From OSQAR[1] Experiments at CERN Towards JURA[2] and VMB@CERN[3]

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Abstract - OSQAR explores the eV/sub-eV range of particle physics from the combined use of high magnetic fields and laser beams in three distinct experiments. The first one looks for Light Shining through the Wall (LSW) and provided the present reference results. The second one is targeting the first measurement of the ultra-fine Vacuum Magnetic Birefringence (VMB) predicted by the QED. The collaboration has been recently extended and the letter of intent VMB@CERN submitted. The third experiment, OSQAR-CHASE, is looking for hypothetical Chameleon particles whose mass depends on the local matter density.

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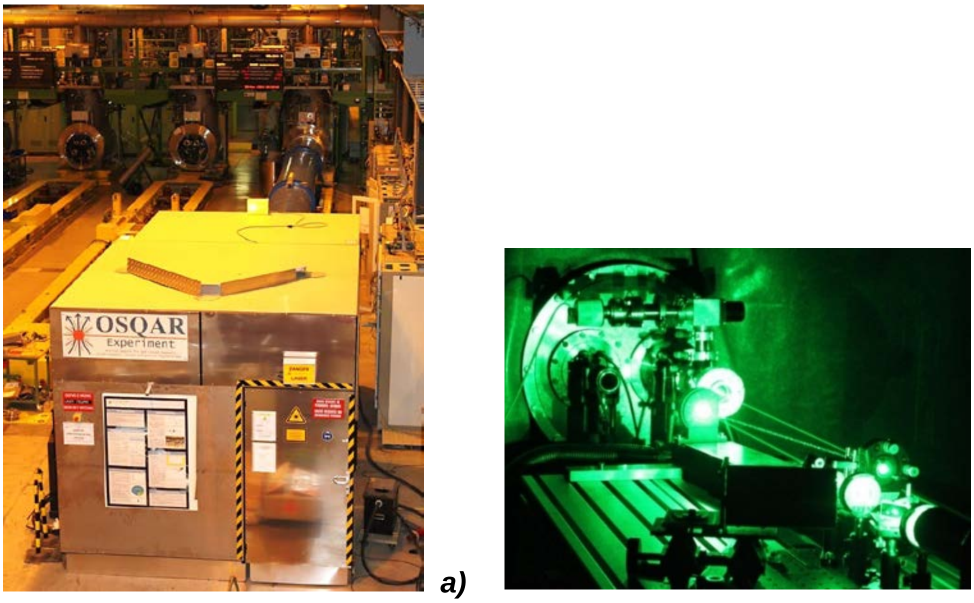
[1] Optical Search of QED vacuum magnetic birefringence, Axion and photon Regeneration (CERN Experiment)
[2] Joint Undertaken Research on Axion and ALPs
[3] Vacuum Magnetic Birefringence

1. Introduction to the Physics case of the OSQAR experiments

Particle physics is not only confined to the high energy frontier. There are unexplored territories at ultra-low energies, *i.e.* sub-eV to eV, which are also very promising, such as for example to explain the origin of dark matter (DM). The emblematic particle of this physics is the axion, a pseudo-scalar particle predicted independently in 1978 by S. Weinberg [1] and F. Wilczek [2], to solve the fundamental problem of the apparent non-violation of the CP symmetry by the strong interaction (QCD) assuming the breaking of the Peccei and Quinn symmetry [3]. The strong CP problem constitutes one of the remaining sand grains in the gear of the standard model of particle physics. Standard axion with coupling at the electroweak scale, *i.e.* with a mass in the keV range, has been excluded after extensive searches in collider experiments. This has led the scientific community to consider the case of "almost" invisible axion, *i.e.* with a mass and coupling to other particles extremely weak. If the axion mass is in the range 10^{-6} to 10^{-2} eV, this particle could also be responsible for the DM of our universe and constitutes one of the rare non-supersymmetric candidates. On the other hand, various ultra-light and weakly interacting scalar and pseudo-scalar particles are naturally present in string theory without the need of solving the strong CP problem. This new family of particles has coined the name of WISPs for Weakly Interacting Slim Particles in complement to the WIMPs standing for Weakly Interacting Massive Particles. P. Sikivie showed in 1983 [4] that the invisible axion as well as axion like particles (ALPs), a subfamily of WISPs, could be detected via a chiral anomaly that modifies Maxwell's equations.

