Abstract – For 2015, the OSQAR collaboration will focus on a new proposal for the search of chameleon, a hypothetical scalar particle postulated as a dark energy candidate with an environment-dependant mass. The required experimental set-up has been successfully tested and validated in 2014 at the SM-18 experimental hall. This proposal will focus on the sensitivity that can be reached during the OSQAR chameleon run in 2015 as well as to possible upgrade phases of the experiment for the coming years.

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1. Introduction

OSQAR aims to explore the low energy frontier of particle/astroparticle physics by combining the simultaneous use of high magnetic fields with laser beams. A recent review of the scientific motivations concerning the search of new particles at ultra-low energy such as axions and WISPs (Weakly Interacting Sub-eV Particles) can be found in [1]. Originally, the OSQAR proposal has focused on two distinct experiments. In the first one, the photon regeneration effect mediated by axions/WISPs is looked for as a Light Shining through the Wall (LSW) [2][3], whereas in the second one, the ultra-fine Vacuum Magnetic Birefringence (VMB) predicted by the QED has been targeted to be measured for the first time [4].

For 2015, a third OSQAR experimental set-up is proposed [5] for the search of a new type of particles called “chameleons” with its mass depending on its surroundings [6]. This new kind of particle provides a way of explaining dark energy as a scalar field evolving in an effective potential, with a self-interaction of the runaway form and a conformal coupling to matter, the minimum of which depend on the local matter density in such a way that the experimental constraints of fifth force and violation of equivalence principle are exponentially relaxed. Based on a possible coupling to photons, chameleons can manifest through a magneto-phosphorescence effect of the vacuum. It is recalled that the phosphorescence is a luminescence that is caused by the absorption of light and continues for a noticeable time after the lighting is switched off, in contrast to fluorescence.

The physics of chameleons is briefly introduced in the next section. It will allow identifying the key ingredients necessary for their search, which concern their production from photons under magnetic field, their confinement crucially depending on their effective potential, and their indirect detection from their conversion into photons that need to be specifically identified. Then the principle of the Chameleon Afterglow Search Experiment (CHASE) will be reminded. Finally, the OSQAR experimental set-up based on the use of a single spare LHC dipole will be presented together with the sensitivity that can be expected to be reached during the 2015 experimental run as well as later on after dedicated upgrades.

2. Overview of chameleon theory

Chameleon physics emerged from the finding that a scalar field might evolve at cosmological scales while being strongly coupled to matter without being detected so far because it acquires a mass that depends on the local matter density [6]. The generic action of the scalar-tensor theory of this quintessence with the gravity is given in the Einstein-frame by

\[ S = \int d^4x \sqrt{-g} \left\{ \frac{M_P^2}{2} \mathcal{R} - \frac{1}{2} (\partial \phi)^2 - V(\phi) \right\} + S_m(g_{\mu\nu}^{(i)}, \psi_i) \]

(1)

where \( S_m \) stands for the matter action. \( g \) is the determinant of the Einstein-frame metric \( g_{\mu\nu}, M_P \) is the Planck mass and \( \mathcal{R} \) is the Ricci scalar. The field \( \phi \) is minimally coupled to gravity, but directly to each matter field \( \psi_i \) through the Weyl rescaled metric \( g^{(i)}_{\mu\nu} = A^{(i)}(\phi)^2 g_{\mu\nu} \). A coupling of the form \( A^{(i)}(\phi) = \exp(\beta_i \phi/M_P) \) is generally considered with coupling constants \( \beta_i \) allowed to be of order unity, which often is simplified as \( A^{(i)}(\phi) = 1 + \beta_i \phi/M_P \) since \( \beta_i \phi/M_P << 1 \) from cosmological models and local gravity experiments. The potential \( V(\phi) \) must lead to the late time acceleration of the expansion of the Universe while avoiding the cosmic coincidence problem of the present era\(^1\) [7]. A prototype fulfilling this

