Search for High Frequency Dark Matter Axions

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August 22, 2014

Abstract

Ground-based dark matter searches such as those performed by the Axion Dark Matter eXperiment (ADMX) can test the viability of the axion as a dark matter candidate. Open resonator technologies can allow ADMX to search for axions at higher frequencies than can be done conveniently with a closed cavity. The Orpheus prototype experiment demonstrates that open resonators can place limits on the axion coupling to two photons. Initial results from Orpheus constrain the axion coupling to be less than 4×10^{-7} for axions between 68.2 and 76.5 μeV.

1 Motivation

Abundant cosmological and astronomical evidence demonstrates that a considerable fraction of the universe is composed of dark matter. The axion, the pseudoscalar boson predicted as a consequence of the Peccei-Quinn solution to the Strong CP problem, is a well-motivated dark matter candidate [1]. Axions couple to two photons through an intermediate fermion loop.

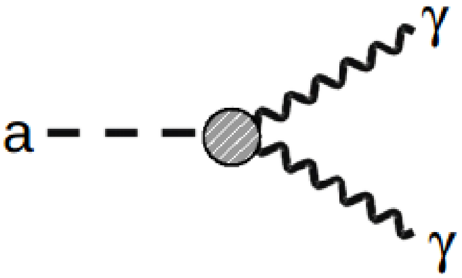

Figure 1: A Feynman diagram of the axion decay into two photons. Theory-dependent axion-fermion interactions are suppressed.

The Lagrangian of the axion-photon interaction is given by [2]

$$\mathcal{L}_{axion} = \frac{1}{2}(\partial_\mu a)^2 + \frac{1}{2}m^2 a^2 - \frac{g_{a\gamma\gamma}}{4\pi} a\mathbf{E}\cdot\mathbf{B}$$

Axion detection is possible using an instrument called an axion haloscope, which takes advantage of the axion decay into two photons [3]. In an axion haloscope, a strong applied magnetic field converts axions into photons which are registered as power in a detector. The measurement is enhanced by placing the experiment in a tunable microwave resonant cavity.

When the cavity is tuned to a particular frequency, the power deposited in the cavity due to the interactions of axions at that frequency is given by

$$P = 2.2 \times 10^{-23}\ \mathrm{W}\left(\frac{V_{eff}}{1000\ \mathrm{cm}^3}\right) \times \left(\frac{B}{1\ \mathrm{T}}\right)^2 \left(\frac{\rho}{0.45\ \mathrm{GeV}\cdot\mathrm{cm}^{-3}}\right) \times \left(\frac{f}{100\ \mathrm{GHz}}\right)\left(\frac{\min(Q, 10^6)}{10^5}\right)$$

where V_{eff} is the effective volume of the resonator, B the magnetic field strength, ρ the density of dark matter, f the axion frequency, and Q the resonator quality factor [4]. Therefore, to ensure maximum signal in the cavity, the applied magnetic field should be made perpendicular to the electric field in the cavity for the resonance mode under consideration.

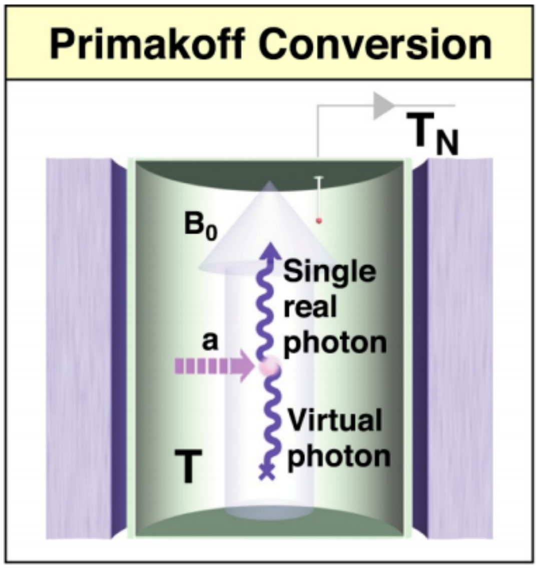

Figure 2: A representation of an axion haloscope, in which a virtual photon realized by a magnetic field with strength B_0 interacts with an ambient axion in the detector to produce a real photon. The noise observed in the experiment depends on the temperature T in the cavity as well as the noise temperature T_N of the detector setup.

2 Experimental Technique

The Axion Dark Matter eXperiment (ADMX) has conducted axion searches sensitive to dark matter axions between 1 and 40 μeV [5]. However, axions with masses between 40 μeV and 10 meV have also been theorized to fit the criteria to be dark matter. A closed resonant cavity such as that at ADMX is not optimally adapted to study axions at high frequencies, as Q and cavity volume decrease with frequency, decreasing the signal power.

An open resonator design provides a method to study high frequency axions that avoids these difficulties [6]. In this setup, which is similar to that of a Fabry-Pérot resonator, an electric field with a particular resonant frequency is produced between two reflectors, one curved and one flat. In a microwave Fabry-Pérot resonator, the electric field of the TEM_{00n} mode takes the form of a sine wave along the axis and a Gaussian radially [7]. In order to maximize the signal power, the sign of the applied magnetic field must match that of the electric field in the resonator. To accomplish this, wire planes are placed inside the resonator at locations corresponding to the nodes of the magnetic field at the approximate axion frequency. The current though alternating wire planes travels in alternating directions, causing the magnetic field between each pair to switch sign.

