

Mississippi State Axion Search: A Light Shining though a Wall ALP Search

Prajwal Mohanmurthy¹, Dipangkar Dutta², Joseph Formaggio¹, Nicholas Fowler², Mikhail Gaerlan², Yipeng Jiang², John Madsen², Noah Oblath¹, Adam Powers², Amy Ray², Robertson Riehle²

MASS Collaboration

¹Laboratory for Nuclear Science, MIT, 77 Mass. Ave., Cambridge, MA 02139, U.S.A.

²Physics Department, Mississippi State University, Mississippi State, MS 39762-5167, U.S.A.

DOI: http://dx.doi.org/10.3204/DESY-PROC-2014-03/mohanmurthy_prajwal

The elegant solutions to the strong CP problem predict the existence of a particle called axion. Thus, the search for axion like particles (ALP) has been an ongoing endeavor. The possibility that these axion like particles couple to photons in presence of magnetic field gives rise to a technique of detecting these particles known as light shining through a wall (LSW). Mississippi State Axion Search (MASS) is an experiment employing the LSW technique in search for axion like particles. The apparatus consists of two radio frequency (RF) cavities, both under the influence of strong magnetic field and separated by a lead wall. While one of the cavities houses a strong RF generator, the other cavity houses the detector systems. The MASS apparatus looks for excesses in RF photons that tunnel through the wall as a signature of candidate axion-like particles. The concept behind the experiment as well as the projected sensitivities are presented here.

1 Introduction

The axion was proposed to solve the strong CP problem [1]. Axions have been proposed as a good cold dark matter candidate [2]. In addition to other super-symmetric dark matter candidates, axions are included as dark matter constituents especially in super symmetric extensions of the standard model [3].

A single parameter, the axion decay constant, f_a is sufficient to describe the physics of axions.

$$f_a = 6 \times 10^{-6} eV \frac{10^{12} GeV}{m_a} \quad (1)$$

where m_a is the mass of the axion. Axions and ALPs are characterized by small masses arising from the shift symmetry of the ALP

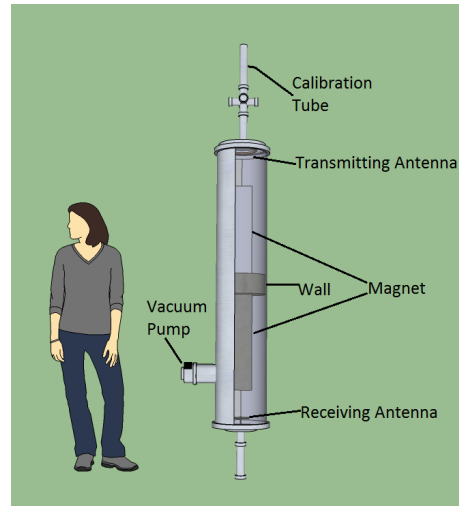


Figure 1: Basic schematic diagram of the MASS apparatus

field, $\phi(x)$. The shift symmetry $\phi(x) \rightarrow \phi(x) + \text{const.}$ prohibits explicit mass terms ($\propto m_\phi^2 \phi^2$) in the ALP Lagrangian. The only way an ALP field could interact with standard model particles is via derivative couplings ($\propto \partial\phi/f_a$). This significantly suppresses their interactions below the f_a scale, effectively making ALPs weakly interacting sub-eV particle (WISP) candidates [4]. Furthermore, the two most relevant two photon couplings can be written for both pseudo-scalar and scalar ALPs respectively as;

$$\mathcal{L}_{\phi^{+(-)}\gamma\gamma} = -\frac{g_{+(-)}}{4} F_{\mu\nu} \tilde{F}^{\mu\nu} \phi^{+(-)} \quad (2)$$

where, $F_{\mu\nu}$ is the electromagnetic field, $g_{+(-)} = g_\gamma(\alpha/\pi f_a)$, $g_\gamma \approx -0.97$ in Kim-Shifman-Vainshtein-Zacharov (KSVZ) model [5] or $g_\gamma \approx -0.36$ in Dine-Fischler-Srednicki-Zhitnitskii (DFSZ) model [6], and α is the fine structure constant.

