Preliminary Study for a New Axion Dark-Matter Haloscope

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A new haloscope for Axion dark-matter search is under study using in a first step the large bore superconducting magnet in construction at the LNCMI in Grenoble, which will produce 9 T in 812 mm diameter and 1400 mm height. Microwave cavities of high quality factor $Q \sim 10^5 - 10^6$ will be developed at CAPP/IBS in Daejeon. Low-noise microwave amplification of the signal will be ensured by DC superconducting quantum interference devices (SQUID) or/and Josephson parametric amplifiers (JPA) cooled-down to 20 mK by a ^{3}He/^{4}He dilution refrigerator. This new haloscope will be designed to probe QCD dark-matter Axions in the mass range of 1-100 μeV with unprecedented sensitivity.

1 Introduction

A light axion represents one of the most serious cold dark matter candidates and the only non-supersymetric one. It can also solve the strong CP problem [1]. Pierre Sikivie has demonstrated in 1983 that if invisible axions constitute the dark matter of our galactic halo, they can be detected in the laboratory from their conversion to monochromatic photons in a microwave cavity permeated by magnetic field [2]. The signal power to be detected is simply given by:

$$P = g_{A\gamma\gamma}^2(\rho_{halo}/m_A)B^2VCQ/2 \tag{1}$$

with $g_{A\gamma\gamma}$ the unknown axion di-photon coupling constant, $\rho_{halo} \approx 450$ MeV/cm^3 the density of dark matter, $m_A \approx 10^{-6} - 10^{-3}$ eV/c^2 the axion mass range as dark matter candidate, B^2V the square of the magnetic field B multiplied by the volume V of the cavity, $C \approx 0.5$ the cavity mode form factor and $Q \sim 10^5 - 10^6$ the cavity quality factor. The resonant conversion condition is achieved when the frequency of the cavity is equal to the mass of the axion, *i.e.* $h\nu = m_Ac^2[1 + O(\beta^2)/2]$, where $\beta \approx 10^{-3}$ is the galactic virial velocity and h the Planck constant. The signal is thus monochromatic to 10^{-6} limiting the interest of high Q to 10^6. The search of axions is performed by tuning the cavity frequency in small overlapping steps and the time integration at each scanned frequency is one of the key limiting factors. The signal to noise ratio (SNR) is of prime importance. In the continuous wave conditions it is given by [3]:

$$SNR = (P/k_B T_{syst})(t/\Delta\nu)^{1/2} \tag{2}$$

with P the detection power in the range of 10^{-23} W, k_B the Boltzmann constant, $T_{syst} = T + T_N$, *i.e.* the sum of the physical temperature T and the intrinsic amplifier noise temperature T_N, t the time integration and $\Delta\nu$ the frequency bandwidth. The haloscope road is being pushed forward by the ADMX collaboration with first study around 1994 [4] and last published results in 2011 [5] following the pioneering work at BNL, FNAL [6] and at Florida University in the late 1980′s [7]. The main figures of merit for haloscope emerging from equations (1) and (2) are B^2V and T_{syst} requiring developments of a high field magnet and working at temperature in the range of a few tens of mK. States of the art cavities with Q reaching 10^6 have also to be developed as well as ultra-low noise amplifier working at the quantum limit and even beyond.

2 The Grenoble hybrid magnet and its large bore superconducting outsert

The Grenoble hybrid magnet under construction in collaboration with CEA Saclay will be a modular experimental platform offering various possibilities of maximum field values and useful warm bore diameters [8]. From the combination of resistive polyhelix and Bitter coils with a large bore superconducting one, a maximum field of at least 43 T will be produced in a 34 mm diameter aperture using 24 MW of electrical power. By combining the Bitter insert alone with the superconducting coil, another hybrid magnet configuration will allow to produce 17.5 T in a 375 mm diameter aperture with 12 MW of electrical power. Finally, the superconducting coil alone will provide a maximum field of 9 T in 812 mm diameter and 1400 mm height bore. The superconducting coil is based on the Nb-Ti and superfluid He technologies. It requires a dedicated He liquefier with a production capacity of 140 l/h [9]. The resistive magnets are cooled with a water flow of 300 l/s.

Compared to other haloscopes such as ADMX [4, 5], the superconducting outsert magnet alone offers an unprecedented value of $B^2V \approx 40$ $\mathrm{T^2m^3}$. A further increase of B^2V up to 75 $\mathrm{T^2m^3}$ is possible but would imply major changes in the structure of the Grenoble Hybrid Magnet as well as significant investments, which might be considered at a later stage. On another hand, adding the resistive magnets can allow further unique possibilities for this new haloscope to probe axion of larger mass using higher magnetic fields.

