LLNL-PROC-751450

LAWRENCE
LIVERMORE
NATIONAL
LABORATORY

The First Experimental Results from the Axion Dark Matter Experiment Generation 2

N. Woollett, G. Carosi, N. Du, N. Force, R. Khatiwada, E. Lentz, R. Ottens, L. J. Rosenberg, G. Rybka, D. Bowring, A. S. Chou, A. Sonnenschein, W. Wester, C. Boutan, N. S. Oblath, R. Bradley, E. J. Daw, A. V. Dixit, J. Clarke, S. R. OKelley, N. Crisosto, J. R. Gleason, S. Jois, P. Sikivie, I. Stern, N. S. Sullivan, D. B. Tanner, G. C. Hilton

May 16, 2018

Rencontres de Moriond
La Thuile, Italy
March 10, 2018 through March 17, 2018

Disclaimer

This document was prepared as an account of work sponsored by an agency of the United States government. Neither the United States government nor Lawrence Livermore National Security, LLC, nor any of their employees makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States government or Lawrence Livermore National Security, LLC. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States government or Lawrence Livermore National Security, LLC, and shall not be used for advertising or product endorsement purposes.

First Experimental Results from the Axion Dark Matter Experiment Generation 2

N. Woollett* & G. Carosi
Lawrence Livermore National Laboratory, Livermore, California, 94550, USA

N. Du, N. Force, R. Khatiwada, E. Lentz, R. Ottens, L.J. Rosenberg, G. Rybka
University of Washington, Seattle, Washington 98195, USA

D. Bowring, A.S. Chou, A. Sonnenschein, W. Wester
Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA

C. Boutan, N.S. Oblath
Pacific Northwest National Laboratory, Richland, Washington 99354, USA

R. Bradley
National Radio Astronomy Observatory, Charlottesville, Virginia 22903, USA

E.J. Daw
University of Sheffield, Sheffield S3 7RH, United Kingdom

A.V. Dixit
University of Chicago, Illinois 60637, USA

J. Clarke, S.R. O'Kelley
University of California, Berkeley, California 94720, USA

N. Crisosto, J.R. Gleason, S. Jois, P. Sikivie, I. Stern, N.S. Sullivan, D.B. Tanner
University of Florida, Gainesville, Florida 32611, USA

G.C. Hilton
National Institute of Standards and Technology, Boulder, Colorado 80305, USA

The QCD axion is a consequence of the Peccei-Quinn solution to the Strong-CP problem and also provides a compelling dark matter candidate in the μeV to meV mass range. The first run of the Axion Dark Matter Experiment (ADMX) Gen 2 campaign has searched for QCD axions with mass in the few μeV range with sensitivity to the DFSZ model. This proceeding will discuss how cryogenic operating conditions with ultra-low-noise RF SQUID amplifiers have enabled this achievement.

1 Introduction

Modern physics describes the world as we see it with astounding precision. However this level has lead to the discovery of anomalies which were not initially evident: dark matter and the strong CP problem are two such anomalies.

Dark matter was first hinted at through the observation of galaxy rotation curves. It was observed that the velocities of stars orbiting a galactic centre are higher than would be expected based on a Keplarian orbit. One solution to this is to surround the galaxy in a halo of gravitationally interacting matter[1], which is otherwise sterile to explain it's non-observation, otherwise referred to as dark matter. Additional support for the existence of a form of non-interacting matter comes through observing the gravitational lensing produced by galaxies and clusters. When the amount of lensing is estimated based on the luminous matter in a cluster the result is an underestimate of what is observed. In addition, colliding clusters separate out the luminous and dark matter with the dark matter being visible through its lensing; this results in images like the now well known bullet cluster false colour image.