2 Method

In the MASS experiment, Primakoff effect is employed to put the LSW technique to test where the incident photon couples with the magnetic field to create lightly interacting ALPs which pass through a barrier, regenerating to photons on the dark side of the barrier, while ideally no photons pass through the barrier. The regenerated photons have the same characteristics as the incident photons, *i.e.* they are of the same frequency, phase and couple to the same electromagnetic mode. Since photons are regenerated via an ALP, the rate of regeneration (R) is given by [7];

$$R = N_\gamma \epsilon_c Q_d P_{\gamma \rightarrow ALP} P_{ALP \rightarrow \gamma} \quad (3)$$

$$P_{\gamma \rightarrow ALP} = P_{ALP \rightarrow \gamma} = \left(\frac{gB}{2\omega} \right)^2 \text{Sin}^2 \left(\frac{m^2 L}{4\omega} \right) \quad (4)$$

where N_γ is the number rate of photons, ϵ_c is photon capture efficiency, Q_d is the detector quantum efficiency, $P_{\gamma \rightarrow ALP}$ is the probability of conversion of a photon to a scalar ALP, $P_{ALP \rightarrow \gamma}$ is the probability of conversion of a scalar ALP to a photon, g is the coupling constant, m is the mass of the ALP, B is the magnetic field strength, ω is the energy of the photons and L is the length of the cavity under magnetic field.

3 Apparatus

The MASS apparatus consists of two tunable evacuated cavities as shown in Figure 1. These two cavities are mutually isolated. The ‘‘light’’ cavity houses a StreakHouse TM transmission

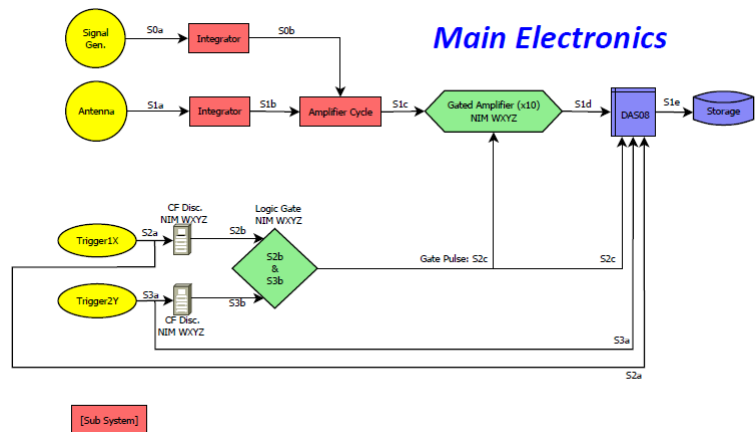


Figure 2: Schematic diagram showing the fast electronics in line before the data is written to disk.

antenna [8], capable of transmitting integral multiples of 410 MHz and the “dark” cavity houses an antenna capable of mapping local field in all three spatial axes. A compact dipole magnet bathes the two cavities in a magnetic field in the radial direction while a solenoid is used to create a magnetic field along the axis of the cavities (Z-direction). The radial magnetic field produced by the dipole magnet was mapped using a DPPH (Di-Phenyl Picryl Hydrazyl) probe and is presented in Figure 3. The solenoid is only used to tune the cavity and thereby has a low field strength output (< 0.5 T). The transmission antenna is mounted at the end of a calibration tube, precise to within 1 nm which allows for additional fine tuning of the cavity. The other end of the calibration tube provides for a number of electronic feed thoughts. Feed through for the receiving antenna electronics is completely separated from the feed through for the main transmission antenna.

The cavities are usually tuned simultaneously to TM_{010} and TM_{020} where the most fundamental mode corresponds to 410 MHz. About 120 W of RF power is dumped into the “light” cavity through the transmission antenna. The transmission power gives a measure of number rate of photons, N_γ , in Eq. (3). A precise measurement of the standing wave ratio (SWR) of the receiving antenna gives a measure of the product of photon capture efficiency and its quantum efficiency, $\epsilon_c Q_d$, in Eq. (3).

MASS experiment employs a redundant frequency lock-in technique to control signal to noise ratio in the apparatus. The primary signal is generated using a 16-bit programmable digital oscillator which is then amplified a number of times to reach 120 W of continuous transmission power. Both the receiver signal and the primary signal are rectified, integrated and normalized (hereby referred to as processed) such that their difference is ideally null except in the case of there being a regenerated photon (Figure 2). Processing involves continuous rectification which converts all negative components to positive. Furthermore, the rectified signal is integrated over 1 ms before the running integrand is reset to zero. The regenerated photons show up as small excesses in the running integrand at the end of the corresponding 1 ms time period. Integrating the receiver signal also reduces the amount of digitized data by a factor of 410×10^3 , since the primary signal is 410 MHz and the integrated signal has a frequency of 1 kHz due to the integration time period being 1 ms. The difference between the processed primary signal and the processed receiver signal has the same frequency and phase information as that of the processed primary signal, therefore the processed primary signal also serves as the reference for the three SR 530 [9] lock-in amplifiers. The difference of the processed receiver signal and the processed primary signal is then subject to three sets of SR 530 lock-in amplifiers which use the processed primary signal as a reference providing a signal to noise ratio better than 10^{18} accounting for residual thermal noise and quantum fluctuations.

