Searching for dark matter through magnetized media: The QUAX proposal of a ferromagnetic axion haloscope

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Light stable axions, originally proposed to solve the strong CP problem of quantum chromodynamics (QCD), emerge now as leading candidates of WISP dark matter. The axion-electron coupling, explicitly predicted by some models, can be exploited to envisage novel detectors complementary to the "Sikivie haloscope". In fact, due to the Earth motion with respect the dark matter halo, the interaction of relic axions with electron spins results in an effective magnetic field that inject power in magnetized media. In this proceeding we present the QUAX proposal of a ferromagnetic haloscope and the related ongoing experimental activity at the National Laboratories of Legnaro (Italy). The experimental parameters required to achieve cosmologically relevant sensitivity with our detector will be discussed. Some preliminary results on the operation of the QUAX prototype are eventually presented.

Keywords: Axion, Dark Matter.

1. Introduction

An impressive result of modern cosmology is that a major fraction of the mass content of the universe is composed of dark matter (DM), i.e. particles not interacting significantly with electromagnetic radiation, ordinary matter, not even self-interacting (cold dark matter). The DM existence is inferred from its gravitational influence on galaxies, clusters and Cosmic Microwave Background, which suggests it dominates by a ratio of 5:1 over ordinary matter described by the Standard Model (SM) of particle physics. In the era of precision cosmology an important threshold has been crossed: the issue nowadays is no longer the existence of particle dark matter, but its nature as new particle(s) Beyond SM (BSM models). Moreover, according to Big Bang cosmology, dark matter particles must be produced thermally similarly to SM particles. Hypothetical Weakly Interacting Massive Particles (WIMPs), e.g. 100 Gev particles from supersymmetric extension of SM, have been a prime DM candidate because of their self-annihilation cross section $\langle \sigma v \rangle \simeq 3 \times 10^{-26}\text{cm}^3\text{s}^{-1}$, that guarantees the correct abundance of dark matter today ("WIMP miracle")[1]. Recently, the WIMP paradigm has started to look less as the obvious solution to the dark matter problem, and the spotlight passed over Weakly Interacting Sub-eV Particles (WISP), that are very light bosons characterized by sub-eV masses and large occupation numbers, such as axions, axion-like particles (ALP) and hidden photons. In particular, the axion, originally introduced in the SM by Peccei and Quinn to solve the strong CP problem of QCD, is a good candidate for DM. The axion is the pseudo-Goldstone boson associated to an additional symmetry of SM Lagrangian which is spontaneously broken at an extremely high energy scale F_a. Current literature favours invisible axion mechanism with $F_a \gg 250$ GeV (weak scale), which has two main implementations: the KSVZ (Kim-Shifman-Vainshtein-Zakharov) models and the DFSZ (Dine-Fischler-Srednicki-Zhitnitsky) models. For scales $F_a \simeq 10^{12}$ GeV, corresponding to typical mass values $m_a \simeq 1$ meV, axions may account for the totality of DM[2]. As a consequence, many different detectors have been proposed over the last decades to search for relic axions. Although theory do not fix the value of F_a, cosmological considerations and astrophysical observations provide boundaries on F_a and suggest a favoured axion mass range $1\mu eV < m_a < 10meV$, i.e. over 10^{15} times smaller than WIMPs mass. In addition, lattice results on QCD topological susceptibility, based on reliable computations of the axion relic density, indicate a preferred window for the axion mass in the range of tens of μeV[3]. With such a small mass, we would expect $n_a \simeq 3 \times 10^{13}(10\ \mu eV/m_a)$ axions per cubic centimeter in our Solar System to account for the observed DM density $\rho_{DM} \sim 0.3$ GeV/cm^3. Most of axion detectors rely on the conversion of axions into photons in a resonant cavity in the presence of a static magnetic field, following the detection scheme proposed by P. Sikivie in 1983 – called axion haloscope – which is based on the inverse Primakoff effect[4]. In particular, the ADMX experiment reached the cosmologically relevant sensitivity to exclude the axion mass range $2.66 < m_a < 2.81$ μeV for DFSZ models and $1.9 < m_a < 3.7$ μeV for KSVZ models[5]. On the other hand, the axion-fermion coupling, explicitly predicted in DFSZ models[6], allows for designing new detectors that exploit the interaction between axions and fermionic spins[7]. In fact, the motion of the Solar System through the DM cloud surrounding the Galaxy results in a gradient of the axion field $\boldsymbol{\nabla} a$ pointing in the motion direction, and one can demonstrate that the effect of $\boldsymbol{\nabla} a$ on spins in a magnetized material plays the rôle of an effective oscillating magnetic field $\boldsymbol{B}_a$ with amplitude, direction and frequency determined by ρ_{DM}, $\boldsymbol{\nabla} a$ and m_a, respectively. The QUAX detector is precisely based on the resonant interaction of $\boldsymbol{B}_a$ with the homogeneous magnetization mode in ferrimagnetic samples. In this proceeding we summarize the main ideas of the QUAX proposal[7] and report on some recent results regarding the cryogenic operation of a QUAX demonstrator[8].