Within the QCD Lagrangian the strong force has a term which allows it to violate charge parity symmetry which is given by

$$L_\theta = \theta \frac{g^2}{32\pi^2} G_{a\mu\nu} \tilde{G}^{\mu\nu}_a, \tag{1}$$

where G is the gluon field strength tensor and g is the coupling constant. The degree to which the strong force can violate CP symmetry is encapsulated in the θ term which can take any value between 0 and 1. A consequence of CP violation is that the neutron would possess a measurable electric dipole moment due to the separation of charge between the quarks expected to be on the order of 10^{-18}e cm. The measured the upper limit for the neutron electric dipole moment has been set at 10^{-26} e cm, posing a fine tuning problem on the parameter θ [2].

2 The Axion

The axion comes about from the Peccie and Quinn solution to the strong CP problem[3] in which the parameter θ is treated as a dynamic field which can be initially set to any value but through spontaneous symmetry breaking allowed to relax to a minima such as that which we see today. It was pointed out by Wienberg[4] and Wilszek[5] that there would be a new particle associated with this new field. This particle would be a psuedo-scalar which possesses a coupling to two photons[6] which is described by

$$\mathcal{L}_{A\gamma\gamma} = -g_{a\gamma\gamma} \mathbf{E} \cdot \mathbf{B} \, \phi_A, \tag{2}$$

where $\mathbf{E}$ and $\mathbf{B}$ are from the standard model electomagnetic field and ϕ_A is the axion field. The parameter $g_{a\gamma\gamma}$ is the coupling of the axion to a two-photon interaction and the magnitude of this number is proportional to the mass of the axion within a given model. This means that while the axion could theoretically take any mass, for a given mass there is a small range of couplings which are likely. Within the community the KSVZ and DFSZ have traditionally been used to bound the QCD axions coupling but there are models outside of this range which are still possible. A broader range of particles known as axion-like particles, ALPs, also exist but they do not follow the mass to coupling proportionality.

3 Axion Haloscopes

The axion has a small mass and a weak coupling to the standard model, making it difficult to search for with collider style experiments. A number of alternate techniques have been suggested but to date the haloscope-style experiments have produced the most sensitive searches. The design was first proposed by Sikivie in 1983[7].

The principal of operation is that the dark matter axions act as the source of the axions and since they are coherent over lengths of kilometres they can be treated as a classical field. The detector is immersed in a magnetic field which provides the virtual photons for conversion. The photons produced from the conversion are captured in a microwave cavity which allows the power to build up to a detectable level. The presence of the cavity means that the experiment is sensitive only to axions within the bandwidth of the cavity. Consequently a tuning mechanism is required to allow the cavity resonance and therefore search mass to be shifted.

