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OSQAR Annual Report 2021

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Abstract – *Ongoing activities and future plans for OSQAR [1] experiments namely OSQAR-CHASE [2], OSQAR-VMB [3] and OSQAR-LSW [4] are briefly reviewed. Based on the interaction of a laser beam with magnetic field lines, they are looking for new hypothetical particles at the low energy frontier, i.e. eV/sub-eV range, that could explain the origin of Dark Energy and Dark Matter. Upgrades of these experiments have been discussed within the scope of the Physic Beyond Collider (PBC) working group at CERN in synergy with other European initiatives from which VMB@CERN and JURA proposals are emerging.*

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Outline

[1] **O**ptical **S**earch for **Q**ED vacuum birefringence, **A**xions and **P**hoton **R**egeneration
[2] **CH**ameleon **A**fterglow **S**earch **E**xperiment
[3] **V**acuum **M**agnetic **B**irefringence
[4] **L**ight **S**hining through **W**all

1. Introduction

The ultra-low energy frontier of particle and astroparticle physics, *i.e.* eV/sub-eV range, is expected to provide evidence of new physics beyond the standard model of particle physics. This status report summarizes the main ongoing activities and perspectives of the three OSQAR experiments based on the interaction of a laser beam with transverse high magnetic field, namely OSQAR-CHASE [1,2,3,4,5,6,7,8], OSQAR-VMB [9,10] and OSQAR-LSW [9,11].

2. OSQAR-CHASE

2.1. Experimental

The chameleon afterglow search experiments (OSQAR-CHASE) were performed during summer 2016 in a preparatory context and during summer 2017 as a fine-tuned experiment. The geometry of the experimental setup is to some extent similar to the one that had been previously implemented by GammeV-CHASE [12] at FERMILAB, with however some differences compared to this experiment and between the two data collections [1-8]. In particular, GammeV-CHASE used a photomultiplier for the afterglow photon detection while OSQAR-CHASE used a Charge Coupled Device (CCD) that allow discriminating a possible signal spatially as well as temporally. This proved relevant to exclude from the outset a fake exponentially time decaying signal through its spatial distribution on the CCD [7,8]. Another advantage of the CCD is that a possible signal of given spatial shape but fully drowned in noise might be extracted by matched filtering. Two plano-convex optical lenses were inserted in the summer 2017 setup of OSQAR-CHASE to further optimize afterglow photon convergence towards the detector with respect to the summer 2016 setup of OSQAR-CHASE that used a single optical lens as GammeV-CHASE. A few counts were moreover recorded with energy filters for the afterglow photons to probe for possible chameleon fragmentation. In all the setups the injected photons during the charging phase are polarized parallel to the applied magnetic field, which is suited for the search of scalar chameleons. Only these will be discussed, although search for hypothetical pseudoscalar chameleons was also performed by inserting at the laser exit a half-wavelength plate to tip up the photon polarization along the direction perpendicular to the magnetic field.

2.2. Analysis status

No afterglow photons could be detected out of the detector noise within the two-sigma window in either of the two data taking, except for the fake signal observed in the Summer 2016 experiment, which was interpreted and experimentally removed from the data collected in the Summer 2017 experiment by subtraction of data recorded under the same conditions with and without applying the magnetic field.

