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SUPAX - A Superconducting Axion Search Experiment

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We present the first results of the SUPAX experiment. A limit for the kinetic mixing parameter of dark photons with masses of $\sim 34\,\mu$eV is presented. The SUPAX experiment is a RF-cavity based haloscope searching for dark matter candidates. The SUPAX experiment has been set up in 2022 at the University of Mainz. From the first measurement, intended to show the proof of concept of the experiment, a limit on the kinetic mixing parameter $\chi < (6.20 \pm 3.15^{(\mathrm{exp.})} \pm 9.65^{(\mathrm{SG})}) \cdot 10^{-14}$ at 95% CL could be set, as first shown in [1]. The results of this paper have been showcased in the presented poster.

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1. Introduction

With the recent rise of and continuing interest in the research into dark matter (DM) several large collaborations have made great progress in the effort to detect DM candidates such as dark photons (DP) or axions by utilising the resonance of a cavity made of high quality copper or even the use of superconductors. The SUPAX experiment has started with a similar scope, searching for these particles at the range between 8 – 10 GHz. The first proof-of-concept paper from August 2023 [1] presents a detailed description of the setup, cavity design and analysis of a first physics run, searching for dark photons. The main points have been presented on a poster at the EPS-HEP2023 and will be briefly discussed in the following.

2. Expected signal

It has been shown that dark photons may be detected via their kinetic mixing[2]. The resulting signal of such an event may be detected with a radio frequency (RF) cavity exploiting its enhancement of signals near the cavity's resonance frequency. A detailed review of the RF power generated in such a resonator can be found in [3–6]:

$$P_S^{A'} = P_0 \frac{\beta}{\beta + 1} L(f, f_0, Q_L) \tag{1}$$

$$P_0 = \eta \chi^2 m_{A'} \rho_{A'} V_{\text{eff}} Q \tag{2}$$

$$\text{with} \quad Q = \begin{cases} Q_L & \text{if } Q_L < Q_{\text{DM}} \\ Q_{\text{DM}} & \text{if } Q_L > Q_{\text{DM}} \end{cases} \tag{3}$$

Where β, η and Q_L are the coupling coefficient of the cavity, the attenuation factor of the experimental setup and the loaded quality factor of the cavity, respectively, while $m_{A'}$ denotes the mass of the DP one is looking for. The local density of the dark matter is commonly assumed to be $\rho_{A'} = 0.45 \frac{\text{GeV}}{\text{cm}^3}$. $Q_{\text{DM}} \approx 10^6$ is the dark matter "quality factor". The effective volume denotes the overlap of the dark photon field and the induced electric field inside the cavity:

$$V_{\text{eff}} = \frac{\left(\int dV \mathbf{E}(\vec{x}) \cdot \mathbf{A}'(\vec{x})\right)^2}{\int dV \epsilon_r |\mathbf{E}(\vec{x})|^2 \cdot |\mathbf{A}'(\vec{x})|^2}. \tag{4}$$

The Lorentzian L in eq. (1) describes the shape of a possible DM mass peak:

$$L(f, f_0, Q_L) = \left(1 + \left(Q_L \frac{f - f_0}{f_0}\right)^2\right)^{-1}. \tag{5}$$

3. Experimental Setup

While the technicalities are detailed in [1] we give here a brief overview of the experimental setup that has been used to obtain the data.

The cavity of outer dimensions $160 \times 40 \times 26.8\,\mathrm{mm}^3$ and its low noise amplifier (LNA) are hung from the lid of a LHe dewar and submerged completely in LHe, filling the cavity with helium. The critically coupled port antenna is connected to a switch which can bypass the amplifier to allow for the characterisation of the cavity via a vector network analyser. If the switch is turned off the LNA amplifies the power inside the cavity by 36 dB, which then is amplified once more by 25 dB by the internal amplifier of the real-time spectrum analyser (RSA) being used to record the data. The rather lengthy process of characterising the cavity will be skipped here, the results of it are listed in Table 1. Unfortunately the readout port antenna was slightly overcoupled ($\beta = 1.627 \pm 0.279$ with an ideal value of 1.0) resulting in a signal loss of $\sim 6\%$.