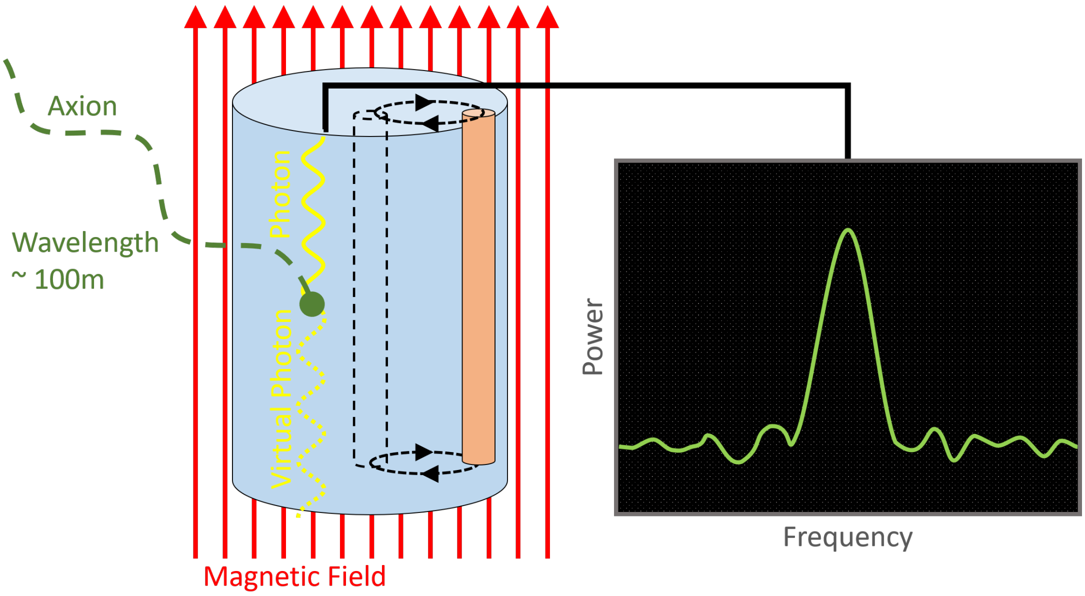

Figure 1 – Schematic of a haloscope experiment. The axions are provided by the dark matter background. The magnetic field provides the virtual photons for Primakoff conversion. The signal which is extracted would appear as a power excess over the background noise.

The open axion mass range is many decades wide and therefore the ability to scan frequency quickly is important. The time taken to reach a desired signal to noise is given by the Dickie radiometer equation

$$\mathrm{SNR} = \frac{P_{\mathrm{signal}}}{k_B T} \cdot \sqrt{\frac{t}{\Delta f}}. \tag{3}$$

The power from the axion field, P_{signal}, is proportional to the cavity properties and the form-factor for the detection cavity resonance

$$P_{\mathrm{signal}} \propto B^2 V Q_{\mathrm{cav}} C_{\mathrm{mode}}, \tag{4}$$

where B is the magnetic field, V is the cavity volume, Q_{cav} is the quality factor of the cavity and C_{mode} is the form-factor. The magnetic field is usually in the form of a solenoidal field to provide a uniform field direction within the cavity: in ADMX a 7 T field was used. The Q is a function of the cavity material. Since there are currently no superconductors capable of operating in a 7 T field annealed OFC copper is used. The form-factor is given by the dot product of the electric field of the cavity and the magnetic field; consequently the majority of modes have a negligible form-factor as can be seen in Fig. 2, but the fundamental mode of the cavity gives a form-factor ≈ 0.67. Due to the presence of a tuning mechanism in ADMX a form-factor of order 0.4 is typical.

The cavity design is not the only controllable part of the experiment which affects the scan rate; the noise temperature of the system is largely dictated by the design of the readout chain. The noise temperature is the temperature of a black body required to produce the thermal noise equivalent to that which is being observed; it is used as a proxy for the noise power of the system. The way noise powers are combined is using the Friis temperature equation

$$T_{\mathrm{obs}} = T_{\mathrm{Phys}} + T_1 + \frac{T_2}{G_1} + \frac{T_3}{G_1 G_2} + \ldots \tag{5}$$

The result of this is that the noise contribution of components later in the readout chain is reduced by the product of the gain of each preceeding stage. In practice this means that

