PROCEEDINGS OF SCIENCE

Supax: A new axion search experiment using superconductive cavities

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We propose a new experiment to search for axions with masses around 30 μeV using superconductive cavities in a strong magnetic field. Axions are hypothetical particles that could solve the well known strong CP problem in the standard model of particle physics. Furthermore axions could explain the dark matter content of the universe. Axions are expected to convert to photons in the presence of a strong magnetic field, where the photon frequency depends on the axions mass. For wavelengths in the microwave regime resonators are typically used to enhance the axion signal. In contrast to existing experiments we propose to use a superconducting radio frequency cavity with high quality factor for the first time. In cooperation with the RADES collaboration we plan to setup the experiment in the first half of 2022. With this innovative approach and by using an existing 14T magnet, the largely unexplored mass region between 20 μeV to 40 μeV could eventually be studied with unprecedented sensitivity. This paper will present the proposed experiment and its estimated sensitivity in comparison to existing RF cavity based axion search experiments.

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PoS(EPS-HEP2021)141

1. Introduction

Axions are a hypothetical particles that solve the strong CP problem in the theory proposed by Peccei and Quinn [1–3]. As became evident later on axions could also explain all of the dark-matter in the universe [4]. They are an intriguing extension to the standard model of particle physics yet notoriously difficult to detect due to their predicted low coupling and small mass. Two commonly cited benchmark models predicting the coupling-mass relation of axion are the Kim-Shifman-Vainshtein-Zakharov (KSVZ) [5, 6] and Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) [7, 8] models. In the following we will also rely on those benchmark models to place the expected sensitivity of the proposed experiment into context.

Axions can convert into photons in the presence of a magnetic field via the inverse Primakoff effect. The detection principle for axions converting to microwave photons in a resonant cavity has been well established by the ADMX experiment [9]. For this purpose a microwave cavity is placed within a strong magnetic field. The cavity is cooled to reduce the thermal noise and read out with low noise amplifies. The R&D in the last decade focused on decreasing the temperature of the cavity to the sub-Kelvin regime, reducing the noise of the readout chain utilising a SQUID based readout and using large volume tune-able cavities, which allow to scan over wide frequency range of ±25% around the central frequency. Aiming at increasing the signal to noise ratio and hence the scanning speed over the frequency range allowed by the cavity. A field of research emerging recently is the use of superconducting radio frequency cavities which offers the prospect of an increased quality factor of up to 10^6, compared to $< 10^5$ achievable with high Q copper structures. The cavity's quality factor linearly impacts the expected axion signal power and hence the scanning speed. Recently D. Ahn et. al reached quality factors of $3 \cdot 10^5$ in a `YBCO` coated cavity in a magnetic field up to $8\,T$ at $4.2\,K$ [10]. This research is still in an early stage and very promising for applications to axion searches.

At Mainz we propose an experiment to optimise superconducting cavities in a magnetic field up to $14\,T$ and search for axions with unprecedented sensitivity in the mass region from $20\,\mu$eV to $40\,\mu$eV. To develop superconducting cavities maintaining a high quality factor in a strong magnetic field we collaborate with the RADES group at CERN. The lowest achievable resonance frequency, given by the aperture of the available magnet of 89mm diameter, is $4.8\,GHz$ at a cavity inner radius of $24\,mm$. This corresponds to $20\,\mu$eV axion mass. The upper bound is set to 12 GHz, corresponding to an axion mass of $50\,\mu$eV, limited by the readout electronics envisioned for the setup. The mass range around $30\,\mu$eV is of particularly interest as there are theoretical calculations predicting the axion mass to be around $26\,\mu$eV [11] if dark matter is made out of axions. Furthermore only two measurements are currently published in this region: Haystac [12] reported limits on the axion coupling in the mass range from $23 < m_A < 24\,\mu$eV in 2018 and ADMX [9] in the mass ranges $21 < m_A < 24\,\mu$eV and $29.66 < m_A < 29.9\,\mu$eV. The region from $30 < m_A < 60\,\mu$eV is currently not studied [13]. The proposed experiment will be probing this interesting mass range.

