PROCEEDINGS OF SCIENCE

Search for the axion dark matter in the mass range of 6.62 - 6.82 μeV

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The axion is a hypothetical particle associated with the spontaneous symmetry breaking of the $U(1)$ symmetry, proposed by Pecci and Quinn to resolve the Charge-Parity (CP) problem in quantum chromodynamics. For invisible axions, cosmological and astrophysical observations impose the lower and upper limits on axion mass of μeV and meV respectively. The axion in such a mass range could be a promising candidate for the cold dark matter. The CAPP-8TB experiment searches for the axion by detecting photons, produced by the axion-photon coupling, resonating in a microwave cavity. The experiment has recently obtained a result of axion search in the mass range of 6.62–6.82 μeV. At the 90 % confidence level we probed the QCD axion down to a theoretical boundary, which is the most sensitive experimental result in the specific mass range to date. In this paper we will explain the detail of the experimental setup, parameters and analysis procedure. A plan for the next phase of the experiment for different mass ranges will also be discussed.

40th International Conference on High Energy physics - ICHEP2020
July 28 - August 6, 2020
Prague, Czech Republic (virtual meeting)

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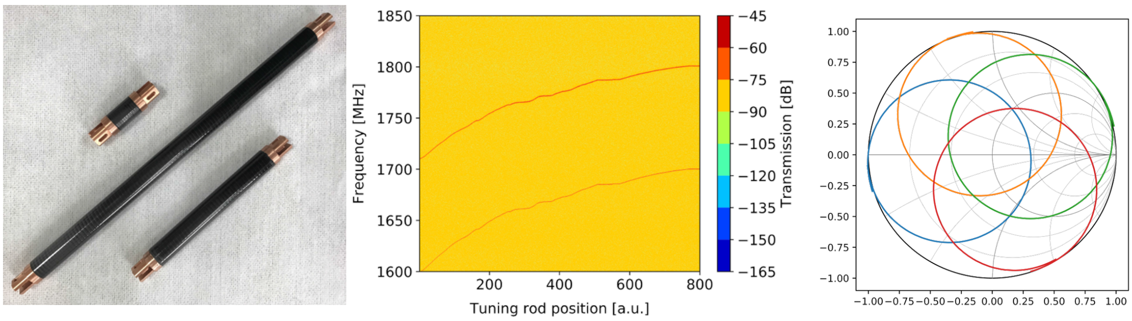
PoS(ICHEP2020)623

The CAPP-8TB experiment [1] is searching for axion, a hypothetical particle originally postulated by Peccei and Quinn as a solution of the Strong CP problem [2]. The axion in a particular mass range is also one of the most promising candidates for the cold dark matter [3, 4]. Although the early models of axion at the electroweak scale were ruled out, the two benchmark models known as Kim-Shifman-Vainshtein-Zakharov (KSVZ) [5, 6] and Dine-Fischler-Srednicki-Zhitnitskii (DFSZ) [7, 8] are still widely discussed to date. The axion in the models is called the invisible axion in terms of its extremely weak coupling and small mass. Sikivie suggested [9] an experimental method of searching the invisible axion, by using a microwave cavity in a strong magnetic field. The axion is resonantly converted to a photon in the condition, and the conversion power is expressed as,

$$P_a^{a\gamma\gamma} \propto g_{a\gamma\gamma}^2 B^2 V C Q_L \frac{\beta}{1+\beta}$$

where $g_{a\gamma\gamma}$ is the coupling strength of the axion, B is the magnetic field, V, C, Q_L are the volume, form factor and loaded quality factor of the cavity respectively, and β is the coupling coefficient of the antenna. The experiment aimed to search axion in a mass range of 6.62 - 6.82 μeV equivalent to 1.6 - 1.65 GHz, with sensitivity to axion-photon coupling down to around the QCD axion band [12].

The cavity is designed to be a cylinder with 134 mm in inner diameter and 246 mm in inner height, in favor of volume usage inside a cylindrical magnet bore. With such dimensions the TM_{010} mode of the cavity has the resonance frequency of 1.712 GHz. The cavity was made of oxygen-free high conductivity copper, and the quality factor of TM_{010} mode was measured to be around 110,000 at 50 mK. For the purpose of reducing eddy current heating in the presence of a high magnetic field, the side wall of the cavity was cut vertically and split into two identical pieces.



(a) (b) (c)

Figure 1: (a) CFRP tubes. (b) Mode map of the cavity with frequency tuning mechanism, lines denote QTM_{010} (lower) and QTM_{011} (upper) modes respectively. (c) Typical Smith chart of reflection coefficient from the strong antenna.