\(^1\) This requires that the field \( \phi \) must roll down the potential \( V(\phi) \) slowly enough in the late era, which includes the present one, so as to have its kinetic energy lower than its potential energy thereby producing the negative pressure associated with Dark Energy. The problem of the present era is to explain why the matter and missing energy densities nearly coincide when these densities decrease at different rates as the Universe expands, which for many forms of potentials often imposes to have recourse to unwanted fine-tuning of the initial conditions. This is avoided if the field \( \phi \) rolls down the potential \( V(\phi) \) towards an attractor insensitive to the initial conditions, which is achieved with the potentials \( V(\phi) \) in which the logarithmic derivative \( \partial \mathcal{L} \phi/V(\phi) \) monotonically decreases as the field \( \phi \) rolls down the potential.
requirement is \( V(\phi) = M_4^4 \exp(\kappa M_4^s/\phi) \), where \( M_4 \) is the Dark Energy scale \( \gamma \), \( \kappa \) is a dimensionless parameter and \( n > 0 \) is a positive integer, which for large field \( \phi \gg M_4 \) is approximated by the constant plus inverse power-law potential \( V(\phi) = M_4^4 + \kappa M_4^s \phi^{-n} \). Chameleon effects are also explored for other choices of Weyl rescaling and field potential, e.g. field-dependent inverse power-law coupling \( \beta_i(\phi) = (\lambda_i M_4^s/\phi)^i \) and potential \( V(\phi) = M^4 \exp(\alpha \phi^N/\Lambda^p) \) or power-law potential \( V(\phi) = M^4 + (\alpha \phi^N/\Lambda^p) \). [8]

The variation with respect to the field \( \phi \) of the action \( S \) in the case of a single non-relativistic matter field \( \psi \) leads to the field equation \( \Box \phi = \varepsilon \phi V_{eff} \) with the effective potential \( V_{eff}(\phi) = V(\phi) + \rho_m A^m(\phi) = V(\phi) + \rho_m \exp(\beta_\phi M_4) \), which is an explicit function of the matter density \( \rho_m \). Although it is required that the potential \( V(\phi) \) must be monotonically decreasing, the potential \( V_{eff}(\phi) \), which effectively governs the dynamics of the field \( \phi \), exhibits a minimum once \( \beta_\phi M_4 > 0 \). The mass \( m_{eff} \approx (\varepsilon \phi V_{eff}(\phi_{min}))^{1/2} \) of small fluctuations at this minimum is computed in linear coupling \((\beta_\phi M_4 M_4 \ll 1)\) and large field approximations \( (\phi \gg M_4) \) to \( m_{eff} = M_4^{4+n} (n+1) \left( \beta_\phi \rho_m \right)^{(n+2)/(2n+2)} \left( n M_4 M_4^{4+n} \right)^{(n+2)/(2n+2)} \), which is the more large as the coupling constant \( \beta_\phi \) and the matter density \( \rho_m \) are large. This basically characterizes the chameleon mechanism by which the scalar field \( \phi \) can hide from the searches of a Fifth Force. This constraint, as well as the more stringent constraint on the violation of the Equivalence Principle in the presence of several matter fields with different coupling constants \( \beta_\phi \) is strongly relaxed when the matter shows a thin shell \([6]\), i.e. when the field potential increases steeply from its background minimum to its matter minimum. The thin shell effect is all the more effective as the matter couplings are large, which means that stronger matter-couplings lead to less restrictive bounds. This counter-intuitive conclusion is the essence itself of the chameleon physics.

