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First QUAX galactic axions search with a SC resonant cavity

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Summary. — Quax is an axion haloscope that can search for axions by means of either their coupling with electron spins or with photons, making use of superconducting resonant cavities. A superconducting NbTi cavity was characterized at $T = 4\,\mathrm{K}$ in a magnetic field. The cavity exhibited a quality factor of $Q_0 = 4.5 \times 10^5$ for the TM010 mode at 9 GHz in a 2 T magnetic field. Since the results were satisfactory, this cavity was also operated in a set-up to measure the axion coupling with photons, $g_{a\gamma\gamma}$. This resulted in an upper limit of $g_{a\gamma\gamma} < 1.03 \times 10^{-14}$ GeV^{-1} for an axion mass of about 37 μeV.

1. – Introduction

To account for the Dark Matter content in our Universe, post-inflationary scenarios predict for the QCD axion a mass in the range (10–10^3) μeV [1]. Searches with haloscope experiments in this mass range require the monitoring of resonant cavity modes with frequency above 5 GHz, where several experimental limitations occur due to linear amplifiers, small volumes, and low quality factors of Cu resonant cavities. This article discusses this last issue.

QUAX is an experiment at LNF and LNL(1) designed to search for axions by means of their resonant interactions with electronic spins in a magnetized sample. In principle, axion-induced magnetization changes can be detected by embedding a sample in an rf cavity in a static magnetic field [2, 3].

The same experimental apparatus can be used as a Sikivie haloscope [4], exploiting an rf cavity immersed in a magnetic field to stimulate the axion conversion into photons [5]. The improvement that Quax introduces with respect to classical haloscopes as ADMX [6] is the use of superconducting resonant cavities. In fact at 10 GHz a copper cavity, cooled

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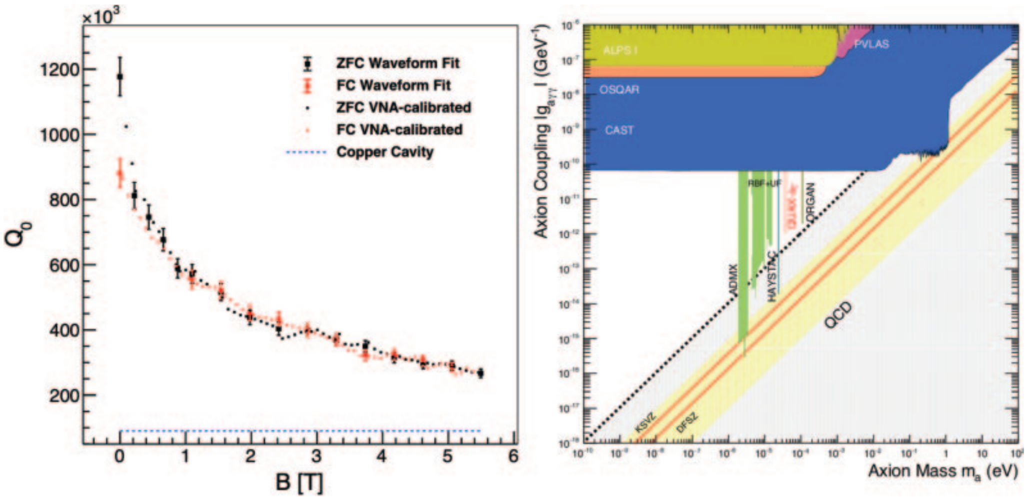

Fig. 1. – (a) Q_0 as a function of magnetic field B at $T = 4.2\,\mathrm{K}$. Both Zero-Field Cooling and Field Cooling curves are shown. (b) Esclusion plot from various experiments, showing the axion-photon coupling constant as a function of the axion mass. The red line is the current Quax upper limit.

at cryogenic temperature, barely reaches a quality factor $Q \sim 10^5$, a value that rapidly decreases with increasing frequency. Here, a substantial improvement obtained for the quality factor with a “superconducting haloscope”? composed of a superconducting cavity (SCC) operated in high magnetic fields is presented.

2. – Description

2˙1. *Characterization of resonant cavity.* – The SC cavity was characterized at LNF and consists of a copper cylinder ($\Phi = 26\,\mathrm{mm}$, $L = 50\,\mathrm{mm}$) with a thin film of NbTi (3–4 μm) deposited on the internal wall. The cylinder ends with two conic-shaped Cu endcaps to reduce the current dissipation at interfaces.

We characterized the cavity in a thermally controlled gas-flow cryostat equipped with an 8 T superconducting magnet. Two tunable antennas were coupled to the cavity mode (TM010 at a frequency $\nu_{010} = 9.07\,\mathrm{GHz}$) and connected through coax cables to a Vector Network Analyzer for the measurement of the reflection and transmission waveforms, $S_{11}(\nu)$ and $S_{12}(\nu)$. The unloaded quality factor Q_0 was extracted from a simultaneous fit of the two waveforms. An expected systematic error of ±5% follows from the fit procedure.

