothesised. The HSP does not couple to SM matter [2,3], but the introduction of HSP terms to the SM Lagrangian can give rise to photon – HSP oscillations. Since the HSP does not interact with matter, it can traverse obstacles that would normally be impenetrable to standard light. The "light shining through wall" (LSW) experiment utilise this phenomenon. Oscillation of a photon to HSP allows it to bypass the obstacle and then oscillate back into a photon for detection.

Typical LSW-type experiments are optical precision measurements that utilize lasers [4-6]. In these experiments, laser light is shone on to a 'wall' and photons reappearing behind the wall are monitored. The same principle can be applied at other wavelengths, and hence microwave cavities can be used in a photon regeneration experiment to search for HSPs. This type of setup consists of two resonance-matched cavities that are isolated from each other and from external RF sources. One of the cavities is powered and a small portion of the photons inside the cavity will oscillate into HSPs. Since the HSPs do not interact with the cavity walls, they can radiate freely towards the second cavity, the detector cavity. If some of these HSPs then oscillate back into photons inside the detector cavity, a signal could be detected.

The probability of transmission from an emitting cavity to a detector cavity is [7]:

$$\mathrm{P}_{trans} = \frac{P_{det}}{P_{emit}} = \chi^4 Q_{emit} Q_{det} \frac{m_{\gamma'}^8}{\omega_\gamma^8} |G|^2 \quad (1)$$

where P_{det} and P_{emit} are the powers inside the respective cavities, χ is the 'kinetic mixing' parameter (a free parameter in the HSP model), Q is the quality factor of the cavity, $m_{\gamma'}$ is the HSP mass and ω_γ is the angular frequency of the photons. G is a dimensionless function that encodes the geometric setup of the two-cavity system [7]:

$$G\left(\frac{k_{\gamma'}}{k_\gamma}\right) = k_\gamma^2 \int_{V_{emit}} \int_{V_{det}} \frac{\exp(ik_{\gamma'}|\boldsymbol{x}-\boldsymbol{y}|)}{4\pi|\boldsymbol{x}-\boldsymbol{y}|} \boldsymbol{A}_{emit}(\boldsymbol{y}) \cdot \boldsymbol{A}_{det}(\boldsymbol{x}) d^3\boldsymbol{x} d^3\boldsymbol{y} \quad (2)$$

where V is the respective volume of a cavity, k_γ and $k_{\gamma'}$ are the photon and HSP wavenumbers and $\boldsymbol{A}$ is the normalized spatial part of the resonant electromagnetic field inside the cavities.

The idea of using microwave cavities in LSW experiments was originally proposed for axion searches [8] requiring an additional magnetic field, and was later applied to HSP measurements [9,10]. So far the latter have been performed with normal-conductive cavities at room temperature or even by heating up the cavities to reduce the thermal fluctuations. The resonance frequencies in these experiments have been 3.9 GHz or higher.

The CASCADE collaboration is studying the possibilities of using two superconducting cavities in HSP searches in the 1.3 GHz region. The limitations in using normal-conductive cavities are the low Q value and relatively low input power. By replacing the normal-conductive cavities by two superconducting cavities, the overall Q of the system can be increased significantly. Also at superconducting temperatures the amount of thermal noise interfering with the measurement is minimized.

Fig. 1 shows the possible exclusion that could be reached with two superconducting cavities utilizing the TM_{010} mode at 1.3 GHz. In the plot the cavities are expected to have $Q = 10^{10}$ and input power of 100 W for the emitting cavity. In the absence of signal, this would give a 5 standard deviation exclusion limit of $\chi = 10^{-11.4}$

when $m_{\gamma'} = \omega_\gamma = 5.37$ μeV when running for 20 days. The sensitivity to χ is impaired due to non-optimal positioning of the cavities. In the calculations the cavities are placed side-by-side and separated by four cavity lengths. In the optimal case for the TM_{010} mode the cavities would be placed on top of each other. However this is not feasible due to the shielding requirements.