The electromagnetic interaction is invariant by Weyl rescaling in \( d = 4 \) dimensions \([9]\). It thus would appear that no coupling of the chameleon field \( \phi \) with electromagnetism is imposing by itself, which to a first sight should invalidate its search by optical means. Actually, this is true only at the classical level. At the quantum level a Weyl anomaly arises, which naturally induces a coupling between the field \( \phi \) and the kinetic term of any gauge field coupled to fermions \([10]\). In the case of the electromagnetic gauge field \( A_\gamma \), this leads to add to \( S \) the action

\[
S_\gamma = \int d^4x \sqrt{-g} \left\{ -\frac{1}{4} e^{\beta_\gamma \phi/M_4} F_{\mu\nu} F_{\mu\nu} \right\}
\]

where \( F_{\mu\nu} = \varepsilon_{\mu\nu\alpha\beta} A_{\alpha\beta} \) is the electromagnetic tensor and \( \beta_\gamma \) is a coupling constant. The effective potential \( V_{eff}(\phi) \) governing the dynamics of the field \( \phi \) in the presence of an electromagnetic field then is characterized by the additional contribution \( (F_{\mu\nu}^2 F_{\mu\nu}^2/4) \exp(\beta_\phi \phi/M_4) = (1/2)(E^\gamma B^\gamma) \exp(\beta_\gamma \phi/M_4) \). Its minimum in the presence of matter and the mass \( m_{eff} \) of small fluctuations at this minimum are shifted accordingly. Inside the matter bulk the matter density \( \rho_m \) is in general much larger than the electromagnetic density \( \rho_\gamma = F_{\mu\nu}^2 F_{\mu\nu}/4 \) so that one can rather safely ignore the electromagnetic field. In actual or laboratory vacuum the matter field is rarefied but not totally absent. The minimum of the effective potential \( V_{eff}(\phi) \) and the mass \( m_{eff} \) of the small fluctuations at this minimum will depend on this residual matter density \( \rho_{m_{\text{vac}}} \), but also on the electromagnetic density \( \rho_\gamma \). Another consequence of the coupling to electromagnetism is that photons in a background magnetic field can oscillate coherently with the chameleon particles associated with the small fluctuations at the minimum of the effective potential \( V_{eff}(\phi) \), provided that the mass \( m_{eff} \) of these particles does not exceed the photon energy. These oscillations are deduced by perturbing about constant background chameleon field \( \phi \) and magnetic field \( \beta \) and are described to first order of perturbation by \([11],[12]\).

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2. \( M_\Lambda = \Omega_\Lambda^{1/4} \left( 3 H_0^2 M_{\text{Pl}}^2 \right)^{1/4} \) is computed around 2.4 \( 10^{-12} \) GeV with \( \Omega_\Lambda \approx 0.7 \), the Hubble constant \( H_0 \approx 2 \times 10^{-42} \) GeV and the Planck mass \( M_{\text{Pl}} = (8 \pi G)^{-1/2} \approx 2.435 \times 10^{18} \) GeV.

3. The action of the electromagnetic interaction in d dimensions \((1/4) \int d^4x (-g)^{1/2} \psi^\dagger \gamma^\mu \gamma^\nu F_{\mu\nu} \) is transformed to \((1/4) \int d^4x (-g)^{1/2} \left( g^\mu \right)^{\gamma_{\dagger}} g^\nu \gamma^\sigma A^{(\dagger)}(\phi)^{3/4} F_{\mu\nu} F_{\gamma\sigma} \) under Weyl rescaling \( g^\mu_{\dagger\nu} = A^{(\dagger)}(\phi)^2 g_{\mu\nu} \).
Writing these perturbations in terms of chameleon and photon amplitudes the probability that in the case of a constant uniform magnetic field $\vec{B}$ a particle in a pure chameleon state with wave vector $\vec{k}$ at an initial time transmute into a pure photon state with energy $\omega = (k^2 + m_{\text{eff}}^2)^{1/2}$ at a later time $t$, or conversely, is obtained, in the relativistic limit, as $^{11,12}$

$$P_\gamma \leftrightarrow \gamma = \left( \frac{2\beta_\gamma}{kM_{\text{P}}m_{\text{eff}}^2} \right)^2 |\vec{k} \wedge (\vec{B} \wedge \vec{k})|^2 \sin^2 \left( \frac{m_{\text{eff}}^2 t}{4k} \right)$$  \hspace{1cm} (4)