2. Proposed setup and expected sensitivity

A schematic drawing of the proposed experimental setup is shown in Fig. 1. The setup consists of a cryostat which will be inserted into the room temperature bore of a 14 T superconductive magnet. The SRF cavity will be located at the centre of the magnetic field. The cold electronics will be installed as close as possible to the SRF cavity, but outside of the magnetic field. The main part of the data acquisition system is a real time spectrum analyser. It has a sensitivity of -167 dBm at a resolution bandwidth of 1 kHz. The signal from the cavity is amplified using a cryogenic amplifier with a noise temperature of 3 K and an amplification of 36 dB around the initial target frequency of 8 GHz. The cryo amplifier can be bypassed using a RF switch. RF signals can be injected into the cavity using a dedicated signal generator. The input signal line is strongly attenuated to avoid the introduction of thermal noise.

The expected sensitivity of any cavity based axion search depends on the expected signal power $P_{\tt sig}$ and the systems noise power $P_{\tt noise}$. The power of the axion signal generated in the cavity can be calculated as follows

$$P_{\tt sig} = \left(\frac{g_\gamma \alpha_{em}}{\pi}\right)^2 \frac{(\hbar c)^3 \rho_a}{\Lambda^4} \frac{B^2 \beta}{(1+\beta)^2} Q_0 V C_{010} \frac{2\pi f_0}{\mu_0}. \tag{1}$$

Most notably it is proportional the the Volume V and the quality factor Q_0 of the cavity as well as the resonance frequency f_0. We aim at increasing Q_0 up to 10^6. The volume can be scaled within the limits of the magnet bore. $P_{\tt sig}$ also depends on the local axion density ρ_0 and the axion photon coupling g_γ. For the following considerations the respective values are taken from KSVZ model. The expected signal power ranges from $P_{\tt sig} = 1.4 \cdot 10^{-23}\,W$ using the first prototype cavity with $f_0 = 8.2\,GHz$, $V = 58\,\mathrm{cm}^3$ and assuming $Q_0 = 5 \cdot 10^5$ to $P_{\tt sig} = 1.4 \cdot 10^{-22}\,W$ assuming $Q_0 = 1 \cdot 10^6$ and increasing the volume by a factor of 5. The noise power from the cavity is calculated as $P_{\tt noise} = k_B T_{sys}/\sqrt{\tau/\Delta\nu_a}$, where τ is the integration time, $\Delta\nu_a = m_a < v^2 > /h$ is the bandwidth of the readout taken to be the line-width of the axion signal. The system noise temperature T_{sys} is calculated as

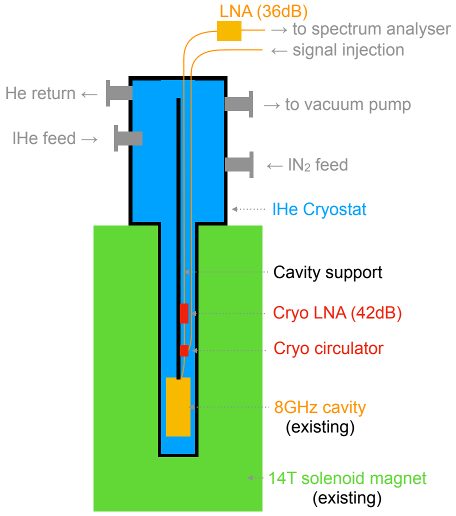

Figure 1: Schematic drawing of the proposed setup. The cavity, cold pre-amplifier (LNA) and circulator are all at LHe temperature. A second amplifier at room temperature is optionally used before feeding the RF signal into a spectrum analyser.