The processed and amplified receiver signal is then digitized and written to disk. A set of trigger antenna within the apparatus located around the “dark” cavity pickup on external

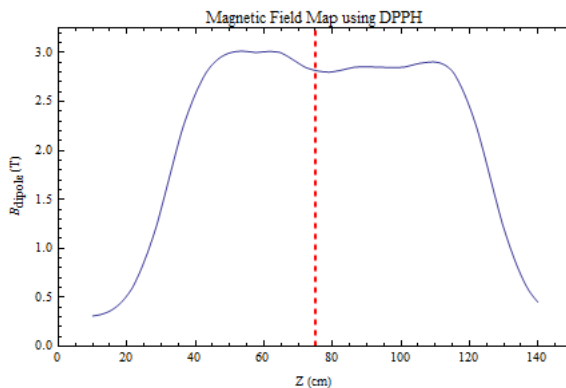


Figure 3: Plot showing the dipole magnetic field profile in the 2 cavities used in MASS. On the left hand side of the red line is the “light” cavity and on the right hand side of the red line is the “dark” cavity.

noises and creates a gate during which time the processed and amplified primary signal is not written to disk.

4 Conclusion

Taking into account the inhomogeneity of the magnetic field, the characteristics of the two main antennae, residual RF field on the “dark side of the cavity” and the thermal noise, all of which contribute to the uncertainty in measured rate of regenerated photons, the possible sensitivity of MASS to scalar and pseudo scalar ALPs is calculated using Eq. (3) & (4), as presented in Figure 4. It might be important to note that since the exclusions that MASS can provide for scalar and pseudo scalar ALPs are similar to each other, Figure 4 has plotted the sensitivities to two different cavity modes, each a multiple of the fundamental frequency of 410 MHz, both of which are accessible in the MASS apparatus.

Even though the sensitivity that MASS can provide in the low mass regime ($10 \mu\text{eV}$ - $100 \mu\text{eV}$) for both scalar and pseudo scalar ALPs will only be comparable to the currently available limits, and not any better, it shall demonstrate the feasibility of using the LSW technique with RF photons.

Acknowledgement

The authors would like to thank Dr. Torsten Clay for his help with setting the group up at the High Performance Computing Collaboratory, the resources of which are used for simulation and analysis. This work is supported by the Mississippi State Consortium and the Jefferson Science Associates through the Thomas Jefferson National Accelerator Facility.

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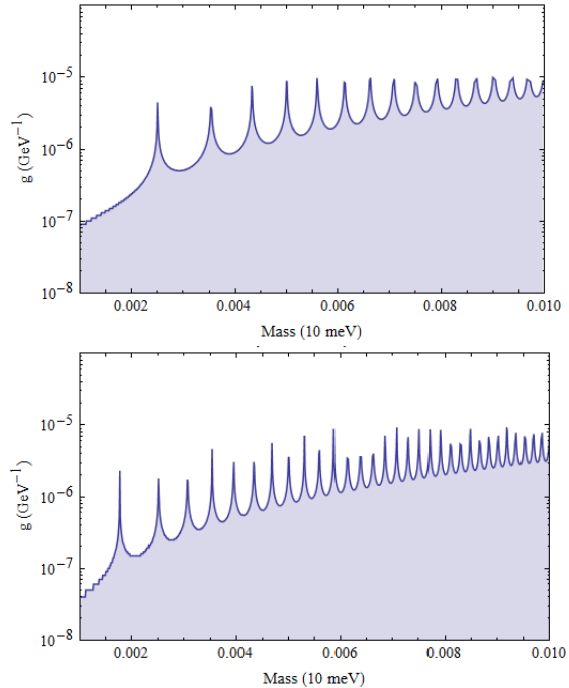


Figure 4: (Top) Plot showing the sensitivity of MASS to scalar ALPs when the cavities are tuned around 410 MHz with a C.L of 95%. (Bottom) Plot showing the sensitivity of MASS to pseudo-scalar ALPs when the cavities are tuned around 820 MHz with a C.L of 95%.