PROCEEDINGS OF SCIENCE

CAPP's axion data with frequency range from 2.45 to 2.75 GHz

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CAPP's flagship axion experiment, CULTASK, employs dilution refrigerators to lower the physical temperature of resonant cavities to less than 40 mK - the coldest ever for axion search. We prepared a complete set of the microwave axion detector (CAPP-PACE) equipped with an 8 T superconducting magnet with 12 cm inner bore in order to search for axions with frequency around 2.5 GHz. The frequency tuning system installed in a split-design resonant cavity with a high Q-factor utilizes piezoelectric actuators with interchangeable sapphire and copper rods and performs flawlessly in searching a wide range of axion mass. The feeble signal ($\sim10^{-24}$ W) from the cavity is amplified and transmitted through the RF receiver chain, specially designed to minimize the noise temperature of the system employing an 1 K HEMT or a quantum-limited SQUID (Superconducting Quantum Interference Device) amplifier in order to raise the sensitivity and eventually speed up the axion search. I will present the results of CAPP's first physics data runs in the axion mass range from 2.45 to 2.75 GHz and discuss our future plans and R&D projects.

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1. Introduction

CAPP has built an axion research facility at the KAIST (Korea Advanced Institute of Science and Technology) Munjji Campus in Daejeon, Korea in the beginning of 2016 with 7 low vibration pads (LVP). We have now 7 refrigerators and 5 superconducting magnets installed in the facility and 4 low temperature microwave axion dark matter detectors are operating on LVP. All of our axion detectors are designed to reach very low physical temperature (mK range for resonant cavities), so we call our axion research, CULTASK (CAPP's Ultra Low Temperature Axion Search in Korea).

The final goal of the CAPP's axion research program is to prove or disprove axions as dark matter once and for all. The powerful (25 T, 10 cm bore) and the big bore (12 T, 32 cm) superconducting magnets which will be delivered in 2020 should be able to boost axion-to-photon conversion power and enable us to explore the wide range of axion masses with enough sensitivity to detect or exclude axions when combined with highly sensitive quantum amplifiers whose noise performance approaches the fundamental limits imposed by the laws of quantum mechanics. These are the technologies that never existed or weren't mature enough 10 years ago.

CAPP-PACE, started as a R&D machine to prepare for the CAPP25T axion experiment, would provide the necessary experience in ultra-low temperature cryogenics, the fabrication of high Q-factor resonant cavities, a reliable frequency tuning system, highly sensitive cryo-RF electronics and a DAQ/control system including monitors ensuring the quality of data and safe environment of data taking. The CAPP-PACE detector has grown into a complete axion detector in the beginning of 2018 and we are now testing every aspect of the axion dark matter experiment in around 2.5 GHz frequency range while taking physics data.

2. CAPP-PACE: Detector Setup

The main elements of the CAPP-PACE detector are BluFors LD400 cryogen-free dilution refrigerator (DR) system with an 8 T superconducting magnet, a resonant cavity with a frequency tuning system and a cryogenic RF receiver chain to read out the power spectrum from the cavity.

The DR system was installed on one of the low vibration pads constructed with one of seven 20 ton concrete block each supported by four air springs to eliminate external vibrations. The microwave resonant cavity hangs in the center of the magnet bore supported by a copper structure, thermally anchored to the DR's mixing plate which is maintained at $T_{MX} \sim 25$ mK (cavity at $T_{CAVITY} \sim 40$ mK) during the operation of the detector. The goal of the cryogenic system is to provide enough cooling power to lower and maintain the physical temperature of the resonant cavity and components of the cryo-RF receiver chain as much as possible to ensure the minimal system noise (mainly from amplifiers in our frequency range).

The 118 mm bore of the AMI 8 T superconducting (NbTi) magnet sets the scale for the available axion-sensitive volume. The outer diameter of the cavity was limited to 100 mm by placing a gap of 9 mm between inner bore of the magnet and the outer wall of the cavity and the thickness was designed to be 5 mm, enough to reduce the risk of breakage due to the smooth nature of the copper. The cavity height was 93 mm to make sure the average magnetic field intensity is maintained at 7.9 T, but has been redesigned to 180 mm (average field intensity of 7.6 T) to maximize the axion-sensitive volume and eventually to increase the scanning efficiency.