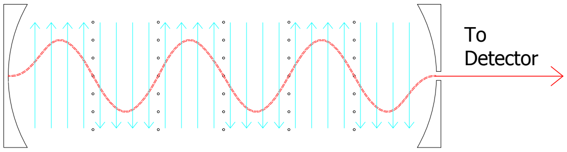

Figure 3: A schematic diagram of the open resonator used in the Orpheus experiment. A series of current-carrying wireframes causes the magnetic field to align with the electric field in the resonator.

The resonator can be tuned in two ways. First, the quality factor can be maximized for a given frequency range by placing the wire planes at the half-wavelength positions corresponding to the nodes at the center frequency of that range. Second, the resonator can be tuned so that the resonance peak occurs at a particular frequency by adjusting the distance between the two reflectors.

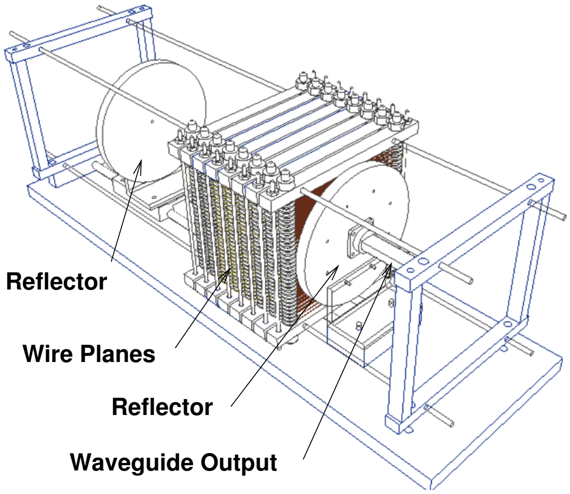

Figure 4: A CAD model of the open resonator used in the Orpheus experiment, showing the positions of the two reflectors and eight wire planes.

In the Orpheus experiment, data was acquired over two frequency ranges, 16.5-17.5 GHz and 17.5-18.5 GHz. For each set of runs, the wire planes were spaced in the resonator using washers to align with the half-wavelength positions for 17 GHz and 18 GHz, respectively. For each run, the position of the curved reflector was adjusted to align the center frequency of the resonance peak with the target frequency for that run.

3 Data Acquisition

An data acquisition program was written in Python to automate the process of taking data. It was set up to tune the resonance and take data in 3 MHz intervals within a given frequency range, and save all data to a local database.

All instruments used in the experimental setup were connected to a single computer using an ethernet switch. A power source supplied a current of 3.5 A through the wire planes throughout the duration of setup and data taking. An HP 8757E Scalar Network Analyzer along with an 83620A Synthesized Sweeper was used to tune the resonator.

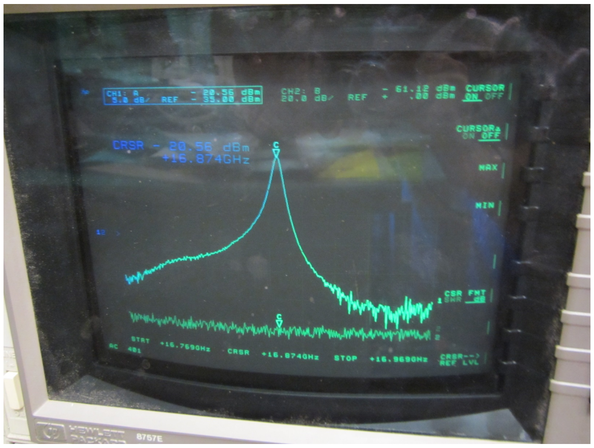

Figure 5: A photograph of the display of the HP 8757E network analyzer using for measuring the cavity resonant frequency. The plot on the screen shows power transmission vs. frequency, with a peak occuring at the resonant frequency.

First, the data acquisition program connected to the network analyzer, switched on the RF signal from the synthesized sweeper at the target frequency, and obtained the current location of the resonance peak in MHz. Using this information, it controlled an Applied Motion 23S-2EE stepper motor to adjust one of the reflectors in order to tune to the new resonance. Once the resonance was tuned, a spectrum was downloaded from the network analyzer and fitted to a Lorentzian, returning values for the resonance center, height, and Q.

If the center was not within 1 MHz of the target, the stepper motor would be used to adjust the resonator again. If the resonance parameters failed to satisfy physical constraints, an error was noted and data acquisition would proceed to the next target frequency. Otherwise, if the resonant frequency was sufficiently close to the target, the RF source was turned off, and data taking would start.

To take the data, the data acquisition program connected to an Agilent N9000A CXA spectrum analyzer set to IQ analyzer mode. A power spectrum measurement was taken over a 10 MHz span with 1024 averages. Once the measurement was complete, the spectrum was uploaded to a database. This process was then repeated for each target frequency. In cases in which the automated data-taking program skipped over a particular frequency, data for that frequency were taken manually.