2. Axion detection by resonant interaction with electron spin

Assuming standard cosmology, we calculate the effective magnetic field $\boldsymbol{B}_a$ with the aim of estimating the power released in a magnetized sample as a function of QUAX parameters. As the DFSZ axion models do not suppress the axion and electron coupling at the tree level, the Lagrangian reads

$$L = \bar{\psi}(x)(i\hbar\gamma^\mu\partial_\mu - m_e)\psi(x) - ig_{ae}a(x)\bar{\psi}(x)\gamma_5\psi(x), \tag{1}$$

where $\psi(x)$ is the spinor field of an electron with mass m_e. Here γ^μ are the 4 Dirac matrices, $\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3$, and $a(x)$ is coupled to matter by the dimensionless pseudo-scalar coupling constant g_{ae}. By taking the non-relativistic limit of L, the resulting interaction term can be written as

$$-\frac{g_{ae}\hbar}{2me}\boldsymbol{\sigma}\cdot\boldsymbol{\nabla} a = -2\frac{e\hbar}{2m_e}\boldsymbol{\sigma}\cdot\left(\frac{g_{ae}}{2e}\right)\boldsymbol{\nabla} a \equiv -2\mu_B\boldsymbol{\sigma}\cdot\boldsymbol{B}_a, \tag{2}$$

which has clearly the form of the interaction between the spin magnetic moment and an effective magnetic field, where e is the electron charge, μ_B is the Bohr magneton, $\boldsymbol{\sigma}$ is the vector Pauli matrices, and $\boldsymbol{B}_a \equiv g_{ae}/(2e)\boldsymbol{\nabla} a$ is the effective magnetic field. For DFSZ axions, the coupling to electrons is $g_{ae} = m_e/(3F_a)\cos^2\beta \simeq 2.8 \times 10^{-15}(m_a/10^{-4}eV)$ assuming O(1) value for the free parameter $\cos^2\beta$. To calculate amplitude and frequency of the effective magnetic field due to the presence of the DM axion we use the standard model of galactic halo: a spherical distribution with a pseudo-isothermal density profile, local density $\rho_{DM} \sim 0.3GeV/cm^3$ corresponding to $n_a \sim 3 \times 10^{12}$ $(10^{-4}$ eV$/m_a)$ axions per cubic centimeter, and local velocity distribution described by the Maxwell Boltzmann distribution with a dispersion $\sigma_v \approx 270$ km/sec. The Earth velocity with respect the galactic halo is $|\boldsymbol{v}_E| \simeq 220$ Km/sec. Therefore the equivalent oscillating rf field has an expected mean amplitude and central frequency

$$B_a = 2.0 \times 10^{-22}\left(\frac{m_a}{200\,\mu\text{eV}}\right)\ \text{T}, \quad \frac{\omega_a}{2\pi} = 48\left(\frac{m_a}{200\,\mu\text{eV}}\right)\ \text{GHz}, \tag{3}$$

with relative linewidth $\Delta\omega_a/\omega_a \simeq 5.2 \times 10^{-7}$ and direction $\boldsymbol{v}_E$. The explicit dependence on ω of the power spectrum of axion field has been calculated in Ref. 6.