The conventionally designed cavity with lid(s) and a cylinder has usually a contact problem (electric) because of the inevitable gaps that cause the Ohmic loss. One of CAPP-PACE research team's early R&Ds was to employ a vertically split cavity which solves contact issues completely and produces reliable measurement of higher Q-factors all the time. CAPP-PACE has applied this design to all cavities during experimental runs to date and achieved very stable Q-factors. The Q-factor measurement agrees with the theoretical prediction within an error range of 1%. The frequency tuning system (FTS) installed in a split-design resonant cavity utilizes piezoelectric actuators with interchangeable sapphire and copper rods and performs flawlessly in searching a wide range of axion mass.

The RF receiver chain inside the refrigerator, especially from a resonant cavity to the first amplifier is carefully designed to provide as little noise (mostly from the first amplifier) as possible. The monopole antenna to pick up the signal from the cavity is made of copper to minimize the attenuation and the rest of the connection to the first amplifier is through NbTi superconducting cables which usually has a very small attenuation of less than 0.5 dB per meter. The circulators are used to block the Johnson Nyquist noise coming from amplifiers and also to block the reflection of the signal.

Two cryogenic switches are used to provide the option to choose a HEMT or an MSA SQUID as the first amplifier and also to make accurate noise temperature measurements *in situ* utilizing DR's MXC and still plates as hot and cold noise sources. Our "cold terminator method" noise measurement of the whole receiver chain shows the noise temperature between 1 K and 1.2 K depending on the frequency.

3. CAPP-PACE: Data Runs

Since January of 2018, CAPP-PACE has been taking physics axion dark matter data around an axion mass of 10 μeV, scanning from the microwave cavity's resonant frequency of 2.45 GHz through 2.75 GHz with the sensitivity of 10*KSVZ, and recently around 2.60 GHz with the sensitivity all the way down to KSVZ, where each run during the experiment takes about 17 hours between frequency steps.

The analysis procedure we follow builds upon the works of ADMX[2] and HAYSTAC[3] mainly, but some simplifications are employed due to the current limitations of our setup. The general procedure for the analysis is to remove the baseline from the spectrum, normalize them and then vertically and horizontally combine to get a grand spectrum.

Our analysis methods are currently being updated to incorporate Monte-Carlo simulations as well, which will help us establish confidence intervals and mitigate any systematic errors that can be found in the analysis. The axion data taking with KSVZ[4][5] sensitivity is in progress. Figure 1 shows the final spectrum and the estimated SNR for ongoing KSVZ sensitivity experiment. Note that the estimated design parameter matches with our design goal (SNR = 5).

4. R&D Projects and Future Plans

The CAPP-PACE axion detector is also equipped with the capability of using SQUID amplifiers instead of HEMT amplifiers. The optimization study for SQUID amplifiers is in progress right

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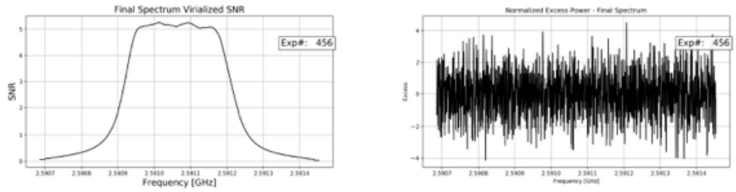

(a) (b)

Figure 1: (a) Virialized SNR for the final spectrum (b) Normalized excess for our final spectrum

now. Once we are confident that the noise temperature of the SQUID amplifier reaches below 1 K, it will replace the 1 K HEMT amplifier and eventually speed up the axion search experiment. Figure 2 shows how much we could speed up the axion search if the system noise temperature shrinks down. On top of that, when the 25 T HTS magnet replaces the conventional 8 T magnet in 2020, we should be able to increase the scanning speed by two orders of magnitude.

T(K)	Scan rate (Hz/s) [KSVZ]	10MHz scan (year) [KSVZ]	10MHz scan (month) [KSVZ]	1year scan range (MHz) [KSVZ]
0.2	6.98	0.045	0.55	220
0.4	1.75	0.18	2.18	55.0
0.8	0.44	0.73	8.73	13.8
1	0.28	1.1	13.63	8.8
1.2	0.19	1.6	19.63	6.1
4	0.017	18.2	218.06	0.55

Figure 2: Scanning speed vs. system temperature

As an R&D project, we also studied the possibility of using superconducting resonant cavities in a high magnetic field to raise Q-factors by sputtering thin layer of NbTi and applying YBCO tapes to the inner surface of a cavity. Another R&D project in progress is replacing tuning rods with dielectric rings to be able to explore axions with higher masses.

5. Acknowledgments

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