Exclusion limits for scalar chameleons can be extracted from the no-detection of afterglow photons according to the count statistics by computing the expected signal. In addition to straightforwardly measurable or formulable quantities, such as the overall detection system sensitivity or the photon-chameleon conversion probability and the photon streaming rate in the chameleon chamber during the charging phase, the afterglow signal depends on the rate Γ_{DEC} at which the chameleon population decays and the rate Γ_{AFT} at which the chameleon population should produce afterglow photons, which must be accurately determined taking account of the particle bouncing in the chameleon and afterglow photon vacuum chambers incorporating the associated photons absorptions and chameleon-photon phase shifts as well as the phase shift due to mass difference. Time consuming Monte Carlo numerical integrations are needed to evaluate these rates in full generality. Accordingly, for systematic analysis of the data the calculations were performed in the 2-point path approximation, where the trajectory of the particle is inscribed inside a same plane whatever its bouncing. Cylindrical symmetry is then preserved allowing formal azimuthal integration. Another advantage is that the matrix techniques for planar propagation of optical rays in the paraxial approximation can be implemented to account for the photon propagation in the afterglow photon vacuum chamber what makes it much easier to account for the effects of the lenses. The paraxial approximation is there fully justified since only photons emerging from the exit window at small incidence angle will have a chance to reach the detector. We checked that this indeed is the case through computations in the 2-point path approximation but without resorting to paraxial approximation. We found that the exclusion limit for the chameleon-photon coupling did not differ by more than 2%. Now concerning the 2-point path approximation, it was reported by GammeV-CHASE[12] that the computations of the chameleon decay and afterglow photon rates in full generality would differ from those in the 2-point path approximation by about only 8% for Γ_{AFT} though by about 40% (possibly more) for Γ_{DEC}. These numbers still need to be checked. In this work, priority has been given to the analysis of the data collected in the Summer 2017 in the setup with two focusing lenses.

As stated in our previous report [8] our computations were validated by reproducing the exclusion limits for the GammeV-CHASE experiment from their published data [12]. These exclusion limits were then compared to those obtained for OSQAR-CHASE from the summer 2016 experiment, the setup of which was similar to the GammeV-CHASE experiment, using in particular a single optical lens. The constraints were improved by one order of magnitude with OSQAR-CHASE (more precisely by a factor of about 12 for chameleon mass $m_{eff} \leq 0.2$ μeV). Our recent computations show that the experimental setup considered in the summer 2017 experiment does not lead to improved exclusion limits. Using two focusing lenses improves these limits only by 2%. On the hand there is a small diameter reduction of the optical chamber in the region of the second lens which deteriorates the exclusion limits by about 4%. The exclusion limits in the (chameleon mass m_ϕ, chameleon-photon coupling β_γ) parameter space deduced from the data collected in the summer 2017 experiment are reported figure 1. Unlike the GammeV-CHASE case they show some dependence on the chameleon potential model V, which we had explained in our previous report [8].

Exclusion limits in the (chameleon-matter coupling β_m, chameleon-photon coupling β_γ) parameter space for a given chameleon potential can be inferred from those above in the (chameleon mass m_ϕ, chameleon-photon coupling β_γ) parameter space through the chameleon mass dependence on β_m, β_γ, local mass density ρ_m, local electromagnetic density ρ_γ and parameters, g or M_Λ, k, of the considered chameleon potential V.

It remains before publication to consider the robustness of these exclusion limits with regard to the approximations that still persist in the analyzes, mainly the 2-point path approximation which is currently being examined. It should be emphasized however that since the expected afterglow signal is proportional to β_γ^4 then β_γ should not be impacted by more than 25% in the pessimistic instance where Γ_{AFT} would differ by 10% and Γ_{DEC} by 45%. We also assess the effects of non-specular photon reflections and of chameleon fragmentation the possibility of which is expected for chameleon potentials with high exponents.

