First axion dark matter search with toroidal geometry

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We, the Institute for Basic Science Center for Axion and Precision Physics Research report the first axion dark matter search with toroidal geometry. In this pioneering search, we exclude the axion-photon coupling $g_{a\gamma\gamma}$ down to about 5×10^{-8} GeV^{-1} over the axion mass range from 24.7 to 29.1 μeV at the 95% confidence level.

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1. Introduction

More than 80% of the content in the Universe is believed to be cold dark matter (CDM) and dark energy according to precision cosmological measurements [1]. One of the most compelling candidates for CDM is the axion [2] provided its mass is above 1 μeV [3] and below 3 meV [4]. The axion search method proposed by Sikivie [5], also known as the axion haloscope search, involves a microwave resonant cavity with a static magnetic field that induces axion conversions into microwave photons. The present state of the axion haloscope employs a cylindrical resonant cavity in a solenoidal field. But we introduced toroidal resonant cavity for axion search instead of cylindrical cavity. A toroidal geometry offers several advantages, two of which are a large volume for a given space and greatly reduced fringe fields which interfere with our amplifiers. In this pioneering search, we exclude the axion-photon coupling $g_{a\gamma\gamma}$ down to about 5×10^{-8} GeV^{-1} over the axion mass range from 24.7 to 29.1 μeV at the 95% confidence level.

2. Experiment

We refer to this axion dark matter search as **ACTION** for "**A**xion haloscopes at **C**APP with **T**oro**I**dal res**ON**ators." The ACTION experiment constitutes a tunable copper toroidal cavity, toroidal coils which provide a static magnetic field, and a typical heterodyne receiver chain. The experiment was conducted at room temperature. As shown in Figure 1, R is the distance from the center

Critical Coupling   R   Hoop for Frequency Tuning   R

Current Supply

R = 40 mm , r = 20 mm
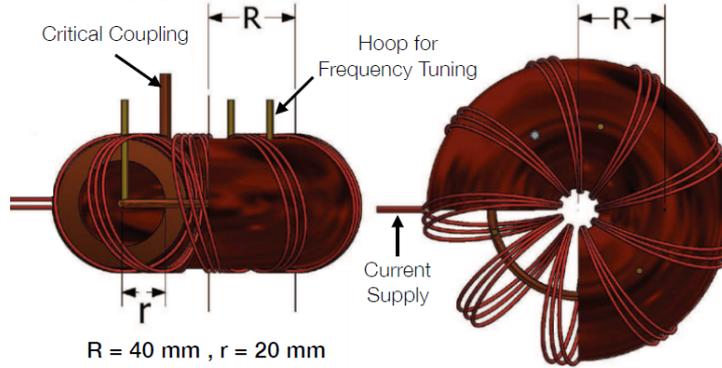
Figure 1: Lateral (Left) and top (right) views of the toroidal cavity, frequency tuning system, and toroidal coils whose dimension are given in the text. Note that it is a cut-away view to show up details of the system.

of the torus to the center of the tube and r is the radius of the tube. Our cavity tube's R and r are 40 and 20 mm, respectively, and the cavity thickness is 10 mm. The frequency tuning system can be moved up and down by the piezo actuator. As a result, it provides a resonance frequency range of about $6 \sim 8$ GHz.

A static magnetic field was provided by a 1.6 mm diameter copper wire ramped up to 20 A with three winding turns, as shown in Fig. 1. Figure 2 shows good agreement between measurement with a Hall probe and a simulation [6] of the magnetic field induced by the coils. The B_{avg} from the magnetic field map provided by the simulation turns out to be 32 G. No fringe magnetic fields are outside of an ideal toroidal magnet, and as shown in Fig. 2, the magnetic field outside of our
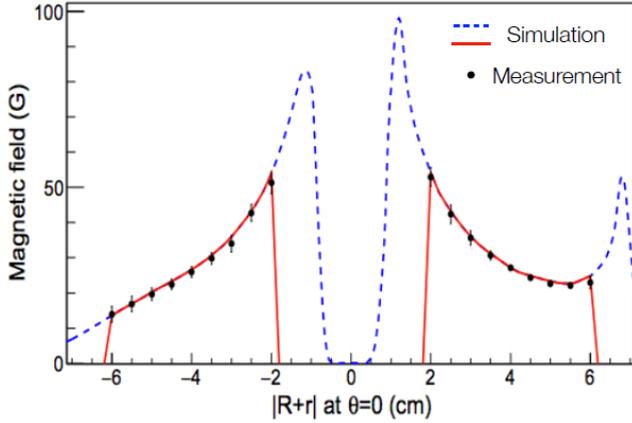
Figure 2: Magnetic field as a function of radial position $|R+r|$ at $\theta = 0$. Dashed blue lines are obtained from the finite element method and correspond to the toroidal cavity system, and solid red line correspond to the cavity tube. Dots with error bars are measurement values. The results at positive $R+r$ are along a coil, while those at negative $R+r$ are between two neighboring coils.

toroidal magnet system also drops drastically, as expected.

