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Abstract. We describe the status of a sensitive search for halo axions with masses in the μeV range. A tunable large-volume and low-loss microwave cavity is operated at low temperature in a strong magnetic field. Resonant Primakoff conversion of axions into photons takes place when the cavity frequency is matched to the axion mass. No positive signal has been found so far, and we are able to exclude hadronic axions as the dominant halo component over a significant axion mass range. Future plans for a detector upgrade are outlined.

1 Introduction

The axion [1] is currently a leading candidate for the cold dark matter (CDM) in the universe. Shortly after the Big Bang, CDM axions are produced by two non-thermal processes [2,3]: (1) misalignment production, and (2) axion string/wall radiation. Their combined contribution (with large uncertainties) to the energy density is

$$\Omega_a \sim \left(\frac{10^{-5}\text{eV}}{m_a}\right)^{7/6}, \tag{1}$$

where m_a is the axion mass. Astrophysical arguments put an upper bound of $\sim 10^{-3}$ eV [4] on the axion mass. Our search is focused on the lower part of the open window, where axions would provide near closure density.

Galactic axions can be detected by their conversion into photons in a strong electromagnetic field (Primakoff effect)[5,6]. With the cavity tuned to the frequency $\nu = m_a c^2/h \sim 242\,\text{MHz}/\mu\text{eV}$, the converted power for Kim-Shifman-

Vainshtein-Zakharov (KSVZ) axions is

$$P_a^{lmn} \sim 10^{-21}\,\mathrm{W}\left(\frac{\nu}{\mathrm{GHz}}\right)\left(\frac{B_0}{8\mathrm{T}}\right)^2\left(\frac{V}{200\,\ell}\right)\left(\frac{Q_L}{10^5}\right)C_{lmn}\left(\frac{\rho_a}{10^{-24}\mathrm{g/cm^3}}\right) \quad (2)$$

where B_0 is the central magnetic field, V is the cavity volume, Q_L is the loaded cavity quality factor, ρ_a is the local axion energy density, and C_{lmn} is the mode dependent form factor

$$C_{lmn} = \frac{1}{B_0^2 V}\frac{\left(\int \mathbf{E}_{lmn}(\mathbf{r})\mathbf{B}(\mathbf{r})\,dV\right)^2}{\int E_{lmn}^2(\mathbf{r})\epsilon_r(\mathbf{r})\,dV} \quad (3)$$

where ϵ_r is the relative dielectric constant of the cavity interior, and the integral is taken over the whole cavity. The TM_{010} mode is exclusively used in our search with $C_{010} = O(1)$. The axion line is expected to have a viralized component (shown in Fig. 1) of width $\Delta\nu/\nu \sim 10^{-6}$, and several narrow peaks due to late infall axions have been postulated[7].

The major background for this experiment is thermal noise originating in the cavity and amplifier. With a critically coupled cavity connected to the amplifier input, the thermal noise power P_n at the output is

$$\frac{P_n}{BG} = \frac{h\nu}{e^{h\nu/k_B T_c} - 1} + k_B T_a \quad (4)$$

where k_B is Boltzmann's constant, T_c is the cavity temperature, B is the bandwidth, and G is the power gain. The first term represents the noise contribution from the cavity, while the last term is present for any linear amplifier (transistors, masers, SQUIDs, etc.) with quantum limit $T_a^{q.l.} = h\nu/k_B \sim 0.05\,\mathrm{K}(\nu/\mathrm{GHz})$. Finally, the signal-to-noise ratio is given by

$$\frac{s}{n} = \frac{P_a}{P_n}\sqrt{\frac{\tau}{\Delta\nu}} \quad (5)$$

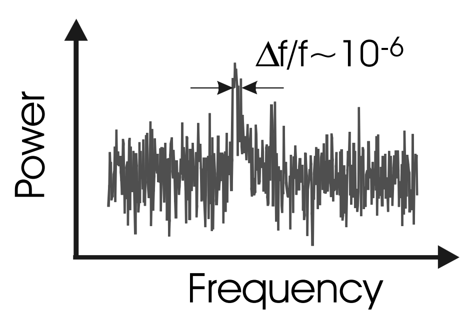

Fig. 1. Simulation of a galactic axion line immersed in white Gaussian noise

where τ is the integration time.

2 Present Experiment

Fig. 2 shows the current experimental hardware, which is designed to cover the axion mass range of $1.3 - 13$ μeV. The experiment was commissioned in late 1995, and production data taking commenced in February 1996.

A detailed description of the apparatus can be found in Peng et al. [8]. The centerpiece is a large superconducting magnet containing a tunable copper-plated microwave cavity and a low-noise HEMT amplifier. Both cavity and amplifier have a physical temperature of ~ 1.3 K, and the NRAO HEMT amplifiers have $T_a \sim 1 - 2$ K. A single right cylindrical cavity fitted with hollow copper or alumina tuning rods has been employed. The TM_{010} mode frequency is tunable between 300-810 MHz with an unloaded $Q \sim 2 \times 10^5$ at LHe temperature and with the magnetic field turned on. The cavity is mechanically tuned by external stepping motors and a reduction worm gear (1:42000) on top of the cavity. The tuning rods are suspended from alumina shafts held in non-magnetic bearings. This mechanism provides a tuning rod position resolution of $\sim$ 100 nm, equivalent to a frequency resolution of ~ 1 kHz.

