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Status and Future of ADMX – the U.S. Microwave Cavity Axion Search Experiment

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STATUS AND FUTURE OF ADMX - THE U.S. MICROWAVE CAVITY AXION SEARCH EXPERIMENT

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I report on the status of the Axion Dark-Matter Experiment (ADMX), the microwave-cavity-based axion search underway at Lawrence Livermore National Laboratory. The ADMX collaboration includes LLNL, the University of Florida, and M.I.T., and has been in operation since February, 1996.

1. Introduction

To date, the most efficient method of searching for dark matter axions comprising the halo of our galaxy is the microwave cavity technique originally proposed by Sikivie[1]. In a static background magnetic field, axions will decay into single photons via the Primakoff effect. The energy of the photons is equal to the rest mass of the axion with a small contribution from its kinetic energy, hence their frequency is given by:

$$h\nu = m_a c^2 \big(1 + O(10^{-6})\big) \tag{1}$$

At present, the allowed mass range of axions is $1 - 1000\ \mu eV$. At the lower end of this axion window, the frequency of the photons lies in the microwave regime. A high-Q resonant cavity, tuned to the axion mass will enhance the conversion process as well as serve as the detector for the converted photons. The expected signal power normalized to typical experimental parameters is[1,2]

$$P_{a\rightarrow\gamma} \approx 10^{-21} W \left(\frac{B}{7.7T}\right)^2 \left(\frac{V}{200l}\right) \left(\frac{C}{0.65}\right) \left(\frac{Q}{90000}\right) \left(\frac{\nu}{0.7\ GHz}\right) \left(\frac{\rho_a}{\rho_{halo}}\right) \tag{2}$$

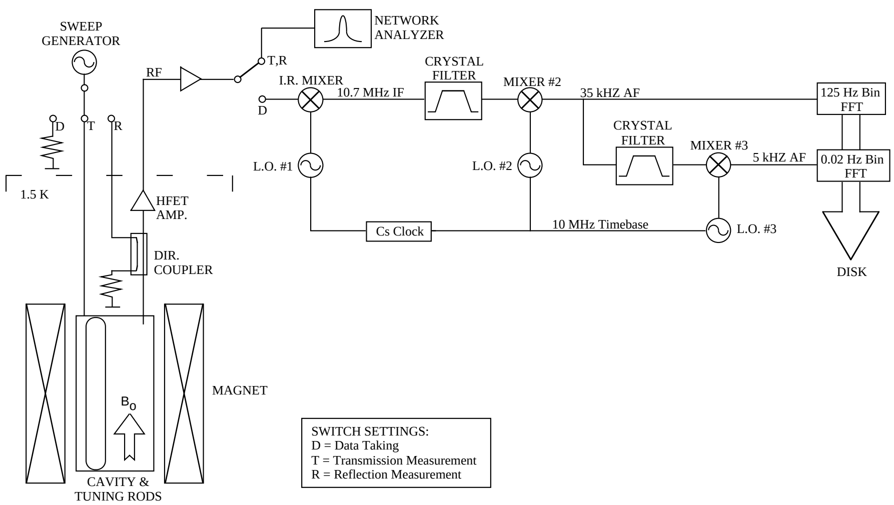

Figure 1. Schematic of the ADMX experiment.

where B is the background magnetic field, V is the cavity volume, C is a mode dependent form factor, Q is the loaded quality factor, f is the resonant frequency, and ρ_a is the local halo axion density. For the parameters of this experiment, the power from KSVZ axions is typically 5×10^{-22} W.

Since the axion mass is unknown, the frequency of the cavity must be tunable. For a given signal-to-noise ratio (SNR) the scanning rate is:

$$\frac{d\nu}{dt} \approx \left(\frac{25MHz}{month}\right)\left(\frac{4}{SNR}\right)^2\left(\frac{6\ K}{T_s}\right)^2 \qquad (3)$$

where $T_s = T_c + T_a$ is the system noise temperature, specifically the sum of the physical temperature of the cavity T_c and the noise temperature of the amplification chain T_a.

2. Present Experiment and Results

Figure 1 is a schematic of the ADMX apparatus showing the magnet, cavity, cryogenic amplifiers, and receiver electronics.

The magnet is a superconducting NbTi solenoid. It is a low current (224 A), high inductance (533 H) design to maximize field stability, which serves to minimize eddy current heating of the cavity. The operating field at the center of the coil is typically 7.62 - 8.0 T.

The microwave cavity is a right-circular cylinder constructed from stainless steel and plated with ultra-high purity, oxygen-free copper. Annealing the cavity after plating increased the conductivity of the copper. The inside diameter is 50 cm and the length is 1 m. Superfluid ^{4}He maintains the physical temperature of the cavity near 1.5 K.

To maximize the form factor from (2), the cavity electric field should be parallel to the static, external magnetic field. The TM_{010} mode has the highest form factor ($C \approx 0.5 - 0.6$), and is therefore used in the search. For this mode, the resonant frequency of the empty cavity is 460 MHz, and the unloaded Q is approximately 200,000.

Moving a combination of metal and dielectric rods, running the full length of the cavity changes the resonant frequency. These rods can move from the center of the cavity to the wall. The single cavity accommodates two rods. Stepper motors with a resolution of 1.8°/step followed by a gear reduction of 42000:1 control the rods. The final step size is approximately 80 nm and the resulting frequency tuning precision is approximately 500 Hz at a cavity frequency of 500 MHz.