$$k_B T_{sys} = h\nu \left(\frac{1}{e^{h\nu/k_B T_{amb}} - 1} + \frac{1}{2} + N_A\right). \tag{2}$$

The noise power mainly depends on the system temperature. The experiment will run initially at liquid helium temperature of 4.2 K, with the option to reduce the temperature to $\approx 1.5\,K$. At these temperatures and using $\tau = 1000$ sec a noise power in the range of $6 \cdot 10^{-23}\,W$ to $2 \cdot 10^{-22} W$ is expected for the prototype cavity. This allows scanning speeds around $d\nu/dt = 1\,kHz/h$ at $T = 4K$ with a signal-to-noise ration of 1. The achieved SNR can be converted into an upper limit on the axion coupling in the absence of an observed signal. Following the analysis used in the Haystac experiment outlined in [14] a null measurement corresponds to a 95% CL upper limit on the axion coupling needed to reach an expected SNR of 5.1. Using the prototype cavity a limit of 1.3 times the KSVZ coupling can be achieved in a small region around the resonance frequency with a scanning speed of 1 kHz/h. This will be a single point measurement and proof of principle of the experimental setup. Using volume optimised, tune-able cavities a coupling larger than 18, 10 and 4 times the KSVZ coupling can be excluded at 95%CL with a scanning speed of $1 MHz/h$ at $4\,K$, $1.5\,K$, $120\,mK$, respectively, assuming a quality factor of $Q_0 = 5 \cdot 10^5$.

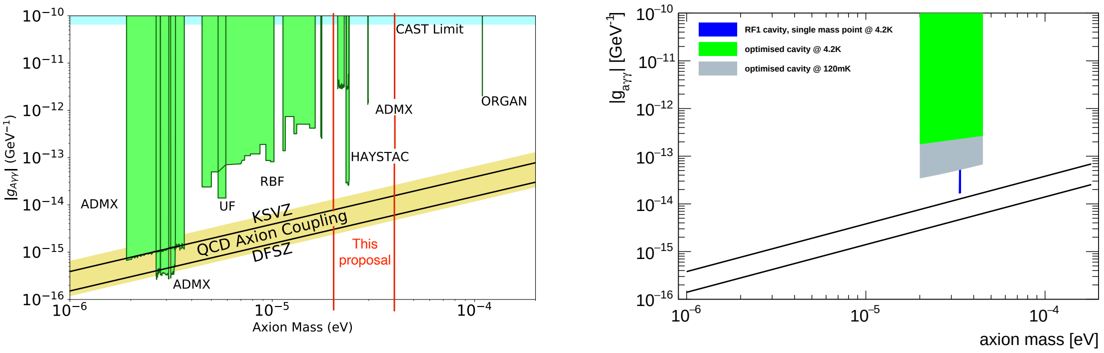

Figure 2: Sensitivity on the axion-photon coupling $g_{a\gamma\gamma}$ in dependence on the axion mass. Left: Experimental limits from various experiments compared to the expectation from the KSVZ and DFSZ models as summarised in [13]. The red lines indicate the mass region targeted by the proposed experiment. Right: Expected sensitivity of the proposed experiment. Blue indicates the single mass point measurable with the prototype cavity. The expected sensitivity using a volume optimised, tune-able cavity is shown in green for a cavity temperatures of $4\,K$ and in green and $120\,mK$ in grey. The cavity's quality factor is assumed to be $5 \cdot 10^5$ in all cases.

3. Summary

The proposed experiment aims at an initial single mass point measurement at an axion mass of $34\,\mu$eV with unprecedented sensitivity. Furthermore this setup would be used to study the SRF cavity properties, in particular the maximally reachable Q_0 in a strong magnetic field. Eventually high Q tune-able cavities could be developed and used to search for axions in the mostly unexplored mass region between $20\,\mu$eV to $40\,\mu$eV with sensitivities competitive to existing experiments.

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PoS(EPS-HEP2021)141

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