It is finally noticed that the above approach can be generalized on phenomenological grounds to a pseudo-scalar field showing the chameleon mechanism, with a coupling to the electromagnetic field now of the form $(F^{\mu\nu} F_{\mu\nu}^* / 4) \exp(\beta_\gamma \phi / M_{\text{P}}) = \vec{E} \cdot \vec{B} \exp(\beta_\gamma \phi / M_{\text{P}})$ where $F_{\mu\nu}^* = (1/2) e^{\mu\nu\tau\sigma} F_{\sigma\tau}$ is the dual of $F^{\mu\nu}$.

3. New proposal from the OSQAR collaboration: The quest of chameleons

3.1. Principle of the chameleon search in laboratory

It follows from equation (4) that a linearly polarized beam of photons propagating in a laboratory vacuum permeated by a uniform magnetic field perpendicular to the photon propagation and to the photon polarization, namely parallel to the magnetic component $\delta\vec{B}$ of the photon field, will be partly transmuted into chameleon particles of same energy for photon energy $\omega$ larger than the effective mass $m_{\text{eff}} (\beta_{\text{vac}} \rho_{\text{vac}} + \beta_\gamma \rho_\gamma)$ of the chameleon field in that laboratory vacuum. If the energy $\omega$ is lower than the effective mass $m_{\text{eff}} (\beta_m \rho_m)$ of the chameleon field inside the matter that encloses the vacuum then the produced chameleon particles will be trapped inside the vacuum and if the enclosing matter is transparent to photons then only chameleon particles will remain inside the vacuum once the source is switched off (Fig. 1). The only way then for these particles of escaping from their trap is to wait for being transmuted back into photons, which gives rise to an afterglow effect thereby providing an experimental mean for detecting the chameleons.

The principle of a magneto-phosphorescence experiment, has been first implemented by GammeV $^{13}$ and improved by the GammeV-CHASE experiment $^{14}$. Most of the technical issues for such type of experiment including the most crucial ones, have been raised and developed in detail in $^{13,15}$. Following the description of GammeV $^{13}$, the flux of afterglow photons can be modeled as:

$$N_{\text{afterglow}}(t) = \frac{\eta P f_{\text{esc}} f_{\text{vol}}}{\omega \Gamma L_{\text{total}}} \frac{c}{c} (1 - e^{-\Gamma \Delta t}) e^{-\Gamma t}$$ \hspace{1cm} (5)

In this expression, $\eta$ is the detector efficiency, $P$ the power of the laser, $f_{\text{esc}}$ and $f_{\text{vol}}$ the chameleon escape fraction and the volume fraction respectively, $\Gamma$ the mean decay rate by chameleon, $L_{\text{total}}$ the total length of the chameleon chamber (larger than the magnetic length $L$ if no segmentation is used) and $\Delta t$ the filling duration.
Fig. 1: Principle of the two phase OSQAR afterglow experiment. In phase 1, an absorber is inserted in front of the CCD detector for its protection against the high power laser beam. The dashed line represents the chameleons, which are supposed of being strongly interacting with matter. Consequently they are totally reflected by the windows of the vacuum chamber, trapped and accumulated during the phase 1. In phase 2, the laser is switch-off allowing the detection of the magneto-phosphorescence effect coming from the conversion of chameleons to photons.

3.2. Integration and validation test of the experimental set-up

The afterglow experiment principle (Fig. 1) can easily be integrated within the OSQAR set-up with minimal investments. Regarding to magnetic requirements this configuration is less demanding than the “Light Shining through Wall” (LSW) experiment as it requires the use of a single spare LHC dipole connected to its cryogenic feed box (CFB) (Fig. 2) to provide magnetic field up to 9 T.

