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Search for QCD axion dark matter around $24.5\,\mu\text{eV}$ using an 8-cell microwave resonant cavity haloscope and a flux-driven Josephson parametric amplifier

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Axion, a hypothetical particle originally emerging from a proposed solution to the strong CP problem of particle physics, is one of the favored candidates addressing the dark matter puzzle. As part of the efforts within the Center for Axion and Precision Physics Research of the Institute for Basic Science, we are searching for axion dark matter using the haloscope method sensitive to masses around 24.5 μeV at Kim-Shifman-Vainshtein-Zakharov (KSVZ) sensitivity. A unique 8-cell cavity, used for the first time in search of KSVZ axions, is cooled down to 40 mK within a magnetic field of 8 T. The expected axion signal resonating with the TM_{010}-like mode of the cavity is picked up using an antenna and transferred to the readout chain. Implementing a flux-pumped Josephson parametric amplifier with 20 dB gain as the first stage of amplification, the system noise temperature was estimated to be 450 mK, corresponding to 1.6 photons. In this paper, we present results from data taken between December 2021 and June 2022, covering approximately 100 MHz.

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1. Introduction

One of the long-standing problems of particle physics is the so-called strong CP problem. The axion emerges as a solution to the strong CP problem as part of a newly introduced $U(1)$ symmetry to the theory [1, 2]. If such axions were produced in the early universe they would result in the dark matter abundance observed today. Their interaction with matter is weak enough that they can be treated as a background field that permeates everything around us. Two prominent models describing their interaction with matter relying on different assumptions are called Kim-Shifman-Vainshtein-Zakharov (KSVZ) and Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) models [3–7]. Both models allow weak interactions with standard model photons, leading to detection methods that can be realized in the laboratory. A type of detector proposed by Sikivie, the so-called axion haloscope, uses photons produced in a microwave cavity due to an interaction between a static magnetic field and the axion field [8]. Since it is a resonant effect, the signal power is reduced significantly if axions are converted to photons with frequencies that fall outside the bandwidth of the cavity. We expect the produced photons to have frequencies given by the relation $f = mc^2/h$ due to energy conservation. Although certain mass regions are favored by recent advances in cosmological axion simulations, there is currently no consensus on the axion mass. This means the cavity frequency has to be tuned to cover all possible axion masses. To this end, haloscopes employ a mechanism to tune the resonance frequency of the cavity. A typical figure of merit quantifying how fast a particular axion haloscope is able to cover a frequency range is given by the scanning rate [9]:

$$\frac{\Delta f}{\Delta t} = \left[\frac{4}{5}\left(\frac{\alpha^2}{\pi^2}\frac{\hbar^3 c^3}{k_B \mu_0 \Lambda^4}\right)^2\right]\left[\eta_d Q_a Q_L \left(\frac{\beta}{1+\beta}\rho_a g_\gamma w_c B_0^2 V C_{010} \left(\mathrm{SNR}\, T_{\mathrm{sys}}\right)^{-1}\right)^2\right] \tag{1}$$

In the above equation, the first pair of square brackets encapsulates the physical constants with the $\Lambda = 75\,\mathrm{MeV}$ term coming from hadronic computations[10]. With $Q_a \approx 10^6$ quantifying the spectral sharpness of the expected axion signal shape and the local dark matter density $\rho_a = 0.45\,\mathrm{GeV}$, the second pair of square brackets contains all the experiment parameters. Here we report a haloscope with a loaded quality factor $Q_L \approx 15000$, antenna coupling $\beta \approx 2$, average magnetic field $B_0 = 6.965\,\mathrm{T}$, cavity volume $V = 3.103\,\mathrm{L}$, TM_{010} mode form factor $C_{010} \approx 0.6$, and system noise temperature $T_{\mathrm{sys}} = 420\,\mathrm{mK}$. For a KSVZ axion ($g_\gamma = -0.97$), this gives a scanning rate of $1.1\,\mathrm{MHz\,d^{-1}}$ for a search around 5.9 GHz.