4 Analysis

The two sets of runs, from 16.5-17.5 GHz and 17.5-18.5 GHz, were analyzed separately. Each set's spectra were processed one by one and combined to create a spectrum over the entire frequency range.

First, the raw data were rebinned with bin size 0.0165 MHz so that each bin approximately corresponded to the axion bandwith at 17 MHz. The edges of each spectrum were removed so that only the center 6.7 MHz of each 10 MHz scan was used, since the uncertainty increases at the edges of each scan. The noise was then removed from each spectrum by normalizing the mean of each spectrum's power to the noise temperature of the system, determined to be 1420 K, and subtracting that noise temperature.

Next, large-scale structure due to the receiver transfer function of the spectrum analyzer was removed from each spectrum by fitting each spectrum to a fifth-order polynomial and dividing out the fit. The predicted axion coupling $G_{a\gamma\gamma}$ was then calculated for each point in the spectrum using the measured power, resonator effective volume, magnetic field strength, and the Q and center frequency for that run. The effective volumes for each run were calculated by combining a model of the electric field in the resonator with a model of the applied magnetic field, while the magnetic field strength for all runs was measured to be 8.5 gauss.

The predicted axion couplings for each run were then combined into a global spectrum for an entire 1 GHz bandwidth.

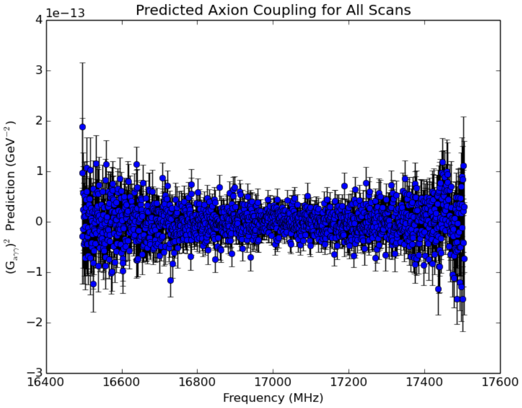

Figure 6: Predicted axion coupling for each frequency in the first scan, from 16.5 GHz to 17.5 GHz. Non-physical negative coupling values are predicted where the power due to random fluctuations about the noise temperature falls below the mean. In these cases, the predicted axion coupling is treated as zero when placing limits.

Since no axion peaks were observed in the spectrum, limits were placed on the axion coupling in the frequency range between 16.5 and 18.5 GHz (68.2 to 76.5 μeV).

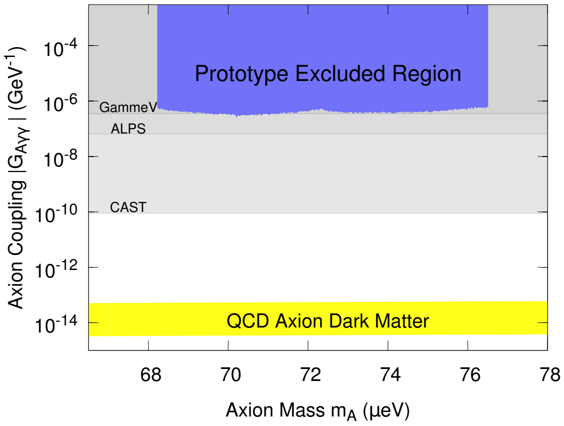

Figure 7: Plot of the exclusion limits placed on the axion coupling to two photons by the Orpheus prototype experiment. For comparison, limits from the laser-based GammeV and ALPS experiments, as well as from the solar axion search CAST, are also shown.

The axion coupling to two photons was constrained to be less than 4×10^{-7} with 95% confidence.

5 Conclusions

Open resonators have the potential to extend ADMX's reach to explore higher axion frequency ranges. The initial run of the Orpheus prototype experiment has excluded axion-photon couplings greater than 4×10^{-7} for axions between 68.2 and 76.5 μeV.

With improvements, open resonators should be able to be made sensitive to QCD dark matter axions. Increasing the magnetic field by upgrading to superconducting wire, decreasing the noise temperature by performing the experiment at cryogenic temperatures, improving the resonator quality factor by using better reflectors, and increasing the effective volume of the resonator offer sensitivity improvements that when combined allow a predicted sensitivity of 10^{-14}.

The Orpheus experiment demonstrates that open resonators represent a feasible method for finding or excluding high frequency dark matter axions.

6 Acknowledgements

I would like to thank my REU advisor, Dr. Gray Rybka, as well as Dr. Andrew Wagner, for their guidance and support this summer. I would also like to thank Dr. Leslie Rosenberg and the ADMX collaboration, including the three undergraduates, Kunal Patel, Robert Perceival, and Katleiah Ramos, who also worked on Orpheus with me.

I am grateful to Dr. Subhadeep Gupta, Dr. Alejandro Garcia, Dr. Shih-Chieh Hsu, Linda Vilett, and Janine Nemerever for running and organizing the REU. Finally, I would like to acknowledge the support given by the National Science Foundation for funding the REU program and the US Department of Energy for funding ADMX.

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