Fig. 2: Layout of a cold test bench with the LHC dipole magnet dedicated to OSQAR. The cryogenic feed box (CFB) constitutes the interface providing the liquid He to the superconducting magnet as well as the electrical interconnections to the power supply. The total length of the LHC dipole plus the CFB is equal to 19.6 m.

Spare LHC dipoles dedicated to OSQAR have been specially prepared, straightened and the geometry of the apertures measured with laser tracker [16]. Anticryostats, one per magnet aperture, developed for LHC dipoles to host long rotating pick-up coils for field quality measurements [17] are planned to be reused. For the OSQAR-CHASE run in 2015 the anticryostat of the selected magnet aperture will be closed at both ends with BK7 windows and will constitute the vacuum chamber. Its electrical powering maintaining
its temperature closed to the ambient one will be switched-off to profit from the cryo-pumping effect. The possibility of removing the anticryostat and using directly the cold bore of the LHC dipole with diameter equal to 50 mm will be considered at a later stage, this only if a real gain can be demonstrated. In Fig.2, the laser beam input is located in the downstream end whereas the detection part of the experiment in the upstream one.

The overall OSQAR-CHASE experimental set-up is schematized in Fig. 3. The new ingredient with respect to OSQAR-LSW experiment is the system allowing the fast and safe laser beam dump within the dark chamber in front of the photon detector at the upstream end. For the phase 1 of the experiment, i.e. the filling of the jar with chameleons (Fig. 1), the valve 1 and the valve 2 are open and the beam is reflected by a mirror to the absorbing brick whereas the valve 3 is close to protect the CCD (Fig. 3). During the phase 2 of the experiment, i.e. the detection of possible afterglow regenerated photons (Fig. 1), the valve 1 and the valve 2 are closed for the darkness required by the photon detection whereas the valve 3 is open (Fig. 3). The status of valves for both phase of the experiment as a function of the various phases of the experiment is summarized in Table 1.

![Scheme of the experiment with the laser in the right side, the CCD in the left one, 3 valves, a mirror and the laser beam dump.](image)

**Fig. 3:** Scheme of the experiment with the laser in the right side, the CCD in the left one, 3 valves, a mirror and the laser beam dump.

<table>
<thead>
<tr>
<th>Valve 1</th>
<th>Valve 2</th>
<th>Valve 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open</td>
<td>Open</td>
<td>Close</td>
</tr>
<tr>
<td>Close</td>
<td>Close</td>
<td>Open</td>
</tr>
</tbody>
</table>

*Table 1: Both configurations of the experiment corresponding to both phases described in Fig. 1*
The OSQAR configuration for the quest of chameleon particles has been tested with two main objectives [5]. The first one was to develop and test dedicated systems allowing risk mitigation in the use of the 18 W laser. A safe running of the experiment for operators and detector shall be demonstrated. The second objective was to reach the shortest time delay between switching off the laser generating particles inside the anticryostat of the LHC dipoles and the opening the CCD shutter for the photon detection. As the afterglow coming from chameleons are expected to decay exponentially with unknown time constant, shortest time should improve in principle the experiment sensitivity.

Both phases of the experiment described in Fig. 1 and Table 1 have been successfully tested with 18.5 W laser beam as well as the operational sequences allowing the transition between them. The time delay of the transition between the phase 1 and the phase 2 has been measured several times and found to be in the range 6-20 s with the use of manual valves. Improvements with automatic valves are under study to detect particles with shorter lifetimes. It can be mentioned that for GammeV [13] the time gap between filling the chamber and observing the afterglow was longer, i.e. in the range 300-1000 s. It should be highlighted that GammeV-CHASE has observed an anomalous orange afterglow effect, which is not yet explained and found to disappear once the vacuum chamber was warmed up. This non-magnetic-phosphorescence effect at a different wavelength than the laser one has prevented GammeV-CHASE to observe possible chameleon afterglow immediately after the laser switch-off, i.e. for t < 120 s [14]. During feasibility tests performed in 2014 [5], no afterglow effect has been observed within the OSQAR experimental set-up but the cryostat of the LHC dipole was not yet cooled down to profit from the cryopumping effect.