2. System overview

The experiment was conceived as a substantial upgrade over the previous CAPP-8TB experiment [11, 12] in terms of scanning rate, sensitivity and stability. The five main components of the system are the cryostat, the magnet, the conversion cavity, the measurement setup, and the data acquisition system. The cryostat is a Bluefors LD400 dilution refrigerator capable of reaching 8 mK temperature at the mixing chamber (MC) stage. It is fitted with an AMI 8T superconducting magnet with 16.5 cm bore diameter. The cavity is a design optimizing the cylindrical volume for a given frequency while minimizing the trade-off for the form factor. The volume optimization for the target frequency is achieved by careful partitioning of the cavity volume into equally angled sections [13]. It can operate from 5.5 to 6 GHz with unloaded quality factor (Q_0) of 40 000 to 45 000 while maintaining a form factor of around 0.6 ± 0.03. We fixed the cavity to the MC plate of the dilution refrigerator using gold-plated copper rods for mechanical support along with additional thermalization structures. With the magnet off (on), we achieved cavity temperatures below 18 mK (25 mK) while the MC temperature T_{MC} was kept at 14 mK (16 mK). In order to prevent experimental stimulus from changing temperatures during the course of experiment, we chose to operate with a higher temperature at 40 mK using a proportional and integral feedback control on T_{MC}.

The cryogenic measurement setup consisted of auxiliary measurement paths required for characterizing the system and the detection chain responsible for amplifying axion signals into detectable levels at room temperature (see Fig. 1). Detection chains unavoidibly decrease the signal-to-noise ratio which is conventionally quantified by a frequency dependent variable called the added noise temperature. For a detection chain consisting of cascaded 2-port elements with noise temperatures $T_1, T_2, \ldots$ and gains $G_1, G_2, \ldots$, the noise contribution is given by the Friis relation:

$$T_n = T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \cdots \tag{2}$$

This relation states that the first amplifier has the dominant noise temperature contribution given that its gain is high. A flux-driven Josephson parametric amplifier (JPA) was used at the first stage of amplification. It is a narrowband amplifier consisting of a capacitively coupled $\lambda/4$ resonator terminated with a DC SQUID [14]. An external magnetic field is used to bias the resonance frequency f_r while an AC field provided by a pump tone at $f_p \approx 2f_r$ leads to parametric amplification. JPAs are shown to reach the lowest noise temperatures[15]. The JPA was put inside a 3-layer magnetic shield made of aluminum, μ-metal and niobium, respectively from inside to outside. This structure was fixed on the MC plate where the residual field is around 0.1 T when the magnet is at 8 T. Inside the shielding, the JPA is fitted in the bore of a superconducting solenoid providing the magnetic field necessary to control f_r. Before the start of experiment, we measure the JPA gain as a function of three control parameters, solenoid coil current i_b, pump power P_p and pump frequency f_p. Using this data set, we construct a look-up table (LUT) for operating at a desired center frequency and gain. During the experiment, this LUT is used to operate at the minimum noise temperature available for a given frequency and gain [16].

3. Results

We ran the experiment from December 28, 2021 to June 1, 2022 covering frequencies from 5.83 to 5.94 GHz with an insensitive region of 10 MHz centered at 5.885 GHz. During these 5 months of operation, the system was warmed up two times for maintenance. The reference noise temperature measurement with the JPA off was performed after each cooldown showed consistent results with noise temperatures ranging from 2 to 2.6 K. The JPA gain was maintained at (19.7 ± 0.1) dB at each tuning step, while the system noise temperature was ranging from 390 to 500 mK(See Fig. 2). The antenna coupling was kept within 15% of its expected optimum value of 2 by adjusting the strong antenna position as needed. The loaded quality factor ranged from 14000 to 16000 during