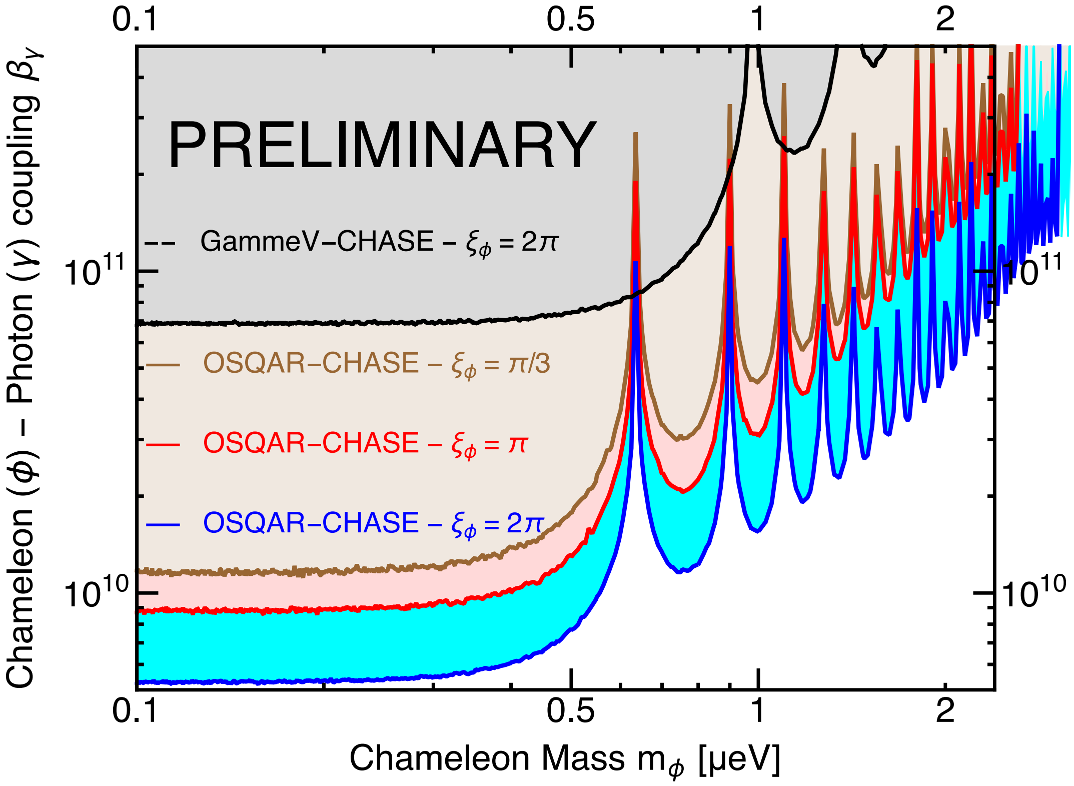

Fig. 1. Exclusion limits in the (chameleon mass m_ϕ, chameleon-photon coupling β_γ) parameter space, deduced from no signal observation and detector noise in the OSQAR-CHASE data collected in summer 2017 with the experimental setup using two focusing optical lenses, for different chameleon phase shifts ξ_ϕ at each bouncing on the walls. These shifts depend on the chameleon potential, more precisely $\xi_\phi = n\pi/(n-2)$ for $V = g\,\phi^n$, $\xi_\phi = n\pi/(n+2)$ for $V = g\,\phi^{-n}$ and $\xi_\phi = \pi$ for $V = M_\Lambda^4[1 + e^{-\kappa\phi/M_\Lambda}]$.

3. OSQAR-VMB

During 2021, some experiments were carried out in the framework of the VMB@CERN collaboration [13]. Optical tests of rotating half-wave plates and full-wave plates as neutral elements were carried out at the optical laboratory of the Technical University of Liberec (Fig. 2 & 3). The effects of the rotational instabilities of the motors on the optical frequencies were investigated, as well as the effects of the optical defects of the phase plates themselves on the measurement results. The measurements were performed in homodyne mode and were an initial test of the instabilities and defects in the conception of the rotation of the optical elements. The effects of temperature on the overall system response were also investigated. The main analysis of rotation and phase element defects was carried out in heterodyne mode in the laboratory of INFN Università di Ferrara by the team of G. Zavattini. A heterodyne system will be installed in Liberec next year to re-analyze and confirm the results obtained in Ferrara. All results will be presented in detail within the VMB@CERN proposal.