In this context, the two distinct OSQAR experiments at CERN, namely the OSQAR-LSW[4] and OSQAR-VMB[5] look mostly for ALPS through studies of optical properties of the quantum vacuum permeated by a strong magnetic field [5]. OSQAR-LSW is complementary to CAST[6] [6], the CERN helioscope searching axion and ALPs that could be produced by the sun. In 2017 OSQAR has been extended with OSQAR-CHASE[7] [7] to the search of chameleons, a special type of particle postulated to have a mass depending on the density of the surrounding medium to explain dark energy. All these experiments will be briefly presented in the next paragraphs with a brief review of their status and perspectives. There are all based on the extensive use of spare LHC dipoles installed in the CERN SM18 hall (Fig. 1) and providing a magnetic field of 9 T over 14.3 m length.



a) ***b)***

Fig. 1: a) *The OSQAR experiments at CERN with the protective area enclosing the high power laser in front of a spare LHC dipole.* ***b)*** *View inside the protective area showing the CW 20 W laser beam aligned within one aperture of the spare LHC dipole.*

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[4] Light Shining through Wall
[5] Vacuum Magnetic Birefringence
[6] CERN Axion Search Telescope
[7] CHameleon Afterglow Search Experiment

It is worth mentioning that OSQAR experiments shed light on *"a hidden sector" of CERN's scientific heritage* since the first proposal to test the QED by measuring the vacuum magnetic birefringence was actually born at CERN in 1979 [8] with some very preliminary tests done in the early '80s. In addition, the possibility to detect nearly massless, spin-zero particles on light propagation in a magnetic field was first theoretically investigated at CERN in 1986 [9].

2. OSQAR-LSW

2.1. Latest results

The OSQAR-LSW experiment aims to detect ALPs from the light shining through wall experimental scheme [10] shown in Fig. 2. This type of experiment can be split in three main parts, one for the photon to axion conversion in strong magnetic field, a second one for the absorption of non-converted photons and the last part for the photon regeneration and detection.

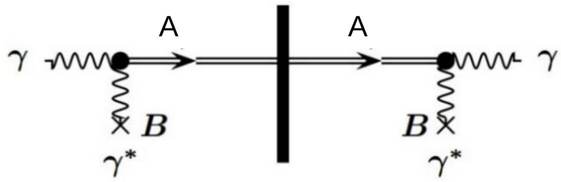

Fig. 2: *Principle of a LSW experiment within two vacuum chambers permeated by a strong transverse magnetic field and separated by an optical absorber.*

The basic ingredient concerns the production of ALPs from a polarised laser beam in the background of a strong magnetic field through the Primakoff process $\gamma\gamma^* \rightarrow A$. Once ALPs are produced, they propagate freely along the same direction as the laser beam, cross the wall due their extremely low coupling strength to matter before entering in the regeneration chamber located on the opposite side of the experiment. All photons not converted into ALPs in the first part of the experiment are absorbed by the wall inserted in between. A second external magnetic field applied within the regeneration area, allows the ALP to be reconverted into a photon via the inverse process $A\ \gamma^* \rightarrow \gamma$ before being subsequently detected.

For the last experimental run of OSQAR-LSW, a 20 W CW laser beam has been aligned within one of the apertures of two spare LHC dipoles (Fig. 1) to interact with the dipolar magnetic field. For the detection of the regenerated photons, state-of-the-art CCD has been used. The sensitivity after data analysis of Bayesian type reached 0.64 x 10^{-3} photon/s at 95 % confidence level [11]. Thanks to the performance of the LHC dipoles, which were pushed to 9 T, *i.e.* close to their ultimate field limit, the last results obtained by OSQAR-LSW are the most sensitive to date for this type of experiment (Fig. 3). More sophisticate statistical data analysis methods are being developed to further improve the sensitivity obtained [12]. They are based on Wiener matched filtering technics and are very similar to the ones used in the analyses of Virgo and Ligo data.