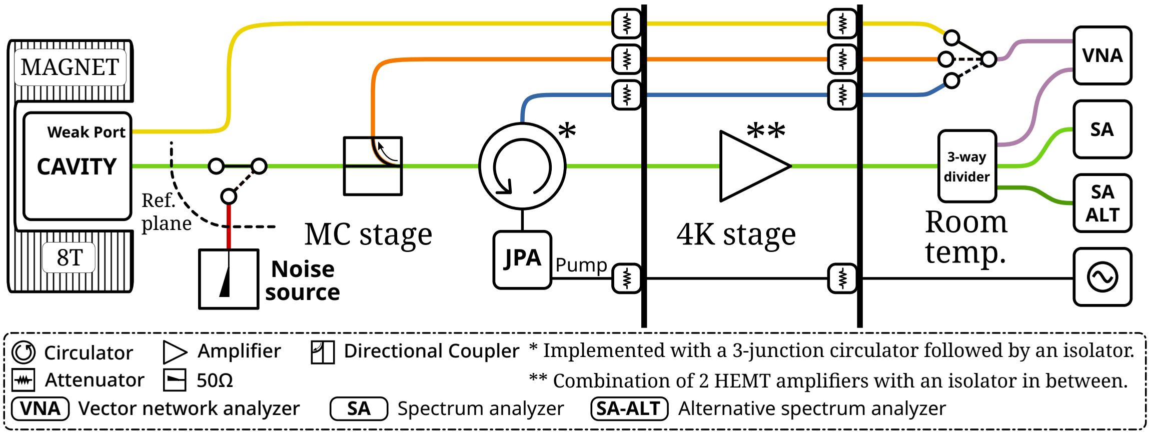

Figure 1: Simplified diagram for the experiment.

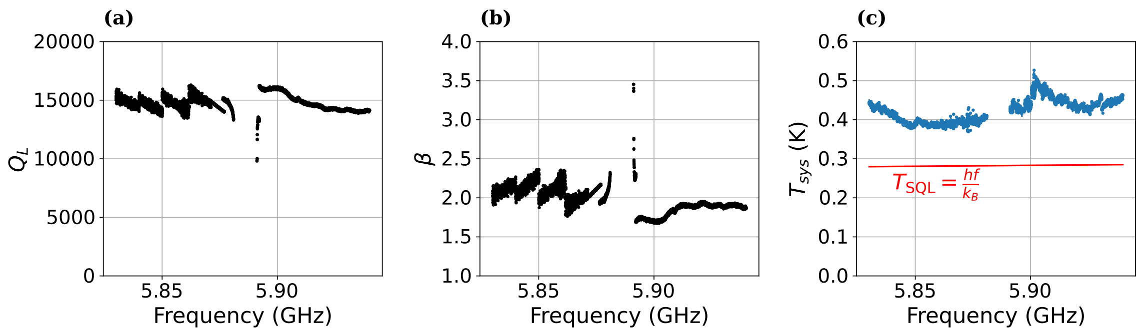

Figure 2: Loaded quality factor Q_L (a), strong antenna coupling β (b), and T_{sys} (c) measured during data taking. The sharp change in β and Q_L at 5.89 GHz is due to the existence of a stationary TE-like mode around that frequency. The TM_{010}-like mode we are tracking interacts with this intruder mode which results in the apparent reduction of the measured quality factor.

operation. Our data shows that we were able to probe axion to two-photon couplings ranging from 1.2 to 1.4 GeV^{-1} in the mass range 24.11 to 24.56 μeV. The 23 candidate frequencies that crossed the SNR threshold for a 90% confidence level did not persist after accumulating more data for those frequencies.

4. Conclusion

We have built an axion haloscope capable of reaching KSVZ sensitivity in the mass range around 24.5 μeV. The whole experimental system is stable enough for uninterrupted operation lasting for months. Reaching system noise temperatures as low as 380 mK, we operated the system with 0.9 $\mathrm{MHz\,d}^{-1}$ scanning rate at KSVZ sensitivity. With our preliminary analysis, we were able to set an upper boundary on $g_{a\gamma\gamma}$ in the regions $24.11 < m_a < 24.32$ μeV and $24.35 < m_a < 24.57$ μeV (see Fig. 3). The analysis shown in this work has about 27 % loss due to the baseline removal procedure. We have recently optimized our baseline estimation filter which reduced this loss to about 16 %. Moreover, we have updated our analysis procedure by the inclusion of idler signal

