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Search for axion dark matter at IBS/CAPP

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The axion, a consequence of the PQ mechanism proposed to solve the strong-CP problem of particle physics, has been considered as a compelling candidate for cold dark matter. The Center for Axion and Precision Physics Research (CAPP) of the Institute for Basic Science (IBS) has been establishing state-of-the-art axion search experiments in Korea since 2013. Relying on the haloscope technique, where axions are resonantly converted into microwave photons in a strong magnetic field, our strategy is to run multiple experiments in parallel to explore a large area of the axion parameter space. The ultimate goal is to probe axion dark matter in the mass range up to 40 μeV with sensitivities of the QCD axion models. The current approaches to achieve this goal are twofold: 1) utilizing well-advanced technologies, including high field superconducting (SC) magnets, cryogenic dilution refrigerators, quantum-limited noise amplifiers, and 2) developing unique features, such as high-Q SC cavities under high magnetic fields, and efficient cavity design for high-frequency axion search. We present the status and future prospects of the experiments and discuss the R&D activities at IBS/CAPP.

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1. Introduction

A lack of the electric dipole moment of neutron is known as the strong-CP problem in particle physics. The most popular solution, proposed by R. Peccei and H. Quinn, introduces a new global symmetry which is spontaneously broken at a particular energy scale, requiring a new pseudo-Goldstone boson, called the axion, to exist [1]. Two theoretical models, KSVZ and DFSZ, were established depending on the strength of the coupling of axions to ordinary matter [2, 3]. Despite its tiny mass, the axion has also been considered to account for at least some of dark matter if its mass falls into a certain range [4].

The most promising detection principle relies on the axion haloscope, where axions are resonantly converted into photons in a microwave cavity immersed in a strong magnetic field [5]. The axion-to-photon conversion power is given by

$$P_{a\to\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B_0^2 V C \min(Q_L, Q_a), \tag{1.1}$$

where $g_{a\gamma\gamma}$ is the axion-to-photon coupling, ρ_a is the local halo density, m_a is the axion mass, B_0 is the magnetic field, V is the cavity volume, C is the cavity mode dependent form factor, and Q_L and Q_a are the cavity and axion quality factors, respectively. As the axion mass (equivalently the photon frequency), is a priori unknown, all possible mass (frequency) ranges need to be searched and the scanning rate (df/dt) is the figure of merit in designing an experiment:

$$\frac{df}{dt} = \left(\frac{1}{\mathrm{SNR}}\right)^2 \left(\frac{P_{a\to\gamma\gamma}}{k_B T_{\mathrm{sys}}}\right)^2 \frac{Q_a}{Q_L} \sim B_0^4 V^2 C^2 Q_L T_{sys}^{-2}, \tag{1.2}$$

where SNR is the signal-to-noise ratio, k_B is the Boltzmann constant, and T_{sys} is the total noise temperature of the system.

The Center for Axion and Precision Physics Research (CAPP) of the Institute for Basic Science (IBS) was established in 2013 desiring to build state-of-the-art experiments for axion dark matter searches in Korea. A tremendous effort has been made to complete the construction of the infrastructure including low vibration pads, cryogenic systems, superconducting magnets, etc. Currently several experiments are under preparation, with one in DAQ mode. The CAPP's strategy is to operate multiple experiments in parallel targeting different mass ranges to cover as large parameter space as possible. Table 1 summarizes the equipment available at IBS/CAPP and on-going or planned experiments.

2. Axion research at CAPP

The major efforts focus on improvement of the sensitivity by enhancing the experimental parameters in the scan rate, $B_0^4 V^2 C^2 T^{-2} Q$. The following subsections describe the research activities at IBS/CAPP in detail.

2.1 Superconducting magnets

Since B_0 contributes to the sensitivity to the same power as $g_{a\gamma\gamma}$, an improvement in magnetic field strength is linearly reflected in the sensitivity to axion-to-photon coupling. CAPP is currently commissioning and procuring two high-field large-aperture superconducting (SC) magnets.

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Table 1: List of major equipment (cryogenic systems and superconducting magnets) at IBS/CAPP. The experiments are named after the magnet to be utilized. The last two rows are for upcoming equipment and planned experiments in the near future.