We measured Q_0 at 4.2 K in the range of magnetic fields 0–5.5 T both in zero-field cooling (ZFC) and field cooling (FC), as shown in fig. 1(a). At $B = 2\,\mathrm{T}$ the cavity reaches $Q_0 = 1.2 \times 10^6$ in agreement with the maximal expected value $Q_0^{\max}$ estimated with ANSYS-HFSS electromagnetic simulations. For $B = 2\,\mathrm{T}$, the nominal field used in our axion search, we measured $Q_0^{2}\,\mathrm{T} = 4.5 \times 10^5$, a factor ~ 5 better than a bulk Cu cavity; at 5 T we measured $Q_0^{5}\,\mathrm{T} = 2.95 \times 10^5$, a factor ~ 3.3 better than a Cu cavity, showing significant improvements.

More details on vortex motion, field trapping and SC losses in the cavity can be found in [7].

2˙2. *Primakoff mode measurement.* – A replica of the cavity described above was mounted in the experimental site at LNL. The main instrumentation of the apparatus includes a magnet providing a 2 T magnetic field immersed in LHe at 4.2 K, an amplification chain, a down-converter mixer and an ADC.

The total gain G and temperature noise T_n of the amplification chain were measured heating a resistor connected with a switch and measuring its Johnson noise, resulting in $G = (1.96 \pm 0.01) \times 10^{12}$ and $T_n = (11.0 \pm 0.1)$ K.

The data have been analyzed with a fast Fourier transform with a resolution bandwith of $\Delta\nu = 7812.5\,\mathrm{Hz}$. The residuals of the power spectum follow a Gaussian distribution, and its standard deviation is $\sigma_P = 6.19 \times 10^{-22}\,\mathrm{W}$, compatible with the Dicke relation [8]

$$\sigma_P = k_B T_S \sqrt{\frac{\Delta\nu}{\Delta t}} \simeq 5.5 \times 10^{-22}\,\mathrm{W},$$

where $\Delta t = 20$ min is the integration time and $T_S = T_n + T_{\mathrm{phys}} = 15.3$ K the system temperature.

We set an upper limit on the coupling constant $g_{a\gamma\gamma}$ from the data. The expected power generated by KSVZ axions in our cavity [5] is

$$P_{\mathrm{a}} = 1.85 \times 10^{-25}\,\mathrm{W} \left(\frac{V}{0.0361}\right) \left(\frac{B}{2\,\mathrm{T}}\right)^2 \left(\frac{g_\gamma}{-0.97}\right)^2 \times \left(\frac{C}{0.589}\right) \left(\frac{\rho_a}{0.45\,\mathrm{GeVcm^{-3}}}\right) \left(\frac{\nu_c}{9.067\,\mathrm{GHz}}\right) \left(\frac{Q_L}{201000}\right).$$

The 95% single sided confidence limit (1.64σ), shown in fig. 1(b), is $g_{a\gamma\gamma} < 1.03 \times 10^{-12}\,\mathrm{GeV}^{-1}$ in a frequency band of 45 kHz at ν_c corresponding to a mass range of $\sim 0.2\,\mathrm{neV}$ around $m_a \simeq 37.5\,\mu\mathrm{eV}$. More details can be found in the main article [5].

3. – Conclusions

Here we have demonstrated that SC rf cavities are capable of reaching quality factors of order 10^6, an optimal value for galactic axion search. Moreover we set up a demonstrator of haloscope with a SC cavity, showing the feasibility of the experiment.

To reach the QCD axion band of fig. 1(b) further improvements are needed. For instance, a new experimental setup is now in preparation consisting of a dilution refrigerator, a quantum limited Josephson Parametric Amplifier (JPA) and an 8 T superconducting magnet. At 50 mK and with $B = 5\,\mathrm{T}$ we expect to set the limit $g_{a\gamma\gamma} < 4 \times 10^{-14}\,\mathrm{GeV}^{-1}$ for $m_a \simeq 37.5\,\mu\mathrm{eV}$, thus touching the KSVZ line.

REFERENCES

[1] Particle Data Group (Tanabashi M. *et al.*), *Phys. Rev. D*, **98** (2018) 030001.
[2] Barbieri R. *et al.*, *Phys. Dark Univ.*, **15** (2017) 135.
[3] Crescini N. *et al.*, *Eur. Phys. J. C*, **78** (2018) 703.
[4] Sikivie P., *Phys. Rev. Lett.*, **51** (1983) 1415 *Phys. Rev. D*, **32** (1985) 2988.
[5] Alesini D. *et al.*, *Phys. Rev. D*, **99** (2019) 101101(R).
[6] Asztalos S. *et al.*, *Phys. Rev. D*, **64** (2001) 092003.
[7] Di Gioacchino D. *et al.*, *IEEE Trans. Appl. Supercond.*, **29** (2019) 3500605.
[8] Dicke R. H., *Rev. Sci. Instrum.*, **17** (1946) 268.