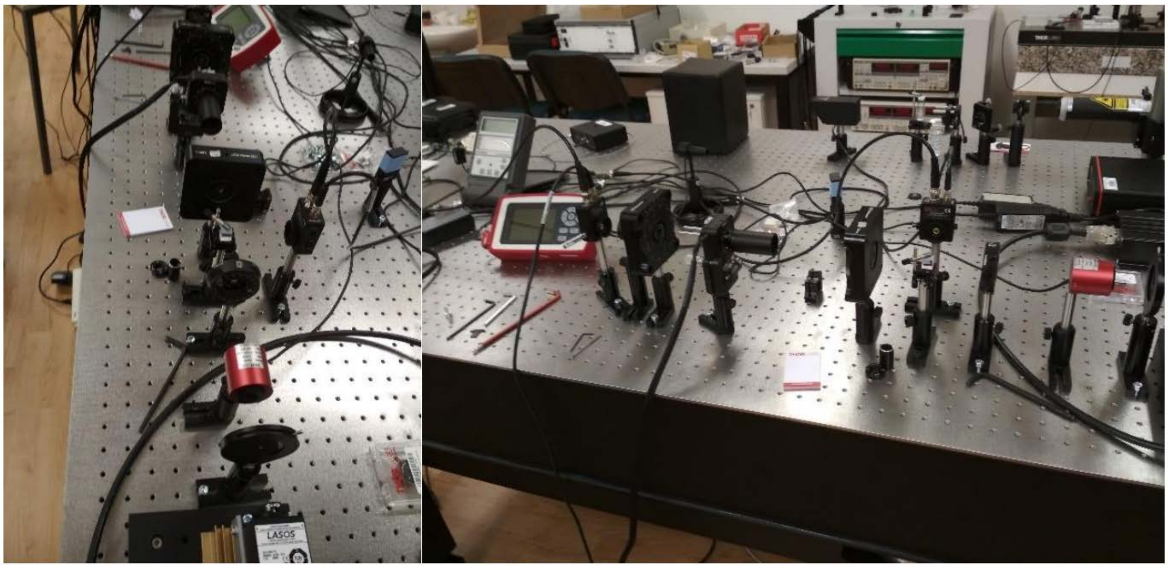

Fig. 2. Optical experimental set-up at the Technical University of Liberec (Czech Republic).

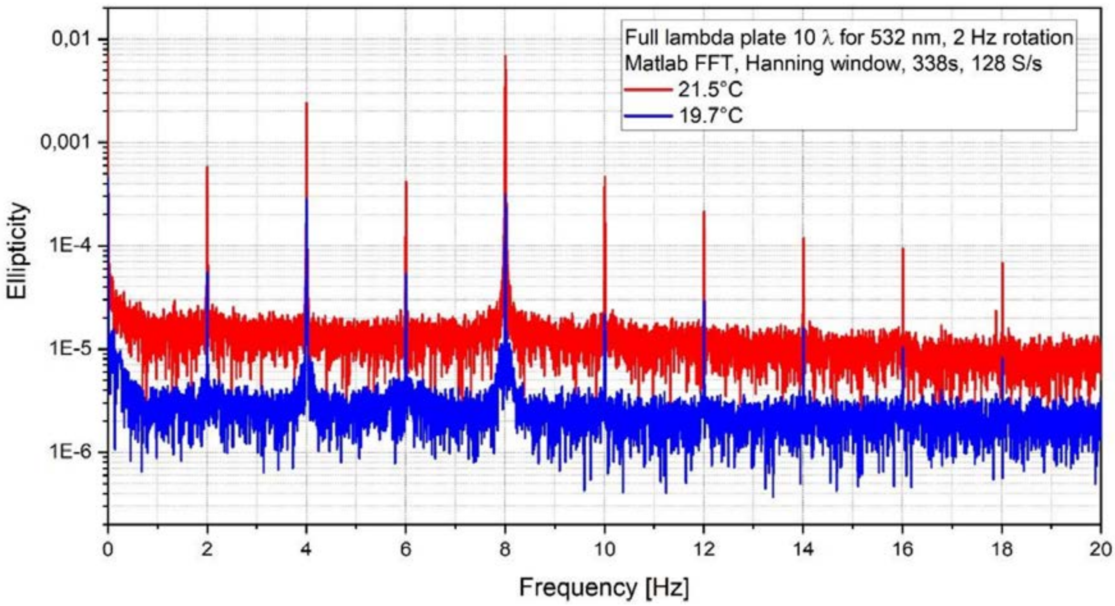

Fig. 3. Temperature dependence of the ellipticity measured with the full rotating wave plate at 532nm.