Refrigerator			Magnet			Experiment
Manufacturer	Model	T_B [mK]	Manufacturer	B_{max} [T]	Bore [mm]	Name
BlueFors	LD400	10				
BlueFors	LD400	10				
BlueFors	LD400	10	AMI	8	125	CAPP-PACE
BlueFors	LD400	10	AMI	8	165	CAPP-8TB
Janis	HE-3-SSV	300	Cryomagnetics	9	125	CAPP-9T MC
Oxford	Kelvinox	30	SuNAM	18	70	CAPP-18T
Leiden	DRS1000	5	Oxford	12	320	CAPP-12TB
			IBS/BNL	25	100	CAPP-25T

A 25 T/100 mm SC magnet is under development as a research project with the Brookhaven National Laboratory. The magnet consists of 28 single pancakes wound with 12 mm wide high-temperature-superconducting (HTS) REBCO tapes. It employs the no-insulation winding technique to take advantage of the self-protecting feature against quenches. This magnet is expected to be delivered in the near future for the CAPP-25T experiment as a strong booster of axion-to-photon conversion.

A 12 T/320 mm SC magnet, designed and manufactured by Oxford Instruments, is in the procurement process. Conventional low temperature superconducting cables (Nb_3Sn) are used to generate a 12 T magnetic field at the solenoid center. The large value of $B_0^2 V$ will enable us to probe the DFSZ axions in a low frequency region between 0.7 and 3 GHz. This magnet is scheduled to be delivered in early 2020 to be installed in the Leiden dilution refrigerator for CAPP-12TB, one of the ultimate experiments at CAPP.

2.2 Quantum limited noise amplifier

A Josephson Parametric Amplifier (JPA) is a non-linear superconducting quantum interference device utilizing two quantum phenomena: Josephson effect and flux quantization. It is expected to play a critical role in axion search experiments to suppress the noise temperature down to the standard quantum limit, which is given by $T_{\text{SQL}} = 48\,\text{mK} \times f$, where f is the frequency in GHz.

CAPP has recently formed a collaborative relationship with RIKEN (Rikagaku Kenkyujo) in Japan to expand the application of their JPA technology to axion searches. Some of the units were tested at CAPP to understand the characteristics, which showed reasonable gains of > 17 dB and low noise temperatures of < 300 mK at around 2.3 GHz. Comparing to conventional low noise high electron mobility transistors (HEMT), whose typical noise temperature is about 1$\sim$2 K, a significant improvement in SNR is achievable.

2.3 Superconducting cavity

Maintaining high cavity Q-factor at gigahertz frequencies is also a crucial component for increasing the sensitivity. A natural approach is to employ the SC cavity technique, which already has a wide range of application, e.g. accelerator science. However, the presence of an external magnetic field destroys the superconductivity, which limits scientific productivity in axion dark matter search. A natural choice of material for SC cavities is type-II high temperature superconductor (HTS) with high critical fields. It is found that $YBa_2Cu_3O_{7-x}$ (YBCO) is a good candidate due to its critical temperature of 92 K and field of > 100 T. We also notice that high-quality, grain-aligned YBCO tapes are commercially available. In order to take advantage of this technology, we designed a polygon-shaped cavity which consists of 12 pieces with the inner surface covered by a strip of tape. The assembly of the cavity gives rise to the TM_{010} resonant frequency of 6.93 GHz.

To measure the quality factor, the cavity was placed at the center of a 8 T solenoid and brought into a low temperature at 4 K, duing which the superconducting phase transition was observed at around 90 K. We continued the measurement while ramping up the magnet to see the effect of an external field. The initial value of the quality factor was 95,000. We observed that the quality factor suddenly dropped to 60,000 until 0.23 T and then rapidly rose to about 150,000 and maintained its value all the way up to 8 T. The sudden drop appeared to be attributed to the Ni-W9 layer of the tape, and the maximum value of 155,000 took place at around 3.5 T. This is the first demonstration that superconducting YBCO cavities show no significant degradation in quality factor under strong magnetic fields [7]. This also indicates potential applications of HTS technology to the research areas which require high fields at high radio frequencies.

2.4 High frequency approach

In haloscopes, exploring high frequency regions requires a smaller cavity size which eventually decreases the detection volume. A conventional way to overcome this defect is to bundle an array of identical cavities and combine the individual signals coherently. An in-depth study of phase-matching for multiple-cavity systems has been performed at CAPP [8]. However, since this approach is still inefficient in usage of a given magnet volume, CAPP introduces a new concept of cavity design, dubbed the pizza cavity [9].