3 RF cavity developments at CAPP/IBS

Large magnet bore allows according to equation (1) large cavity volume to enhance the axion signal to be detected. However as the T_{M010} frequency, and thus the axion mass, scales inversely with the cavity radius, probing the whole dark matter axion mass range implies the use of several cavities of different radius. Indeed for a single cavity equipped with conducting rods, its resonant frequency can be typically varied by a factor of about 2. Examples of various RF cavity configurations that can fit within the large bore superconducting magnet are shown in Fig. 1.

The simultaneous use of several cavities implies a coarse tuning of all cavities at the same frequency with phase matching but also individual fine tuning with proper control for each single cavity. In a first step, the optimal selection of five of the cavity configurations shown in Fig. 1, will allow scanning continuously the axion mass in the range from 1.4 to about 15 μeV. RF cavities with high quality factor $Q \approx 10^5 - 10^6$ have to be built to amplify the signal. This requires further developments to improve the Q factor of typical copper cavities or/and developing superconducting ones. This constitutes one of the main ongoing R&D programs at CAPP/IBS [10] with informal collaboration with CERN.

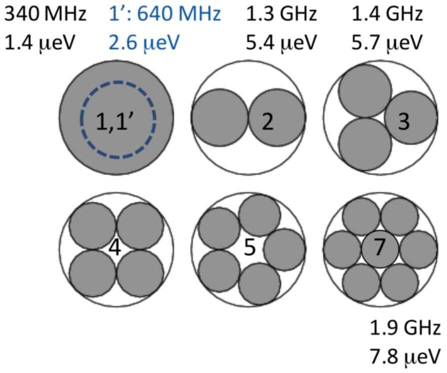

Figure 1: Schematic view of possible RF cavity arrangements within the superconducting magnet aperture with the corresponding resonant frequencies converted in axion mass.

4 Developments of ultra-low noise amplifiers in the range 0.3-10 GHz

One of the main figures of merit of an amplifier is its input noise temperature (T_N). It is defined as the power spectral density at the output of the amplifier divided by its gain, with a matched load at the input of this latter. This parameter is of high relevance, since for $T_{syst} \approx T_N$ inserted in equation (2) the time t required to obtain a given SNR is proportional to T_N^2. In the microwave range, the best performances are obtained using cryogenic devices such as high electron mobility transistor amplifiers [11], SQUID-based amplifiers [12] or parametric devices [13]. To achieve the lowest possible T_N, Josephson parametric amplifiers (JPAs) have become the technology of choice for the supGHz range. Indeed its possible to reach the quantum limit of amplification using such devices [14], as it was demonstrated in various experiments around the world such as [15]. Moreover they can be fabricated using standard lithography techniques and their operating frequency can be adjusted in-situ to follow the one of the resonant cavity.

5 Dilution refrigerators and cryostats

According to equation (2), large SNR requires ultra-low temperature of the overall system at the limit of cryogenic achievements. Not only the quantum amplifier but also the RF cavities have to be cooled typically down to 20 mK. Based on extensive experiences in building ^{3}He/^{4}He dilution refrigerators as well as dedicated cryostats for large underground detectors [16] and space mission such as Planck [17, 18] Néel Institute can provide the required technical expertise and support. The warm magnet aperture needs to be filled with a dilution cryostat optimizing the 20 mK volume for the RF cavity. From a first-cut design of the larger cryostat fitting with the warm superconducting magnet bore, 5 temperature stages from 300 K down to 20 mK with 10 mm space in between are needed, resulting in ≈40 mm radius loss over 812 mm for the axion detection volume. Cryostat with LHe flow and with LHe bath will be both considered with the aim to select the most compact solution. No show stopper has been identified to manufacture the dedicated ^{3}He/^{4}He dilution refrigerator needed to cool down large cavity volumes.

6 Conclusion

The QCD dark-matter Axion is within gunshot range. The sensitivity of the new haloscope under study is expected reaching for the first time the ultimate Dine-Fischler-Srednicki-Zhitnitsky (DFSZ) limit [19]. Important topics have not been addressed in this paper such as for example the coil to compensate the magnetic field at the level of the quantum amplifier, the overall experimental layout but also and mostly the full exploitation of the various maximum field values and bore diameters provided by the Grenoble hybrid magnet under construction. This latter point will be described in a separated paper. The next steps of this project will be the signature of a MoU between participants and the definition of the first haloscope configurations.

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