The cryogenic amplifiers used in this search are double-balanced GaAs HFET amplifiers supplied by NRAO.[3] The *in situ* measured noise temperatures range from 1.7 - 4.5 K. Cascading two of these amplifiers achieves sufficient gain (35 dB) to render downstream noise contributions negligible.

The amplifiers are capacitively coupled to the cavity using a short length of low thermal conductivity semi-rigid coax. The strength of the coupling is varied by changing the insertion depth. Critical coupling is maintained throughout the run, meaning that on resonance the cavity presents a matched load to the first amplifier.

Figure 1 also shows the two major components of the room temperature electronics, the setup for measuring transmission through the cavity and the receiver electronics.

Before data is taken at a given frequency, a transmission measurement is made. For the measurement, power is fed through a second, very weakly coupled port in the cavity and the transmitted power is measured using a scalar network analyzer. A fit of the transmission curve to the sum of a Lorentzian and constant background determines the resonant frequency and Q.

The receiver is simply an extremely sensitive radio receiver with the cavity as the LC tank circuit. First, the 35 dB cryogenic amplification described earlier is followed by 35 dB of room-temperature post-amplification. Next, the signal passes through an image-reject mixer shifting the resonant frequency down to 10.7 MHz. From there, an oven-stabilized, eight-pole crystal filter sets the bandwidth of the measurement at 30 kHz. This filter also prevents image power from entering the subsequent mixing stages. Next, a second mixing stage shifts the center frequency to 35 kHz. This audio signal is then sent to both medium- and high-resolution search channels.

The medium resolution search channel consists of a commercial FFT spectrum analyzer. The sampling period of the analyzer is 80 msec, giving a frequency resolution of 125 Hz. Each step involves averaging 10000 such spectra, resulting in a 400 point power spectrum with 125 Hz bins. These data are coadded and the result searched for Maxwellian peaks a few bins wide (about 700 Hz) characteristic of thermalized axions in the halo.[4]

An independent, high-resolution search channel operates in parallel to explore the possibility of fine-structure in the axion signal.[5,6] The 35 kHz signal passes through a six-pole crystal filter and third mixing stage to shift the center frequency to 5 kHz. During the 80 seconds that the medium resolution channel is averaging spectra, a PC based DSP takes a single 50 second spectrum and performs an FFT. The resulting frequency resolution is 20 mHz, about the limit imposed by the Doppler shift due to the earth's rotation. These data are searched for coincidences between different scans, as well as coincidences with peaks in the medium resolution data.

So far, no axion signal has been detected. Based on these results, we exclude at 90% confidence a KSVZ axion of mass between 2.5 and 3.3 μeV, assuming that thermalized axions comprise a major fraction of our galactic halo (ρ_a = 450 MeV/cm^3). This exclusion region and model predictions are shown in Figure 2. For more details see Ref. [7].

3. Future Plans

There are two major directions for this experiment to go in the future, up in frequency and down in sensitivity. Higher frequencies will require smaller cavities, which can be power combined to maintain effective use of the magnet volume. Work on this is already underway. Much higher frequencies may be achievable with a lattice of posts inside a larger cavity.

The ultimate goal of this experiment is to scan as much of the axion window as possible with DFSZ sensitivity. Since the expected power from DFSZ axion conversion is an order of magnitude lower than that from KSVZ axions it would take one hundred times longer to reach similar sensitivity. From Equation (3), the scanning rate goes as T_s^{-2}, therefore, an order

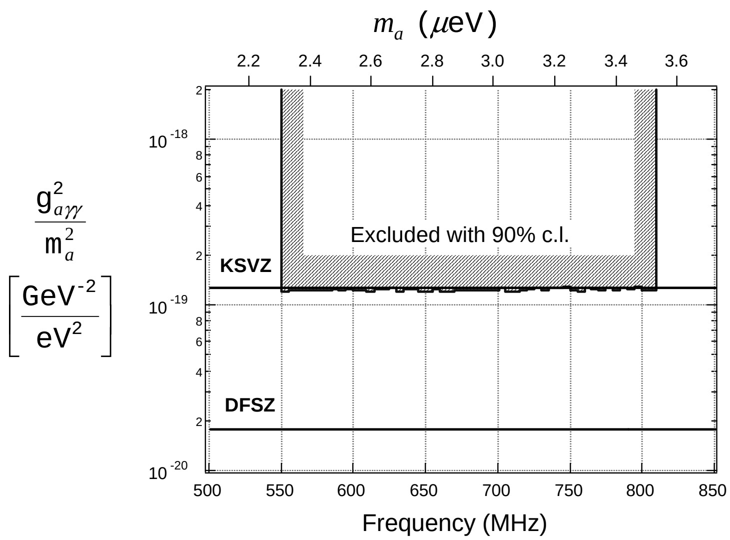

Figure 2. The range of $g^2_{a\gamma\gamma}$ excluded at 90% confidence by the 6-bin search. Also shown are the KSVZ and DFSZ model predictions.

of magnitude reduction in system noise temperature would allow a scan at DFSZ sensitivity with the same rate as the present scan with KSVZ sensitivity. This is achievable with new dc SQUID based RF amplifiers which are already achieving noise temperatures within a factor of 3 of the Standard Quantum Limit.[8]

4. Conclusion

The ADMX experiment has been operating since February 1996 and has excluded KSVZ axions in the mass range 2.3 to 3.5 μeV with greater than 90% confidence. The mass range below 2.3 μeV is presently being scanned. An upgrade is being planned to incorporate SQUID amplifiers which should allow us to reach sensitivity to DFSZ axions.

Acknowledgments

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