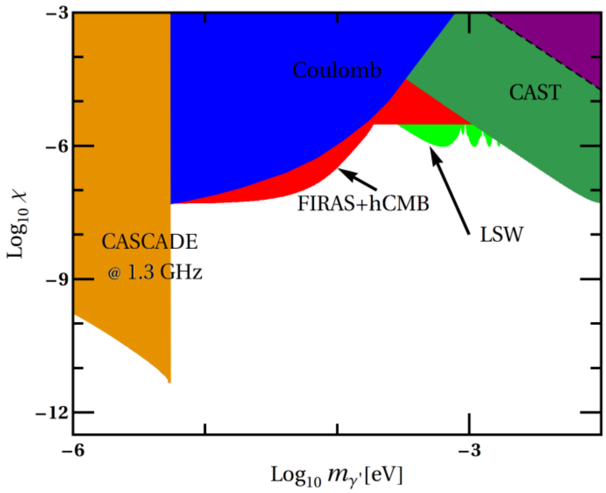

Figure 1: Expected reach of the CASCADE superconductive cavity setup. In the plot the other exclusion limits come from Coulomb law tests, searches of solar hidden photons with the CERN axion solar telescope CAST, laser-based LSW experiments and cosmic microwave background measurements of the effective number of the neutrinos and blackbody nature of the spectrum [11].

CASCADE EXPERIMENT

The experiment is proposed to capitalise on the existing program of research into 1.3 GHz SRF cavities at Daresbury Laboratory. Several single-cell cavities have been produced and are regularly tested in a vertically cryostat. The experiment would ideally have two cavities with high external Qs as in most standard vertical tests. This would maximise the HSP flux transmitted to the second cavity as both Q factors would be high. However this would also require both cavities to be at the same frequency to within a cavity bandwidth. Even if the two cavities could be reliably tuned to be that close together, microphonics would certainly make the frequencies vary with time to within several hundred Hz. The transmitter cavity could in principle be tuned with piezoelectric tuners, however, as the receiver cavity is unfilled, it is not possible to measure and tune its frequency. The solution is to ensure that one of the cavities has a bandwidth wider than the maximum frequency excursion due to microphonics. As it is beneficial that the transmitter cavity, which has the higher losses, has the highest Q factor it was decided to widen the bandwidth of the receiver cavity. The bandwidth is chosen to be ~1 kHz, hence a Q of around 10^6 is required.

In the initial phase of the project both the transmitter cavity and the receiver will be copper pillbox cavities mounted on top of each other, as shown in Fig. 2. Initially these will be at room temperature but will later be cooled with LN_2. In the second stage the transmitter cavity will be a single cell 1.3 GHz cavity inside the vertical cryostat, while both the copper cavities will be utilised as receivers placed in the service tunnel beside the vertical test cryostat. The product of the Q factors in the second scenariois higher, however the positioning of the cavities is not ideal. For TM modes the pattern is maximised in the direction of the electric field. When the two pillbox cavities are on top of each other the G is 0.4 - 1.0 depending on the distance between the cavities. For the two copper cavities plus an SRF emitter cavity the G value is of the order of 0.005-0.01. This depends on the distance between the cryostat and the service tunnel and of the angle between the emitter and the detector cavities.

While it may seem like a good idea to place both cavities inside a single cryostat, this could lead to a small RF leakage between the cavities providing a false-positive result, hence this option is not considered practical.

The copper pillbox cavities have been manufactured and have a room temperature Q factor of 22,000. When cooled with LN_2 the Q factor is expected to increase to around 10^5 although this has yet to be measured. Further increases in the product of Q factors in a two-cavity experiment could be obtained by placing a second Niobium cavity inside a cryo-cooler near the cryostat. This design is currently being investigated.