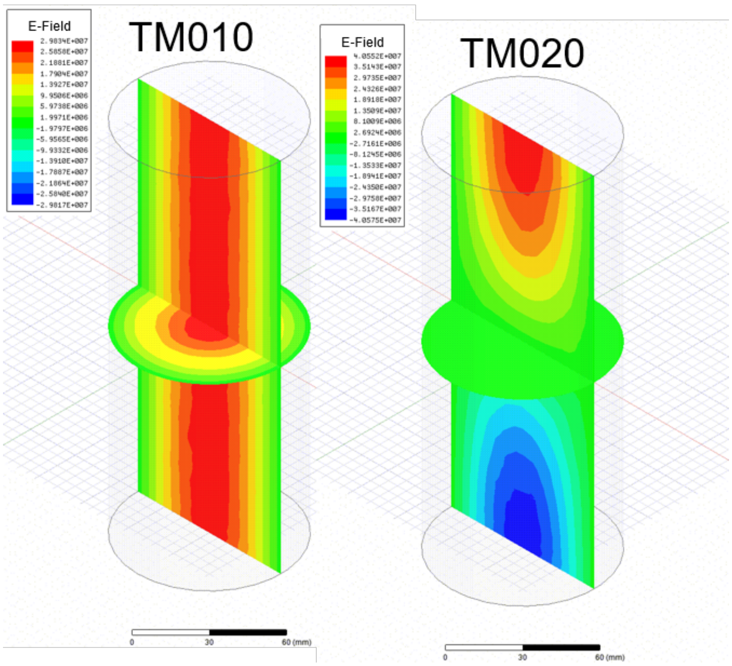

Figure 2 – Simulated mode structure of a bare pillbox cavity with the colour indicating the magnitude of the field in the 'z' direction. If we consider the dot product of both modes with a uniform magnetic field it is that the result will be a net positive in the case of the TM010 mode. However for the TM020 mode the lobes at the top and bottom of the cavity will cancel out resulting in a form-factor of 0.

the lowest noise amplifiers should be closest to the signal source. In ADMX we use tunable micro-strip SQUID amplifiers developed by the Clarke group at Berkeley, which approach the quantum limit when operated below 100 mK and provide 20 dB of amplification over a 400 MHz range.

The physical temperature of the system, T_{Phys} acts as a irreducible noise source. This is dominated by the temperature of the resonant cavity, and so a custom built dilution fridge is used to cool the cavity and quantum electronics. The quantum amplifier adds T_1 of noise and any further stage is reduced by its gain, G_1 making their contribution minimal.

When these factors are taken into account the integration time required per frequency bin is on the order of 1000 s. The integration time is split across several integration periods between which the cavity resonance is moved a tenth of a bandwidth, thereby avoiding discontinuities in the data due to uncertainty in the tuning motion. In addition to the integration time there are a number of RF measurements required for verification which are performed between each step, leading to an experimental cadence of approximately 2 minutes per position.

4 Results

We searched the range of mass between 645 - 680 MHz for axion signals between January 18, 2017 and June 11, 2017. The consequence of optimizing for an efficient scan speed enabled us to achieve a signal-to-noise ratio sufficient to be sensitive to DFSZ axions. No statistically significant signals were observed. A detailed discussion of the results can be found in the April 2018 publication[8].

Acknowledgments

This work was supported by the U.S. Department of Energy through Grants No. DE-SC0009723, No. DE-SC0010296, No. DE-SC0010280, No. DE-SC0010280, No. DEFG02-97ER41029, No. DE-FG02-96ER40956, No. DEAC52-07NA27344, and No. DE-C03-76SF00098. Fermilab is a

U.S. Department of Energy, Office of Science, HEP User Facility. Fermilab is managed by Fermi Research Alliance, LLC (FRA), acting under Contract No. DE-AC02-07CH11359. Additional support was provided by the Heising-Simons Foundation and by the Lawrence Livermore National Laboratory and Pacific Northwest National Laboratory LDRD offices.
LLNL-PROC-751450

References

1. J. H. Oort. Some problems concerning the structure and dynamics of the galactic system and the elliptical nebulae ngc 3115 and 4494. *Astrophysical Journal.*
2. P. Schmidt-Wellenburg. The quest to find an electric dipole moment of the neutron. 2016.
3. R. D. Peccei and Helen R. Quinn. CP conservation in the presence of pseudoparticles. *Phys. Rev. Lett.*, 38:1440–1443, Jun 1977.
4. Steven Weinberg. A New Light Boson? *Phys. Rev. Lett.*, 40:223–226, 1978.
5. Frank Wilczek. Problem of Strong p and t Invariance in the Presence of Instantons. *Phys. Rev. Lett.*, 40:279–282, 1978.
6. H. Primakoff. Photoproduction of neutral mesons in nuclear electric fields and the mean life of the neutral meson. *Phys. Rev.*, 81:899, 1951.
7. P. Sikivie. *Experimental Tests of the Invisible Axion*, volume 51, pages 1415–1417. 1983. [Erratum: Phys. Rev. Lett.52,695(1984)].
8. N. Du et al. Search for Invisible Axion Dark Matter with the Axion Dark Matter Experiment. *Phys. Rev. Lett.*, 120(15):151301, 2018.