A pizza cavity consists of a single large cavity fitting into a magnet bore with multiple identical cells split by metal partitions placed with equidistant intervals. This multiple-cell design yields an improved sensitivity compared to the conventional multiple-cavity design by a factor of two. In addition, an innovative idea of introducing a hollow gap in the middle of the cavity provides various critical advantages: 1) breaking the frequency degeneracy; 2) enabling a single pick-up antenna to extract the signal from the entire cavity volume and thereby simplifying the readout chain; and 3) facilitating the phase-matching mechanism by suppressing the coupling strength to the higher modes. An experimental demonstration using a double-cell cavity showed the stability of the tuning mechanism and a negligible DAQ dead-time owing to phase-matching, which verified that this unique design is promising for high mass axion searches.

3. Axion experiments at CAPP

The strategy of CAPP for axion dark matter searches is to run several experiments in parallel targeted at different frequency regions in order to cover as large a parameter space as possible. The following subsections describe the status of the individual experiments at CAPP.

3.1 CAPP-PACE

CAPP-PACE, a R&D machine for the CAPP-25T experiment, provides the necessary experience in dealing with comprehensive detecting systems. The major components of the experiment include an ultra-low temperature cryogenic system and a 8 T/125 mm SC magnet. The complete detector consists of a high Q-factor resonant cavity, a reliable frequency tuning system, highly sensitive cryo-RF electronics and a DAQ/control system including monitors ensuring the data quality and safe environment. The goal of CAPP-PACE lies in filling out the unexplored frequency gap by the RBF collaboration, $2.45-2.62$ GHz, with a sensitivity to the KSVZ axions. In 2018, the experiment was involved in two physics runs: one to cover the region using a receiver chain of a series of HEMT amplifiers targeting at 10×KSVZ, and the other to cover a small range (1 MHz) around 2.591 GHz with the KSVZ sensitivity. The smooth operation confirms that the experiment is ready to play a serious role in axion searches. The experiment is currently down for a major upgrade which involves the installation of a JPA and plans to be back in DAQ mode in late 2019.

3.2 CAPP-8TB

The CAPP-8TB experiment utilizes a 8 T SC magnet with a bigger bore (165 mm). Taking advantage of the large volume and relying on a single dielectric tuning system, it aims to be sensitive at a relatively low frequency region, $1.5-1.6$ GHz. A cryogenic environment below 50 mK was achieved using a dilution refrigerator. The cavity response and the system noise were well understood by intensive studies. The experiment plans to run at two stages: the first stage uses a HEMT-based detector chain to touch the theoretical QCD axion band with three month operation, while the second stage will receive a SQUID-based amplifier to reach near the KSVZ QCD axion model.

3.3 CAPP-9T MC

An experiment, named CAPP-9T MC, is currently under preparation in order to exploit the pizza cavity design described in Sec. 2.4. The experiment utilizes a wet-type He-3 cryogenic system and a 9 T SC magnet. Operation of the He-3 system in continuous (non-evaporating) mode enables us to maintain the cavity temperature below 2.0 K. Multiple-cell cavities with 110 mm inner diameter and 220 mm inner height were designed to maximize the sensitivity. A cryogenic readout chain is composed of a series of low noise HEMT amplifiers. The CAPP-MC experiment consists of three phases depending on the cell multiplicity of the detector: double-cell, quadruple-cell and octuple-cell. Each phase will explore a frequency range of $2.8-3.3$, $3.8-4.5$ and $5.8-7.0$ GHz, respectively, with a target sensitivity of 10 times the KSVZ QCD axion model.

3.4 CAPP-18T

CAPP-18T is characterized by a 18 T HTS SC magnet manufactured by a local company, SuNAM Inc. The magnet fabricated using GdBCO HTS tapes is featured by multi-width and no-insulation technologies to be robust against mechanical stress and magnet quenches, respectively.

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The performance of the magnet shows a good uniformity (93% at $z \pm 100$ mm) and stability ($<$ 0.05% for 2 weeks) of the magnetic field at full load. A smaller bore size of 70 mm leads to a cavity design sensitive to relatively high frequency regions, 3.6−4.2 GHz. The experiment will pursue a Josephson parametric converter to prospect for the KSVZ axion model in this frequency range.