3.3. Results from measurements and simulation of the photon collection efficiency

3.3.1. Measurements of the reflection coefficient of the anticryostats

The optical reflectivity of the inner part of the anticryostat has been measured at the Technical University of Liberec as a function of the reflection angle with a 532 nm laser beam (Fig. 4). A high contribution of diffuse reflection has been observed and the minimum reflectivity measured is equal to 32 %. Fig. 5 shows as a comparison the results obtained for a polished stainless-steel. Teflon can offer an

<table>
<thead>
<tr>
<th>Parameters</th>
<th>OSQAR-CHASE</th>
<th>GammeV</th>
<th>GammeV-CHASE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l_1$ (m)</td>
<td>1.25</td>
<td>2.36</td>
<td>1.61</td>
</tr>
<tr>
<td>$L$ (m)</td>
<td>14.3</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>$l_2$ (m)</td>
<td>4.05</td>
<td>1.16</td>
<td>1.74</td>
</tr>
<tr>
<td>$l_4$ (m)</td>
<td>0.25</td>
<td>2.03</td>
<td>0.64</td>
</tr>
<tr>
<td>$l_5$ (m)</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>$\phi_1$ (mm)</td>
<td>40</td>
<td>47.6</td>
<td>63.5</td>
</tr>
<tr>
<td>$\phi_{lens}$ (mm)</td>
<td>40</td>
<td>50.8</td>
<td>50.8</td>
</tr>
<tr>
<td>$\phi_{detect}$ (mm)</td>
<td>13</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Detector efficiency</td>
<td>0.85</td>
<td>0.29</td>
<td>0.29</td>
</tr>
<tr>
<td>$t_0$ (s)</td>
<td>≥ 6</td>
<td>1006</td>
<td>120</td>
</tr>
<tr>
<td>$\Delta t$ (s)</td>
<td>600-3600</td>
<td>3616</td>
<td>600-3600</td>
</tr>
<tr>
<td>$&lt;f_{ref}&gt;$ measured (%)</td>
<td>32-33</td>
<td>53</td>
<td>53</td>
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<tr>
<td>$k \approx 10$ (eV)</td>
<td>2.33</td>
<td>2.33</td>
<td>2.33</td>
</tr>
<tr>
<td>$P_{laser}$ (W)</td>
<td>18.5</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>$B_{max}$ (T)</td>
<td>9</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>$V_{pump}$ (m$^3$)</td>
<td>NA</td>
<td>0.026</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Table 2: Characteristics of the OSQAR-CHASE, GammeV and GammeV-CHASE experiments
optimal reflectivity of 99% and both options are under investigation for the upgrade of the experiment. All these data have been used for the simulations presented in the next section.

![Graph](image)

**Fig. 4.** Reflection coefficient of the inner part of the anticryostat measured at 532 nm as a function of angle of incidence of the light; the green line corresponds to s-polarized light (i.e. electric field oriented perpendicular to the plane of incidence), blue to the p-one (i.e. electric field oriented parallel to the plane of incidence) and red to the average value.

![Graph](image)

**Fig. 5.** Reflection coefficient of polished stainless-steel measured at 532 nm as a function of angle of incidence of the light; the green line corresponds to s-polarization of the light, blue to the p-one and red to the average value.

3.3.2. First results from simulations with Zemax®

The sensitivity of the OSQAR-CHASE experiment depends strongly on a geometrical factor that needs to be calculated. Surfaces with high optical absorption act as a filter and select only photons with trajectories parallel or nearly parallel to the vacuum chamber axis before reaching the detector.