Once the calculation is tailored for the gradient of the axion field, the coherence time and correlation length for the QUAX detector read

$$\tau_{\nabla a} \simeq 0.68\,\tau_a = 17\left(\frac{200\,\mu\text{eV}}{m_a}\right)\left(\frac{Q_a}{1.9\times 10^6}\right)\ \ \mu\text{s};$$
$$\lambda_{\nabla a} \simeq 0.74\,\lambda_a = 5.1\left(\frac{200\,\mu\text{eV}}{m_a}\right)\ \text{m}, \tag{4}$$

where the standard DM halo parameters were used[7].

2.1. *The QUAX proposal*

In the QUAX proposal we focused our analysis to frequencies in the $40 \div 50$ GHz range. To measure the power released by extremely small rf field B_a we make use of the Electron Spin Resonance (ESR) in magnetic samples[7]. To enhance the interaction, the ferromagnetic resonance of the sample – i.e. the Larmor frequency $\omega_L = \gamma B_0$ of the electron spin precession in an external magnetic field B_0 – is tuned to the frequency ω_a associated with mass value of the searched for axion. Here $\gamma/2\pi = e/m_e = 28GHz/T$ is the electron gyromagnetic ratio. In the limit of weak rf field, the steady state solutions of Bloch Equations of the magnetization $M_a(t)$ relative to the ESR Kittel mode reads

$$M_a(t) = \gamma\mu_B B_a n_S \tau_{\min}\cos(\omega_a t), \tag{5}$$

where n_S is the material spin density and $\tau_{\min} \equiv \min(\tau_{\nabla a}, \tau_2, \tau_r)$ is the shortest coherence time among the axion wind coherence $\tau_{\nabla a}$, magnetic material relaxation τ_2 and radiation damping τ_r, and it represent the coherence time of $M_a(t)$ oscillatiions. However, the radiation damping mechanism may result in an issue for the QUAX detector. In fact, in free space, the energy damping due to magnetic dipole emission $\tau_r = (c^3/\omega_L^3)/(\gamma\mu_0 M_0 V_s)$, and so high Larmor frequency, large magnetization M_0, and large volume V_s of magnetized material imply $\tau_r << \tau_a$. However, the radiation damping mechanism can be inhibited by inserting the magnetized material inside a microwave resonant cavity in the strong coupling regime. In this case, the hybridization between Kittel magnetic mode of the sample and a suitable cavity mode occurs, and the limited phase space of the resonant cavity inhibits the radiation damping mechanism, thus providing a more favourable damping time equal to the cavity decay time. In the hybridization regime we have $\tau_{\min} = \min(\tau_{\nabla a}, \tau_2, \tau_c)$, where τ_c is the cavity decay time[7].

In the presence of the axion wind, the average amount of power absorbed by the magnetized sample in each cycle is

$$\begin{aligned} P_{\text{in}} &= \mu_0 \mathbf{H}\cdot\frac{d\mathbf{M}}{dt} = B_a\frac{dM_a}{dt}V_s \\ &= \gamma\mu_B n_S \omega_a B_a^2 \tau_{\min} V_s. \end{aligned} \tag{6}$$

In a steady state condition, the power balance ensures that P_{in} will be emitted as rf radiation, and so $P_{\text{in}}/2$ can be collected by using an antenna critically coupled to the hybridized mode. The output power can be expressed in terms of the relevant experimental design parameters

$$P_{\rm out} = \frac{P_{\rm in}}{2} = 3.8 \times 10^{-26} \left(\frac{m_a}{200\,\mu{\rm eV}}\right)^3 \left(\frac{V_s}{100~{\rm cm}^3}\right) \left(\frac{n_S}{2\cdot 10^{28}/{\rm m}^3}\right) \left(\frac{\tau_{\rm min}}{2\,\mu{\rm s}}\right) {\rm W}, \tag{7}$$

where the chosen axion mass is determined by a magnetizing field $B_0 = 1.7$ T, and the value of the spin density is typical of paramagnets at low temperature or material as YIG (Yttrium Iron Garnet) even at room temperature. To measure such a low power is a very difficult experimental challenge. To reach the QUAX goal of detecting cosmological QCD axions, we need to improve the detector sensitivity along the following lines:

1) Study of materials: decrease linewidth of ferromagnetic resonance in the $10 \div 100$ GHz frequency range at low temperatures and increase spin density of magnetized materials (YIG, GaYIG, LiF or BDPA and other paramagnets); make use of ultrapure material (e.g. by trying to minimize rare earths contamination); highly accurate polishing and smoothing of surfaces.
2) Cavity design: design of a high-Q ($\sim 10^6$) cavity to be operated in few Tesla magnetic fields; cavity design should also maximize SNR and allow for housing the required amount of magnetized material.
3) Static magnetic field source: realization of a highly uniform magnetic field (up to 10 ppm for a few Tesla field to avoid inhomogeneous broadening).
4) Decrease of noise level: use a dilution refrigerator to lower thermal noise that also allow for the operation of a Josephson Parametric Amplifier (JPA); a crucial issue is the concurring development of a single photon counter in the microwave frequency range in order to overcome the Standard Quantum Limit of linear amplifiers.

It is worth noticing that only the component of the equivalent magnetic field $\boldsymbol{B_a}$ orthogonal to the magnetizing field $\boldsymbol{B_0}$ will drive the magnetization of the sample, therefore QUAX is a directional detector and it shows a daily modulation of the axion signal that can be exploited to get rid of spurious noise sources[7].

2.2. *The QUAX demonstrator*

We have addressed experimentally some issues that affect the sensitivity of a ferromagnetic haloscope, such as ferrimagnetic dissipation, cavity quality factor, magnetic field homogeneity[8]. Thus we have set up a demonstrator of the QUAX experiment which is made of 5 GaYIG (Gallium Yttrium Iron Garnet), 1 mm diameter spheres, placed in a cylindrical copper cavity (diameter ~ 26 mm and length 50 mm), and immersed in a ~ 0.5 T magnetic field. We use the TM110 mode with resonance frequency $f_c \simeq 13.98$ GHz and linewidth $k_c/2\pi \simeq 400$ kHz at liquid helium temperature. The degeneracy of this mode has been removed by digging two symmetric grooves in the lateral surface of the cylinder. The TM110 mode is characterized by a uniform maximum magnetic rf field along the cavity axis, and therefore we can house more YIG spheres along it. Moreover, cavity volume can be increased by lengthening the cylinder without changing the TM110 mode resonance frequency. With cylindrical geometry we can also exploit the uniformity of magnetic field produced by a solenoid along the symmetry axis so as to avoid the inhomogeneous broadening of the resonances. In fact, the Larmor frequency f_L of the GaYIG spheres is established by an highly uniform solenoidal magnetic field (1 part in 10^4), and the hybridization condition $f_L \simeq f_c$ is met when $B_0 \simeq 0.5$ T. In the strong coupling regime, the hybrid mode frequencies are $f_+ = 14.061$ GHz and $f_- = 13.903$ GHz. The detection electronics (a cascade of a room temperature and a cryogenic amplifier) was calibrated with a Johnson noise source at different temperature. The output of the cavity is down-converted in its in-phase and quadrature components with respect to a local oscillator and sampled at 2 MHz. The power of hybridized modes was estimated with $\sim 2 \times 10^6$ FFTs of 8192 bins each (frequency resolution of 244 Hz), which were square averaged and rebinned into 7.8 kHz bandwidths (256 bins), close to the expected axion bandwidth. The standard deviation of the estimated power is $\sigma_P = (2.2 \pm 0.1) \times 10^{-22}$ W, compatible with the Dicke radiometer equation. No significant excess power consistent with DM axions was found. Therefore we can set the upper limit $\sigma'_P \sim 10^{-21}$ W within the 3 MHz band around 13.903 GHz at the 95% C.L.. This value translates to the upper limit $B_a \leq 1.6 \times 10^{-17}$ T of the equivalent axion field, corresponding to a axion electron coupling $g_{ae} \leq 5 \times 10^{-10}$ for axion masses $58.527 \leq m_a \leq 58.541$ μeV at 95% CL[8].

3. Conclusions

We have reported on the QUAX proposal, i.e. a ferromagnetic haloscope sensitive to DM axions through their interaction with electron spin. Our findings by means of the QUAX demonstrator indicate the possibility of performing ESR measurements of a sizable quantity of material inside a cavity cooled down to cryogenic temperatures. The sensitivity of the demonstrator reached the limit of the Dicke radiometer equation, the overall behavior of the apparatus is as expected, and we are confident that the QUAX detector can reach a cosmological relevant sensitivity.

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