2.2. Perspectives with OSQAR-LSW, towards JURA

The sensitivity of an LSW experiment expressed by the di-photon coupling constant $G_{A\gamma\gamma}$, varies as $(BL)^{-1}$ with B the magnetic field and L the magnetic length, which are the dominant factors. Targeting a sensitivity of $G_{A\gamma\gamma} \sim 2\text{x}10^{-11}$ GeV^{-1}, the ALPS-II experiment in construction at DESY [13], will use 10 + 10 Hera superconducting dipoles providing a field integral of 2 x 468 Tm with a very challenging optical scheme to implement within a 200 m long experiment. The OSQAR-LSW+ proposal upgrade with 4 + 4 LHC dipoles, has a slightly larger field integral equal to 2 x 514 Tm but on the much shorter length of about 120 m, and for a similar magnet free aperture once the LHC dipoles are straighten as demonstrated during the LHC construction [14]. With 7 + 7 LHC dipoles corresponding to a 200 m long experiment, OSQAR-LSW++ proposal would roughly improve by a factor 2 the sensitivity of ALPSII with the same challenges for the optical scheme to implement [15]. To fully exploit the CERN unique opportunity by increasing the number of spare LHC dipoles that could be used (up to a maximum equal to 45), the problem of the divergence of the laser beam has to be addressed. In this line, the Czech institutes participating to the OSQAR collaboration are studying the possibility of using low divergent Bessel beams [16]. All these various possibilities for upgrading OSQAR-LSW have been discussed within the Technology working group of the PBC (Physics Beyond Colliders) in synergy with ALPS perspectives, from which the JURA initiative has emerged. A first estimate of the sensitivity of JURA has been reported by the PBC working group [17] and is given in Fig.4 highlighting the unique opportunity to explore a significant domain of the BSM landscape. Better sensitivities (not shown in Fig. 4) are also targeted to be obtained by new haloscopes under construction such as MADMAX [18] and GrAHal [19] but will depend on some assumptions.

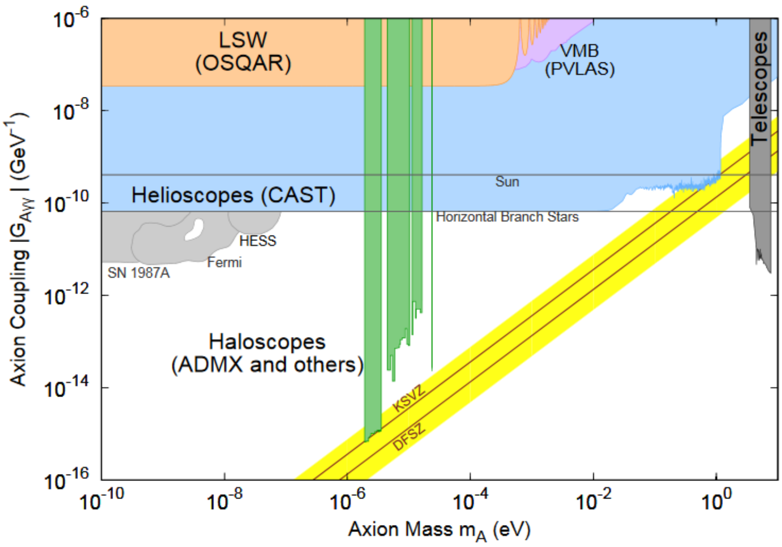

Fig. 3: *Exclusion plots for axion and axion-like particles as a function of the axion mass and the di-photon coupling constant (extracted from [20]). QCD axions are constrained within the yellow band by the two KSVZ and DFSZ theoretical models. Both these theoretical constraints are still questionable [21]. Haloscopes are today the most sensitive experiments to detect QCD Axion from the inverse Primakoff effect assuming they are the main component of dark matter of our galactic halos. The CAST helioscope is sensitive to QCD axion and ALPs produced within the sun up to the eV range and independently on whether such particles are component or not of dark matter.* ***Despite LSW experiments such as OSQAR are today the less sensitive ones, their performance will be improved (ALPS-II & JURA) and they are the only ones fully model independent.***