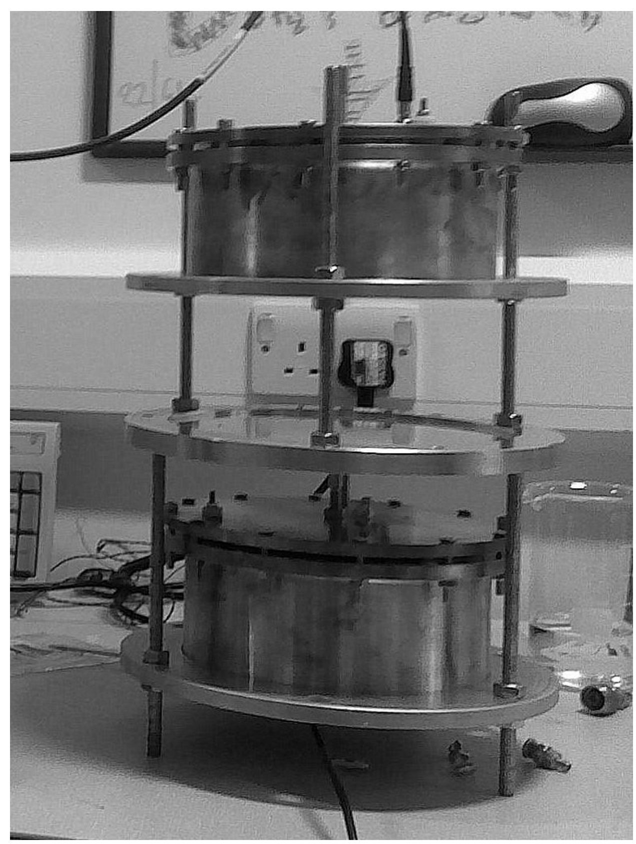

Figure 2: The copper pillbox cavities on their test stand.

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CAVITY ISOLATION

At the exclusion limits we intend to reach, the HSP flux is around 10^{-25} Watts, which requires that the shielding between the cavities attenuates the input signal by around -220 dB. The typical cross coupling between the two cavities is measured to be around -100 dB, by connecting the network analyser to the SMA connections on the input coupler on each cavity hence additional shielding is required. In order to avoid false positive results the shielding must be actively monitored. However it is difficult to measure attenuation of -200dB. It is proposed to enclose the receiver cavity inside two or three 100dB shielded boxes such that the attenuation of each box can be verified independently. The shielding of each box will be verified using transmitters/receivers at frequencies close to the cavity frequency but not within the cavity bandwidth as shown in Fig. 3.

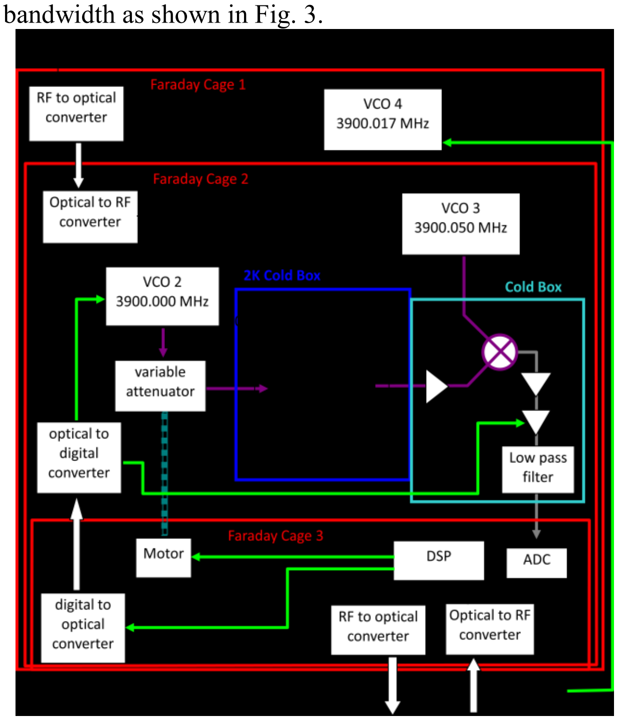

Figure 3: The proposed circuit diagram to excite/measure the signals and verify shielding.

The difficulty is then how to have a measurement system shielded to -100 dB. All feed-through and cable connections must be accounted for. The first cage will contain the cavity, cold box and an oscillator and mixer to down-convert the signal coming out of the cavity to 50 kHz. The oscillator will be synchronised to a 10 MHz master oscillator via an RF-to-optical converter. The 50 kHz signal will then be fed into a second shielded box within the first box where it will be read into a DSP and passed to an optical converter. The whole system will be enclosed in a 3rd shielded box. Batteries or thermoelectric converters are proposed to avoid power leads passing between the shielded box, and all connections to the outside will be via optical connections. At no point is a 1.3 GHz signal passed between the boxes.

CONCLUSIONS

The CASCADE experiment proposes to use coupling between isolated RF cavities as a potential method of detecting hidden sector photons. In order to increase the sensitivity of the experiment a superconducting transmitter cavity is proposed with copper receiver cavities cooled with liquid Nitrogen. The proposed experiment allows us reach further into the unconstrained region of the HSP parameter-space enabling us to search for these elusive particles.

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