A dielectric rod was placed inside the cavity in order to tune the resonance frequency of TM_{010} mode. A stepper motor was installed on top of the system at room temperature to rotate the tuning rod. The motor at room temperature and the tuning rod at the base temperature of the refrigerator are connected with tubes made of carbon fiber reinforced polymer (CFRP) (Fig. 1a), known to have very low thermal conductivity. As a result, the Quasi-TM_{010} (QTM_{010}) mode frequency is able to be tuned from 1.43 GHz to nearly 1.7 GHz. No mode crossing was found from the measurement in the frequency range as shown in Fig. 1b. The antenna coupling was obtained by a least square circle fitting of the Smith chart around the resonance. Firstly the reflection coefficient was calibrated, then the coupling was deduced from the diameter d of the circle as [13],

$$\beta = \frac{d}{2-d}.$$

For the tuning of antenna coupling, a room temperature linear stepper motor was installed and for the same reason mentioned earlier, CFRP tubes were employed to connect the motor and the antenna.

A superconducting solenoid magnet, with 165 mm magnet bore diameter and 8 T of maximum field was used for the experiment. The form factor is defined as,

$$C = \frac{|\int dV \mathbf{B} \cdot \mathbf{E}|^2}{B_{avg}^2 V \int dV \epsilon |\mathbf{E}|^2}$$

where $\mathbf{E}$ is the electric field of the cavity mode, $\mathbf{B}$ is the external magnetic field, B_{avg} is the average magnetic field in the cavity volume, and ϵ is the dielectric constant. The electric field profile of the QTM_{010} mode was obtained from simulation [10]. A magnetic field profile provided by the manufacturer was used, in order to get a more realistic result including misalignment of the fields. As a result the form factor was calculated as shown in Fig. 2, and the average magnetic field inside the cavity volume was found to be 7.3 T.

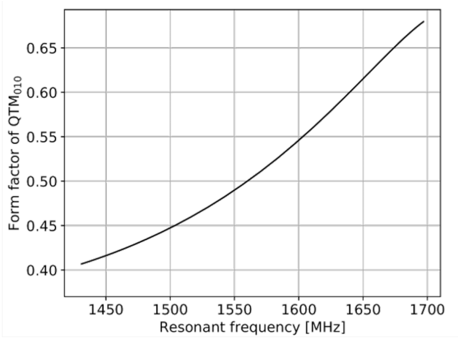


Figure 2: Form factor of QTM_{010} mode.

Signals from the cavity coupled to the antenna were amplified by two cryogenic low noise amplifiers (LNA) at 1 K and 4 K stage of the refrigerator respectively, then amplified again by the room temperature electronics (Fig. 3). The major contribution to the total system noise temperature is the noise added by LNA at 1 K stage, which is typically around 1 K. To measure the total system noise temperature and the total gain of the receiver chain, we used the cavity as a noise source. The total gain of the receiver chain is,

$$G = \frac{P_h - P_c}{k_B B (T_h - T_c)}$$

where k_B is the Boltzmann constant, B is the resolution bandwidth of the spectrum analyzer, and P_c and P_h are the noise powers on resonance measured at $T_c = 50$ mK, $T_h = 200$ mK of the cavity temperatures respectively. Then the noise temperature can be obtained by fitting each

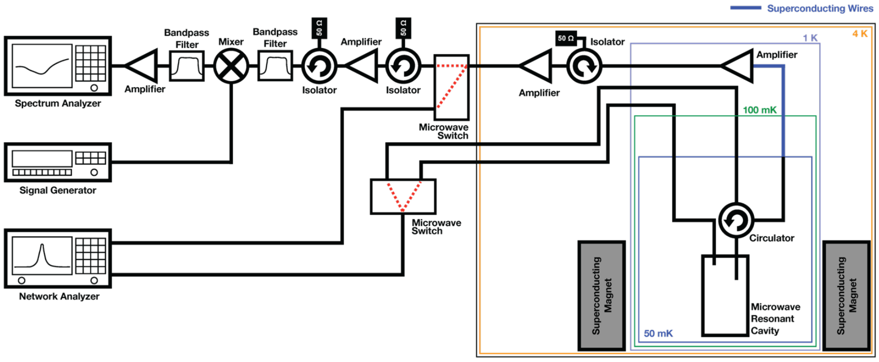
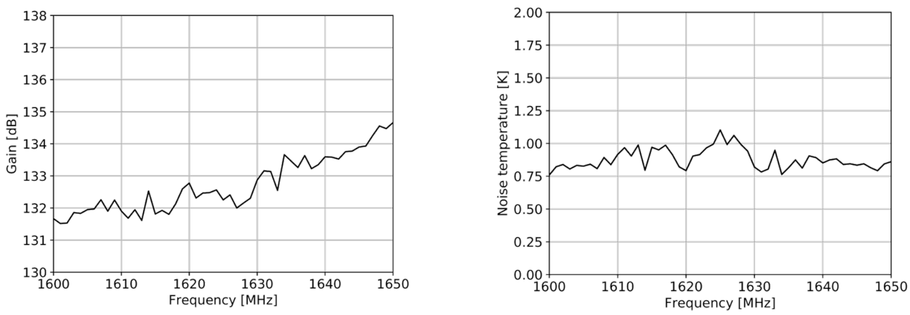


Figure 3: Schematics of the entire receiver chain in the CAPP-8TB experiment.