4. Prospects

The first phase of the experiments at IBS/CAPP, described in Sec. 3, will prove their capability as axion haloscopes by probing different ranges of axion mass. More interesting physics is expected in the next few years by incorporating the R&D efforts, detailed in Sec. 2. The high-field/large-volume SC magnets, quantum-limited noise amplifiers, high-Q SC cavities will allow us to probe DFSZ axion physics. Furthermore, the cavity designs for efficient detection volume will extend the haloscope's sensitivity to far higher frequency regions. Figure 1 summarizes the frequency coverage and expected sensitivities by IBS/CAPP within five years.

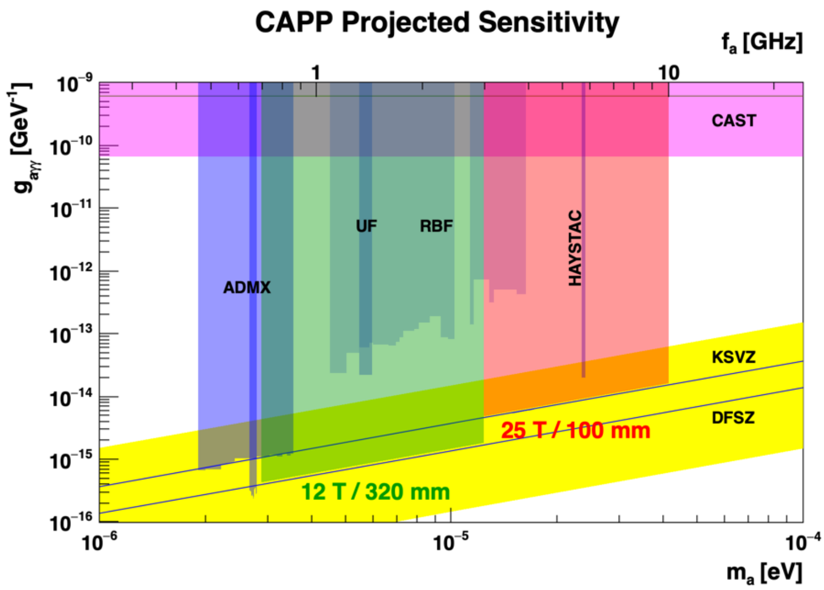

Figure 1: Projected sensitivities of the CAPP experiments in the parameter space of the axion-to-photon coupling vs. axion mass. The expected coverage regions within the next five years using the 12T/320mm and 25T/100mm SC magnets are represented by the green and red filled areas, respectively.

References

[1] R. D. Peccei and H. R. Quinn, Phys. Rev. Lett. **38**, 1440 (1977); S.Weinberg, Phys. Rev. Lett. **40**, 233 (1978); F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978).

[2] J.E. Kim, Phys. Rev. Lett. **43**, 103 (1979); M. A. Shifman, A. I. Vainshtein, and V. I. Zakharov, Nucl. Phys. B **166**, 4933 (1980).

[3] A. P. Zhitnitsky, Yad. Fiz. **31**, 497 (1980) [Sov. J. Nucl. Phys. **31**, 260 (1980)]; M. Dine, W. Fischler and M. Srednicki, Phys. Lett. B **104**, 199 (1981).

[4] J. Preskill, M.B. Wise and F. Wilczek, Phys. Lett. B **120**, 127 (1983); L. F. Abbott and P. Sikivie, Phys. Lett. B **120**, 133 (1983); M. Dine and W. Fischler, Phys. Lett. B **120**, 137 (1983).

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

[6] A. Matlashov, M. Schmelz, V. Zakosarenko, R. Stolz, Y. K. Semertzidis, Cryogenics, **91**, 125 (2018).

[7] D. Ahn *et al.*, arXiv:1904.05111 (2019).

[8] J. Jeong., S.W. Youn, S. Ahn, C. Kang and Y. K. Semertzidis, Astropart. Phys. **97** 33 (2017).

[9] J. Jeong, S. Youn, S. Ahn, J.E. Kim, and Y. K. Semetrzidis, Phys. Lett. B. **777**, 10 (2018).