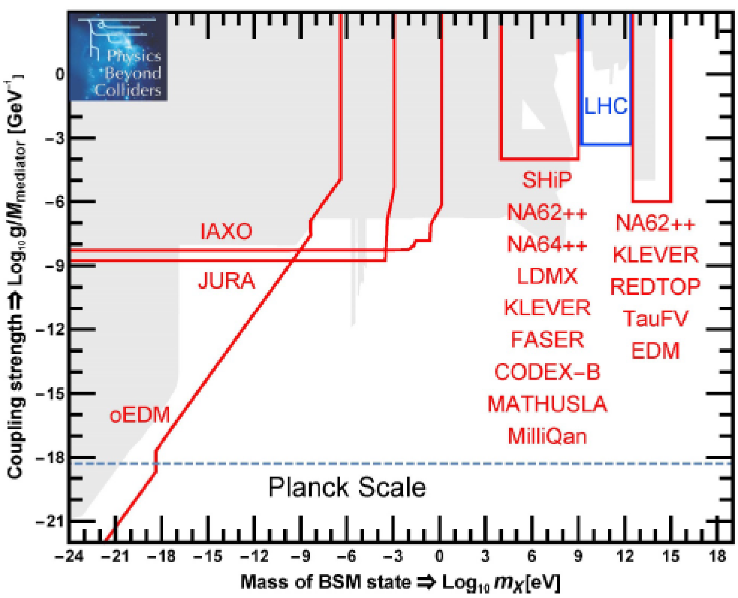

Fig. 4: *Schematic overview of the BSM landscape, based on a selection of specific models with a rough outline of the areas targeted by the experiments considered in the PBC sensitive studies [17].*

3. OSQAR-VMB

Since its prediction in 1936 by Heisenberg and Weisskopf in the early development of the Quantum Electrodynamic (QED), the measurement of the Vacuum Magnetic Birefringence (VMB) is still one of the most difficult challenges in optical metrology. According to QED, the vacuum permeated by a transverse magnetic field is an active medium able to change the polarization of light from linear to elliptical. This "*n-1*" anomaly to be measured is of the order 10^{-22}, which corresponds to the relative difference of the vacuum refractive indices in a magnetic field of 9.5 T. Contributions to the VMB could also arise from new light scalar/pseudoscalar particles like axions that couple to photons and this would manifest itself as a sizeable deviation from the pure QED prediction [9]. Because of the critical issues to be solved, OSQAR-VMB is still in its preparatory phase at CERN and in collaborating institutes [22]. The perspective discussed within the PBC technology working group was to merge the worldwide expertise in this field into a single meta-collaboration, from which the Letter of Intent VMB@CERN has emerged [23]. The main objective is to build a fully dedicated experiment at CERN for measuring for the first time the QED-VMB, possibly up to the second term in α^3 with α being the fine-structure constant, thanks to the unique opportunity of using state-of-the-art superconducting accelerator magnet(s) and related infrastructures.

4. OSQAR-CHASE

Following the pioneering work of the GammeV-CHASE experiment at Fermilab [24], OSQAR-CHASE is looking for a magneto-phosphorescent or afterglow signal of the vacuum permeated by a transverse magnetic field [6]. The key ingredient is still the di-photon chameleon coupling, assuming this time they can interact strongly with matter. When chameleons attempt to penetrate materials, such as walls and windows of the vacuum chamber, their effective mass grows sharply and they reflect. Therefore, chameleons with energy less than the effective mass in the material will be completely reflected by this material, allowing them to be trapped inside the vacuum chamber during the charging phase of the experiment, via the Primakoff effect. Chameleons produced in the vacuum chamber will be confined until they are being regenerated into photons in the magnetic field from the inverse Primakoff process, which emerge as an exponential decaying afterglow signal once the original laser photon source is turned off. The analysis of the 2017 run performed with a single LHC dipole is in progress and will significantly improve the present reference result obtained by the GammeV collaboration [25]. The upgrade of OSQAR-CHASE is also studied.

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