(a) **(b)**

Figure 4: (a) Total gain and (b) system noise temperature of the CAPP-8TB receiver chain.

spectrum with the five parameter fit function [11]. The total noise temperature of the system and the total gain of the chain was then obtained as shown in Fig. 4. For the measurements, the resonance frequency was tuned with 1 MHz step to get 51 points in the frequency range of 1.6 - 1.65 GHz. Physical temperatures of the amplifiers were maintained during the measurements.

The resolution bandwidth and the frequency span of the spectrum analyzer were chosen to be 20 Hz and 60.48 kHz respectively for the data acquisition. In total, 12,000 spectra were averaged at each step, and the step size was decided to be 20 kHz resulting in 2501 steps in 50 MHz of the total scan range. With the particular frequency span and the frequency step size, three individual spectra overlap the frequency bins throughout the scan range. During the scan, the coupling coefficient of the strongly coupled antenna was tuned to 1.9 ± 0.1. The efficiency of the data acquisition was typically about 46 %.

In the beginning of the data analysis we merged five neighboring bins in each spectrum. The baseline of the data was modeled as the five parameter fit function [11]. Narrow peaks in the data exceeding the threshold corresponding to 4.5 σ were removed and the baseline was fitted repeatedly until no excess to remove is found. After that, five neighboring bins were merged again

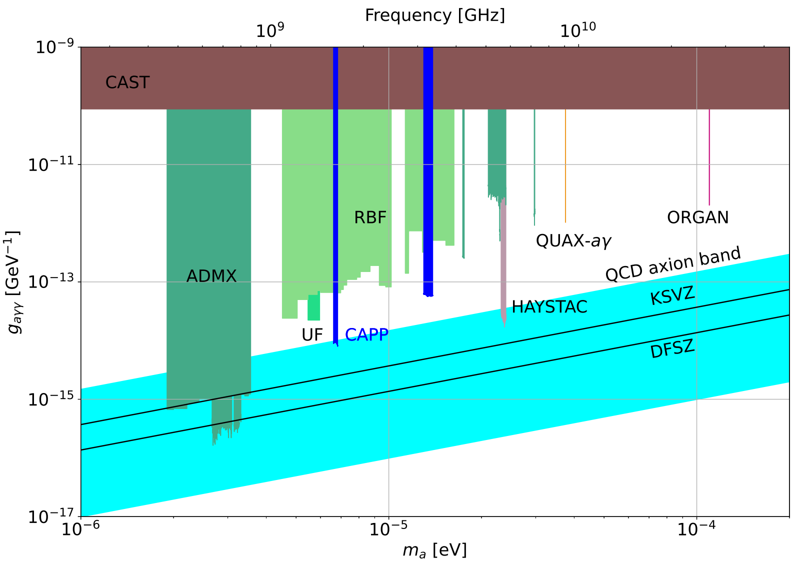


Figure 5: Excluded regions in the parameter space by this work (around 6.7 μeV [15]), CAPP (around 13.4 μeV [23]), ADMX [16], UF [17], RBF [18], HAYSTAC [19], QUAX-aγ [20], ORGAN [21] and CAST [22], together with the theoretical expectations of KSVZ [5, 6] and DFSZ [7, 8] models wit the uncertainty band [12].

to have 500 Hz of bin size. The data subtracted by the resultant baselines and normalized by the uncertainties followed the standard normal distribution. The overlapping data from individual baseline subtracted spectra at the same frequency were combined to construct a single spectrum throughout the frequency range. The single spectrum of the data also followed the standard normal distribution. In the combined single spectrum, groups of ten adjacent bins were weighted by the axion signal shape [14] and co-added.

The correlation coefficient matrices among the frequency bins co-added, were obtained from a Monte-Carlo simulation of 5000 experiments. Consequently the grand spectrum were constructed again with the correlation matrices taken into account, and after the normalization the power excess followed the standard normal distribution. 36 bins in the grand spectrum after the procudure, exceeded the threshold of 3.718 σ corresponding to the 90 % confidence bound for the axion signal with SNR=5. For those bins we rescan with much heavier number of spectra, and all were excluded at the end.

Fig. 5 shows the excluded region of this work at a 90 % confidence level [15]. So far, the result is the most sensitive in the particular range of the axion mass. The experiment is currently in preparation for a frequency range of 1.5 - 1.6 GHz.

This work was supported by IBS-R017-D1-2020-a00.

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