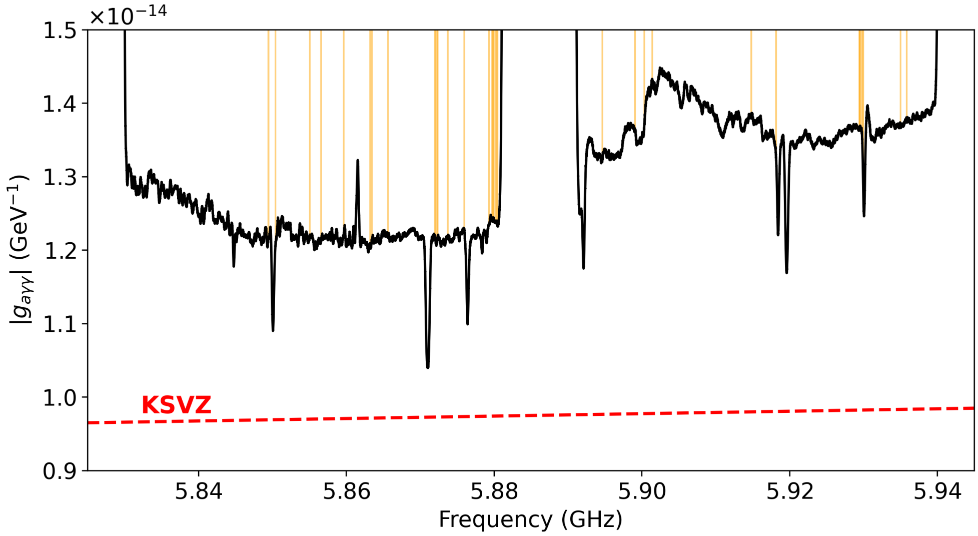

Figure 3: Upper limit for $g_{a\gamma\gamma}$ at 90% confidence level (black line). The shaded yellow regions are where the candidates crossing the SNR threshold were observed and subsequently rescanned.

which improves our SNR efficiency by 4 to 12 % depending on the frequency. We expect these two improvements to reduce the upper limits shown in this work by about 12 %.

Acknowledgments

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References

[1] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. **38**, 1440 (1977).

[2] J. Preskill, M. B. Wise, and F. Wilczek, Phys. Lett. B **120**, 127 (1983).

[3] J. E. Kim, Phys. Rev. Lett. **43**, 103 (1979).

[4] M. A. Shifman, A. I. Vainshtein, and V. I. Zakharov, Nuclear Physics, Section B **166**, 493 (1980).

[5] M. Dine and W. Fischler, Phys. Lett. B **120**, 137 (1983).

[6] S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978).

[7] F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978).

[8] P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983).

[9] S. A. Kenany, M. Anil, K. Backes, B. Brubaker, S. Cahn, G. Carosi, Y. Gurevich, W. Kindel, S. Lamoreaux, K. Lehnert, S. Lewis, M. Malnou, D. Palken, N. Rapidis, J. Root, M. Simanovskaia, T. Shokair, I. Urdinaran, K. van Bibber, and L. Zhong, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **854**, 11 (2017).

[10] S. Borsanyi, Z. Fodor, J. Guenther, K. H. Kampert, S. D. Katz, T. Kawanai, T. G. Kovacs, S. W. Mages, A. Pasztor, F. Pittler, J. Redondo, A. Ringwald, and K. K. Szabo, Nature **539**, 69 (2016).

[11] J. Choi, S. Ahn, B. R. Ko, S. Lee, and Y. K. Semertzidis, Nuclear Instruments and Methods in Physics Research, Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **1013**, 165667 (2021).

[12] S. Lee, S. Ahn, J. Choi, B. R. Ko, and Y. K. Semertzidis, Phys. Rev. Lett. **124**, 101802 (2020).

[13] J. Jeong, S. Youn, S. Bae, J. Kim, T. Seong, J. E. Kim, and Y. K. Semertzidis, Phys. Rev. Lett. **125**, 221302 (2020).

[14] T. Yamamoto, K. Inomata, M. Watanabe, K. Matsuba, T. Miyazaki, W. D. Oliver, Y. Nakamura, and J. S. Tsai, Appl. Phys. Lett. **93**, 042510 (2008), 0808.1386 .

[15] L. Zhong, E. P. Menzel, R. Di Candia, P. Eder, M. Ihmig, A. Baust, M. Haeberlein, E. Hoffmann, K. Inomata, T. Yamamoto, Y. Nakamura, E. Solano, F. Deppe, A. Marx, and R. Gross, New Journal of Physics **15** (2013), 10.1088/1367-2630/15/12/125013, 1307.7285 .

[16] Ç. Kutlu, S. Ahn, S. V. Uchaikin, S. Lee, A. F. van Loo, Y. Nakamura, S. Oh, and Y. K. Semertzidis, in *Proceedings of 29th International Conference on Low Temperature Physics* (in press).