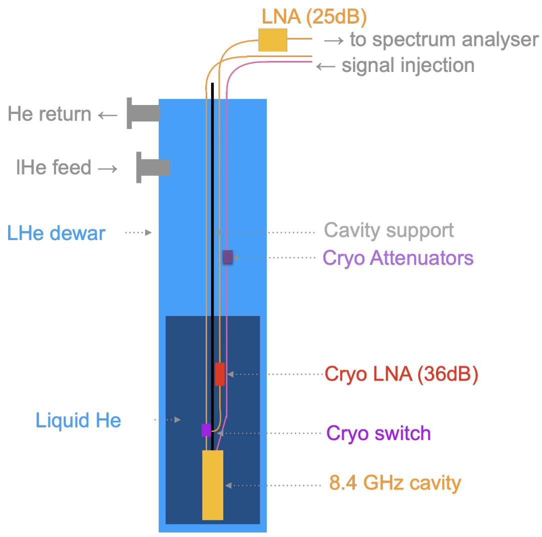

Figure 1: Schematic setup of the cavity and amplifier submerged in liquid helium[1].

	measurement	simulation
Q_L	15096 ± 1576	16277 ± 212
Q_0	–	39660 ± 518

Table 1: Loaded and unloaded quality factors at LHe temperature. Due to a dysfunctional switch Q_0 could not be determined in liquid helium but has later been determined to be consistent with the simulation in a separate measurement[1].

The resonance frequency of the cavity in LHe has been determined to be

$$f_0 = 8.303\,\mathrm{GHz}. \tag{6}$$

This determines the mass of a possible DP to probe for to be

$$m_{A'} = h \cdot f_0 = 34.34\,\mu\mathrm{eV} \tag{7}$$

4. Data Analysis

The readout system is calibrated using a dedicated measurement to make sure that no electronic artifacts influence the analysis and that the noise of the readout behaves in a Gaussian manner. Then data was recorded with the attached cavity cooled to 4 K. The analysis contains four main steps. In steps 1 and 2 the electronic imprint, the variable gain curve and the resonance structure of the cavity itself are being removed utilising a Savitzky-Golay filter. In steps 3 and 4 the resulting spectrum is normalised and subsequently used to set the limit on the kinetic mixing parameter χ.

The signal to noise ratio (SNR) shows no excess above the threshold of $3.455\,\sigma$ in the signal region, corresponding to the absence of an associated SNR of $5\,\sigma$ at a 95% confidence level.
After incorporating all experimental uncertainties and simulating the choice of slightly non-optimal choice of SG-filter parameters we were able to obtain a first limit of

$$\chi_{\text{prelim}} < (1.24 \pm 0.63^{(\text{exp.})} \pm 1.93^{(\text{SG})}) \cdot 10^{-14}.$$

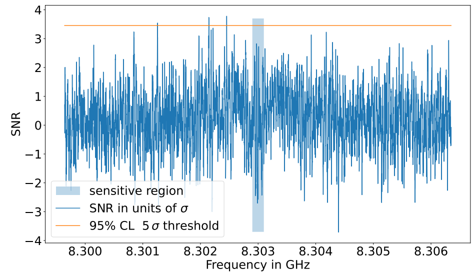

Figure 2: SNR of the 126 min data acquisition in units of the standard deviation σ. The considered signal region is indicated as shaded area[1].

To cross-check if the analysis would indeed reconstruct a signal with given χ_{prelim} as an excess in the SNR distribution a simulated peak has been inserted into the data. Doing so revealed that only a peak corresponding to $\chi = 5 \cdot \chi_{\text{prelim}}$ would be considered as possible signal with SNR $< 3.455\sigma$. The observed reduction in sensitivity is attributed to the SG filter. This cross-check led to the claim of the limit $\chi_{\text{limit}} = 5 \cdot \chi_{\text{prelim}}$.

$$\chi_{\text{limit}} < (6.20 \pm 3.15^{(\text{exp.})} \pm 9.65^{(\text{SG})}) \cdot 10^{-14} \tag{8}$$

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