Searching for wave-like Dark Matter with QSHS

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Abstract

In 2021 the Quantum Sensors for the Hidden Sector (QSHS) collaboration was founded in the UK and received funding to develop and demonstrate quantum devices with the potential to detect hidden sector particles in the μeV to 100 μeV mass window. The collaboration has been developing a range of devices. It is building a high-field, low-temperature facility at the University of Sheffield to characterise and test the devices in a haloscope geometry. This paper introduces the collaboration's motivation, aims, and progress.

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1 Introduction

The nature of dark matter is an outstanding problem in physics. There is much interest in exploring the possibility of light dark-matter candidates, particularly the QCD axion. Assuming a local dark matter halo density of approximately $0.45\,\mathrm{GeV\,cm^{-3}}$, it can be shown that cold low mass particles ($\lesssim 1$ eV) will have a high number density and a long de-Broglie wavelength. Consequently, they can be treated as a classical pseudo-scalar field.

QCD axions couple electromagnetically, augmenting Maxwell's equations to give additional terms [1]. The axion field would interact with a static magnetic field to produce an effective current leading to a propagating electromagnetic wave. Achieving the necessary sensitivity for detection requires the use of resonant methods. Ultra-low cryogenic temperatures are required to permit the expected signal, having an expected power of order yocto-watts even in resonant detectors, to be discernable above the noise inherent to the detector. The QSHS collaboration is building a test facility to integrate and test several ultra-low noise detection technologies and understand their operation in a microwave cavity haloscope operating at a nominal frequency of approximately 5 GHz.

2 The strong CP problem

Measurements of the neutron electric dipole moment (nEDM) have failed to detect a significant EDM. Recent results from PSI [2] report an upper limit on this value of approximately 10^{-26} e cm. This is surprising as there is no reason why the neutron should not have an EDM. It would arise as a consequence of CP violation which is not forbidden by the QCD Lagrangian; this is known as the strong CP problem. Consequently, the evidence suggests that CP violation in the QCD sector is either coincidentally small or a physical principle is driving it towards zero.

One favoured mechanism for explaining the non-existence of CP violation is the Pecci-Quinn (PQ) mechanism [3]. Not only does it provide an elegant solution to the strong CP problem but it also produces a massive pseudo-scalar boson called the QCD axion, a potential dark matter candidate. However, the mass of this axion remains unknown. Details of the PQ mechanism are discussed extensively in the literature [4, 5].

As the existence of QCD axions would alter Maxwell's equations, they would interact with both electric and magnetic fields. Direct decay of these axions to photons is possible. Still, as the coupling $g_{a\gamma\gamma}$ is expected to be very small due to the high symmetry-breaking energy scale of the axion field, the QCD axion can be considered a stable particle. The rate of axion 'decay' can be increased via the inverse Primakoff effect [6, 7]. Here, QCD axions couple to virtual photons sourced from a strong magnetic field to produce real photons. The strength of the coupling is model-dependent. The effective axion to two-photon coupling is given by

$$g_{a\gamma\gamma} = \frac{\alpha_{em}}{2\pi f_{PQ}}\left(\frac{E}{N} - \frac{2(4+z)}{3(1+z)}\right), \tag{1}$$

where z is the ratio of up and down quark masses and is assumed to be approximately 0.56. E is the axion electromagnetic anomaly, and N is the axion colour anomaly. f_{PQ} is a scaling constant, and is inversely proportional to the axion mass. Finally, α is the fine structure constant. Note the far right term, containing z, approximately equals 1.95.

Axions must couple to colour-charge to solve the strong CP problem, but the tree-level coupling of axions to leptons is model dependent. One implementation of the PQ mechanism is the Kim-Shifman-Vainshtein-Zakharov (KSVZ) model [8], which assumes the coupling to electrons is strongly suppressed; here $E/N = 0$. A second model, the Dine-Fischler-Srednicki Zhitnitsky (DFSZ) model [9] assumes that there is coupling to both hadrons and leptons and here $E/N = 8/3$. The bounded parameter space taken up by the axion mass to photon coupling rate as predicted by these QCD axion models is shown in figure 1.

3 QCD axions and resonant detection

Microwave resonant cavity detection is suitable for searching for QCD axions in the mass range of μeV to 100 μeV. In natural units, the axion's mass is equal to the frequency of the photon produced via the inverse Primakoff effect; the axions are cold, so the kinetic energy associated with their Maxwellian velocity distribution represents a small correction. Sensitivity to small values of $g_{a\gamma\gamma}$ required to detect QCD axions can be achieved using a tuneable cavity resonant in a TM_{010} mode at the frequency of interest, where the cavity is placed in a strong magnetic field of several Tesla at cryogenic temperatures. The cavity size is constrained by the bore achievable with an affordable magnet.