To date, the mass range $2.27 - 3.35$ μeV (550-810 MHz) has been scanned with sufficient sensitivity to detect KSVZ halo axions. Offline the spectra were

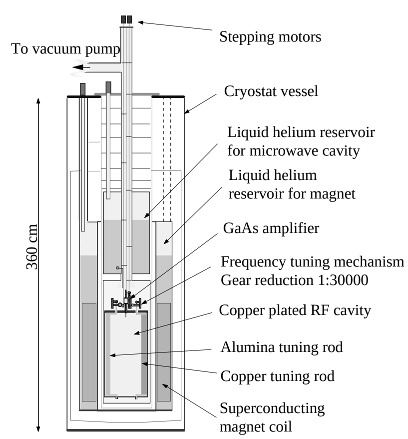

Fig. 2. Present experimental setup. A superconducting magnet held at $T = 4.2$ K provides a field of $B_0 = 7.7$ T. Both cavity ($V = 200$ ℓ) and HEMT amplifier are operated at $T = 1.3$ K.

searched for peaks above the mean noise power level and several candidate frequencies were found. However all peaks were eliminated as axion signals because either (1) they did not persist, or (2) they were traced to radio interference in the room. This allowed us to exclude KSVZ halo axions within the searched mass region as the dominant component of the halo [9,10]. The axion mass-coupling space that has or could be excluded by this and other experiments is shown in Fig. 3.

Recently, we commissioned a new cavity consisting of an array of four identical, but independently piezo-tuned sub-cavities. During an axion search, the cavity frequencies remain locked together with the outputs power-combined in phase. Thus they act as a single large cavity but with the TM_{010} frequency determined by the geometry of the sub-cavity. The tuning range of the 4-pack cavity is 800-1650 MHz using single alumina or metal rods in each cavity.

3 Upgrade Plans

In future, we intend to improve our sensitivity by replacing the HEMT amplifiers with SQUIDs, and cooling both cavity snd SQUID to $T \sim 0.1$ K. Mück et al. [12–14] have recently demonstrated SQUID amplifiers in the GHz range with power gains of ~ 20 dB, bandwidths of ~ 10 %, and noise temperatures $T_a \sim 0.1$ K at a physical temperature $T = 0.5$ K. The noise temperature T_a is expected to fall further with physical temperature down to $T \sim 0.1$ K where hot electron effects set in [15].

To work in our experimental environment, the SQUIDs must be extremely well shielded against external magnetic fields. This will be accomplished with a

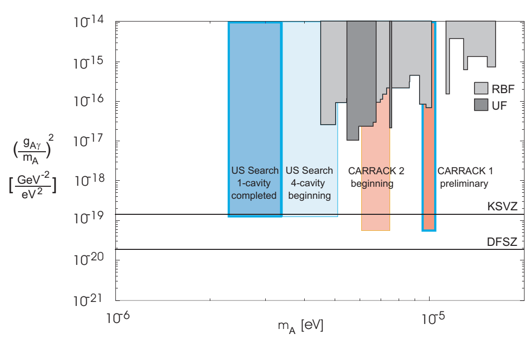

Fig. 3. Axion mass-coupling exlusion plot assuming an axionic halo with $\rho_a = 7.5 \times 10^{-25}$ g/cm^3. The axion mass-coupling regions already covered or are planned to be scanned by the U.S.[9,10] and the Japanese CARRACK experiment [11] are indicated. Also shown are the results from the previous Florida and Rochester-Brookhaven-Fermilab pilot experiments.

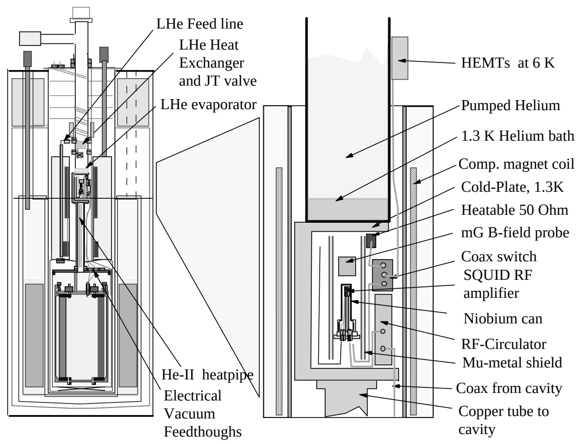

Fig. 4. Planned dewar modifications to accomodate the SQUID receiver. In Phase I, a ^{4}He pot will provide a thermal reservoir at $T \sim 1.3$ K for cooling of both SQUID and cavity. A commercial dilution refrigerator will replace the He pot during the second stage of the upgrade. The cavity and tuning rods are held in thermal equilibrium by a superfluid ^{4}He film inside the hermetically sealed cavity vessel. Active and passive magnetic shielding establishes a stable, low-field environment for the superconducting electronics.

superconducting bucking coil and layers of ferromagnetic and superconducting materials. The coil consists of two oppositely wound sections with a negligible net force with respect to the main magnet. Fig. 4 shows some design details of the envisaged experimental setup.

A quantum-limited SQUID amplifier in combination with large-volume cavities, both cooled to $T \sim 0.1$ K, would enable us to detect or definitely rule out the 7× weaker signal associated with Dine-Fischler-Srednicki-Zhitnitskii (DFSZ) halo axions over a decade in mass in ~ 3 years of data taking.

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