4. OSQAR-LSW

4.1. From OSQAR to JURA

As already addressed previously [8],[14] and discussed within the PBC working group[15], OSQAR-LSW is preparing the JURA proposal (Joint Undertaken Research on Axion/ALPs) for which the Baby-JURA/OSQAR-LSW+ preparatory step is presently considered. In this context, research on structured beams, which are used to adjust the positions of various components of the detectors at CERN, is ongoing in collaboration of Technical University of Liberec with the Engineering Department of CERN. This new method is very important because in Light Shining-through-the-Wall experiment there will be used a number of resonant optical cavities in future that will need to be very precisely set up before they are triggered. A number of simulations and experiments have been carried out which show that the required pre-alignment accuracy can be very well achieved for this type of experiment. It is shown that accuracies of 0.001 mm at 100 m distance can be achieved and that the position of the optical beam will be stable in vacuum. Research is also underway to apply this method to the positioning of other optical elements such as mirrors and lenses. Using simulations and experiments, a methodology has been developed to adjust the positions of these optical elements very accurately.

Fig. 4. Structured light beam with almost non-diverging bright central part, useful for optical elements alignment.

Technical University of Liberec is also working on basic research on the polarization structure of these structured beams. Using theoretical analysis, experiments and simulations. We have shown that it is possible to create optical beams in which the electric field or magnetic field is locally parallel to the direction of wave propagation. In the center of the beam there is then a hollow beam, where no energy is propagated, but an electromagnetic wave is propagated which has locally non-classical properties. This electromagnetic field can be adjusted in such a way that the electric and magnetic components with the light wave can be parallel to each other. Moreover, they can oscillate together with a phase difference that can be adjusted by special optical elements. We would like to use these non-classical optical fields for experiments measuring magnetic induced birefringence in vacuum.

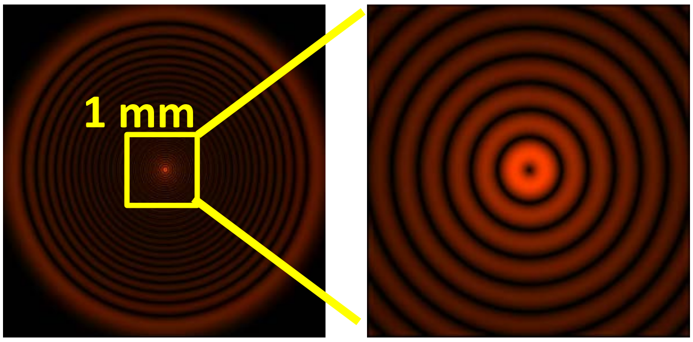

Fig. 5. Hollow structured light beam with longitudinal electric or/and magnetic field in central part.

4.2. Toward new initiatives

Prospects and preliminary studies for complementary magneto-optical experiments in various directions are being pursued. The alternative scheme based on a resonant atomic or molecular transition induced by resonant axion absorption [16] is still under evaluation in collaboration with the atomic physic group of Warsaw University. Among the interests of this proposal is that the obtained signal in second order in the axion-electron coupling constant may become of first order, if interferences are allowed between the axion-induced transition amplitude and the transition amplitude induced by the electromagnetic radiation producing the axions.

5. Conclusion & Perspectives

OSQAR-CHASE data analysis is close to completion with a better sensitivity than anticipated [1], thanks mostly to the better performance of the CCD detector used.

OSQAR-VMB activities are being pursued within the new broader collaboration VMB@CERN. Technological challenges, mostly in optical metrology, are deeply investigated and promising results were obtained and will be presented in the VMB@CERN proposal.

OSQAR-LSW activities is focused on the long term JURA initiative and the first step Baby-JURA is in line with the OSQAR plan[14] and will profit from the development of long fabry-Perot cavities for VMB@CERN. A new experimental scheme based atomic or molecular transitions due to the absorption of axions is still under investigation. Its scientific interest is to be complementary to most axion/ALP worldwide search experiment by providing access to the axion-electron coupling.

Future activities for VMB@CERN and Baby-JURA are planned to be conducted in parallel. Both these activities will require for the coming years the installation of a dedicated spare LHC dipole on the OSQAR cryogenic bench in the CERN SM18 hall.

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Annex – Highlights

Knowledge Transfer

- "Structured Laser Beam", Miroslav Šulc (Technical Univ. Liberec, Czech Republic) & Jean-Christophe Gayde (CERN)

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  .https://home.cern/news/news/knowledge-sharing/long-sighted-laser-beam