Several experiments operate and take data in this mass range, see figure 1. Broadband searches, notably the CERN axion solar telescope (CAST), have already pushed the coupling rate down to 10^{-10} GeV^{-1} over the mass range of interest [10]. As previously noted, the signal output power from a microwave cavity experiment is expected to be very small, typically on the order of yocto-watts. It can be shown that the power output from a haloscope is given by

$$P = \left(\frac{g_{a\gamma\gamma}^2 \rho_H \hbar^2}{m_a^2 c} \right) c^2 \epsilon_0 B_0^2 V \omega_0 Q f_{nlm} , \tag{2}$$

where ρ_H is the density of the halo, Q is the quality factor of the cavity and f_{nlm} represents the frequency of the cylindrical cavity mode. For cavity searches, only the transverse magnetic modes are considered, primarily the TM_{010} mode, as this provides the best form factor, ultimately maximising the power extracted by the cavity. Usually, the terms are normalised to the experimental geometry, giving a pre-factor of approximately a yocto-watt.

The Dicke Radiometer equation can be used to calculate the signal-to-noise ratio of an antenna. By suitable substitution, the power output from a microwave cavity, which is coupled to an antenna, a figure of merit for a cavity can be determined:

$$\text{Figure of Merit} \propto \frac{B^2 V}{T_S} . \tag{3}$$

The search frequency dictates the cavity geometry. Multiple cavities may be operated in phase to increase the effective volume at the cost of increased complexity. Magnets with a bore of order 1 m utilising NbTi windings and achieving fields of around 8 T have not changed much in several decades, though higher field magnets using NbSn or high T_c superconductor windings can achieve higher fields, albeit at a far lower volume and far higher cost. The system temperature T_S is comprised of the cavity's physical temperature plus the electronics' noise temperature. On the same timescale, significant improvements in the system temperature have been made due to improvements in the reliability and capabilities of dilution refrigerators and the development of new quantum electronic amplification and photon counting techniques.

4 The QSHS facility

QSHS is a UK-based, STFC-funded, test stand that will couple various quantum sensors to a nominal 5 GHz cavity. A dilution fridge with a target temperature of 10 mK (≥ 12 μW of cooling power at 20 mk) coupled with an 8 T magnet, has already been ordered from Oxford Instruments.[1] The magnet has a nominal bore diameter of 20 cm and depth 20 cm, and can contain up to three small cavities. As part of the magnet design, field cancellation coils will give a low field region (≤ 100 gauss) a short distance from the magnet core; this is crucial to the

[1] https://www.oxinst.com/

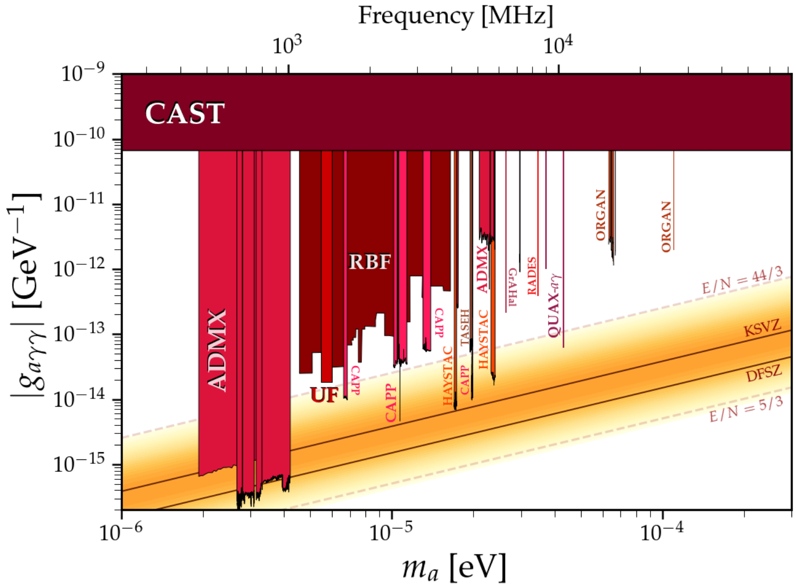

Figure 1: The red regions show the regions of axion parameter space explored by current and past microwave cavity experiments compared with the expected bounds of the QCD axion models shown by the diagonal yellow band [11].

operation of some of the instrumentation. Refurbishment of lab space at Sheffield University has commenced. Installation of the dilution fridge is anticipated later in 2023.

Collaboration members are developing qubit arrays, bolometers, travelling wave parametric amplifiers and a superconducting low-inductance undulatory galvanometer (SLUG) to provide higher frequency coupling to a cavity. Characterising the behaviour of these sensors, particularly for those sensors that may be sensitive to single photon counting in the low system temperature limit, is the principal aim of the QSHS test stand. A quantum mechanical understanding of the signal-to-noise ratio will help to improve the detector's sensitivity to QCD axions and other hidden sector particles. It may also have implications for improving the scan rate. The facility will inform the UK expertise in haloscope development and pave the way for a large-scale facility in hidden sector particle searches.

5 Conclusion

QSHS provides the UK with a technology test bench for collecting and analysing data from quantum technologies coupled to traditional microwave cavities at a target test temperature of 10 mK. QSHS has a memorandum of understanding with the Axion Dark Matter Experiment (ADMX) for cavity design and data analysis. The experience and expertise that ADMX [12] has will make a useful collaborative partner with this project.

Our longer-term aim is to build up a core of expertise in the UK so that a larger facility can be built to complement the existing searches for QCD axions and other hidden sector particles in the μeV to 100 μeV mass window.

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