Our receiver chain consists of a single data acquisition channel which is analogous to that adopted in ADMX [7] except for the cryogenic parts. Power from the cavity goes through RF components, is then measured by a spectrum analyzer. Cavity associates, ν and Q_L are measured with a network analyzer by toggling microwave switches. The gain and noise temperature of the chain were measured to be about 35 dB and 400 K taking into account all the attenuation in the chain, for the frequency range from 6 to 7 GHz, as reported in Ref. [8].

3. Conclusion
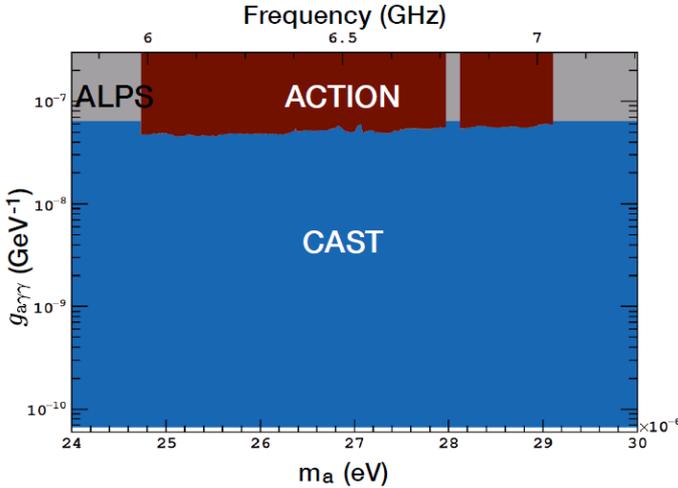
Figure 3: Excluded parameter space at the 95% C.L. by this experiment together previous results from ALPS [9] and CAST [10]. No limits are set from 6.77 to 6.80 GHz due to with a quasi-TE mode in that frequency region [8].

Figure 3 shows the excluded parameter space at a 95% C.L. by the simplified ACTION experiment. We demonstrate an axion haloscope with toroidal geometry and our result supersedes the pre-existing exclusion limits reported by ALPS [9] in the relevant mass ranges.

The goal of this experiment was a demonstration of an axion haloscope with toroidal geometry. We expect to reach of sensitivity of the KSVZ [11] and DFSZ [12] models by using larger-scale toroidal geometries with cooling in the future, as shown in Ref. [8]. This work was supported by IBS-R017-D1-2017-a00.

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References

[1] P. A. R. Ade *et al.* (Planck Collaboration), Astron. Astrophys. **594**, A13 (2016).

[2] S. Weinberg, Phys. Rev. Lett. **40**, 223 (1978); F. Wilczek, Phys. Rev. Lett. **40**, 279 (1978).

[3] 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).

[4] John Ellis and K. A. Olive, Phys. Lett. B **193**, 525 (1987); Georg Raffelt and David Seckel, Phys. Rev. Lett. **60**, 1793 (1988); Michael S. Turner, Phys. Rev. Lett. **60**, 1797 (1988); Hans-Thomas Janka, Wolfgang Keil, Georg Raffelt, and David Seckel, Phys. Rev. Lett. **76**, 2621 (1996); Wolfgang Keil, Hans-Thomas Janka, David N. Schramm, Günter Sigl, Michael S. Turner, and John Ellis, Phys. Rev. D **56**, 2419 (1997).

[5] P. Sikivie, Phys. Rev. Lett. **51**, 1415 (1983); Phys. Rev. D **32**, 2988 (1985).

[6] CST EM Studio, CST-Computer Simulation Technology.
https://www.cst.com

[7] H. Peng *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **444**, 569 (2000).

[8] J. Choi, H. Themann, M. J. Lee, B. R. Ko, and Y. K. Semertzidis, Phys. Rev. D **96**, 061102 (2017).

[9] K. Ehret, M. Frede, S. Ghazaryan, M. Hildebrandt, E. A. Knabbe, D. Kracht, A. Lindner, J. List, T. Meier, N. Meyer, D. Notz, J. Redondo, A. Ringwald, G. Wiedemann, and B. Willke, Phys. Lett. B **689**, 149 (2010).

[10] V. Anastassopoulos *et al.* (CAST Collaboration), Nature Physics **13**, 584-590 (2017).

[11] J. E. Kim, Phys. Rev. Lett. **43**, 103 (1979); M. A. Shifmann, A. I. Vainshtein, and V. I. Zakharov, Nucl. Phys. B **166**, 493 (1980).

[12] A. R. Zhitnitskii, Yad. Fiz. **31**, 497 (1980) [Sov. J. Nucl. Phys. **31**, 260 (1980)]; M. Dine, W. Fischler, and M. Srednicki, Phys. Lett. B **140**, 199 (1981).