Simulations have been performed using Zemax® [18] using the optical reflectivity measured and shown in Fig. 4 and Fig. 5. An isotropic and homogeneous source of photons inside the volume of the
anticryostat immersed in the magnetic field has been assumed. This volume corresponds to a cylinder of length \( L = 14.3 \) m and diameter \( \varnothing_1 = 40 \) mm whereas the total distance between windows enclosing the vacuum chamber is equal to \( l_1+L+l_2 = 19.6 \) m (Fig. 3 and Table 2). The fractions of photons reaching two important locations of the experiments have been calculated. The first one corresponds to the exit window of the anticryostat and the second one to the sensitive area of the photon detector. A focusing plano-convex lens clamped to the output window has been added. The position of the detector has been adjusted to the focal length to increase the number of photons reaching the sensitivity area but the shape of the lens has not yet been optimized. Because optical rays are pointing in all direction, they cannot be focused to a small area of the detector as shown for two cases in Fig.6, i.e. for the stainless-steel of the anticryostat (Fig. 6a) and for perfectly polished stainless-steel (Fig. 6b).

![Fig. 6. Distribution of photons in the detector sensitive area of dimension 13 x 13 mm² focused by a non-optimized lens, i.e. irradiance in W/cm², assuming the optical reflectivity of a) the stainless-steel of the anticryostat and b) polished stainless-steel.](image)

A summary of results obtained from first simulations are given in Table 3. These numbers can be used to estimate the sensitivity of the OSQAR-CHASE experiment during the 2015 run and to anticipate possible upgrades. The calculated fraction of photons reaching after the focusing lens, the detector of surface area equal 13 x 13 mm² are close to the ones given by GammeV and GammeV-CHASE equal to \( 1.57 \times 10^{-4} \) and \( 0.984 \times 10^{-4} \), respectively \[^{[15]}\].
Table 3: Photon collection efficiency calculated as a function of the material of the vacuum chamber at various locations within the OSQAR experiment (NOLP: Not Optimized Lens & Position)

<table>
<thead>
<tr>
<th>Locations where the fraction of photons were calculated</th>
<th>Output window</th>
<th>Detector without lens</th>
<th>Detector with lens (NOLP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stainless-steel of the anticryostat</td>
<td>$2.294 \times 10^{-4}$</td>
<td>$0.276 \times 10^{-4}$</td>
<td>$1.009 \times 10^{-4}$</td>
</tr>
<tr>
<td>Polished stainless-steel</td>
<td>$3.228 \times 10^{-4}$</td>
<td>$0.362 \times 10^{-4}$</td>
<td>$1.072 \times 10^{-4}$</td>
</tr>
<tr>
<td>Teflon, 99 % reflectivity</td>
<td>$4.588 \times 10^{-4}$</td>
<td>$1.340 \times 10^{-4}$</td>
<td>$1.810 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

4. OSQAR-CHASE experimental runs and possible upgrades

4.1. Experimental run in 2015-2016

4.1.1. Objectives

As a first step the OSQAR-CHASE will focus on:
- The study of the “anomalous” orange afterglow effect observed by the GammeV-CHASE collaboration [19] and investigate its impact on chameleon search,
- The validation of simulations results and crosscheck of input parameters with dedicated in-situ measurements, and
- The improvement of the massless limit of Chameleon search obtained by GammeV-CHASE.

The anomalous orange afterglow has been attributed by GammeV-CHASE [14],[15] to the photoluminescence induced by the green laser of organic compounds such as vacuum grease. If it is the case, thorough cleaning of the vacuum chamber should prevent its occurrence. The ACES collaboration has proposed another possible source for the orange afterglow and has attributed it to the optical de-excitation of the stainless-steel vacuum chamber at low temperature after lighting [20].

Because of time constraint, it is not planned at this first step to perform multiple runs with different magnetic field values and the magnetic field will be fixed to the maximum of 9 T. The request for 2015 from the collaboration concerns the possibility of using one of the LHC dipoles at 1.9 K committed for OSQAR together with dedicated resources for minimum experimental run duration of 6 weeks planned from mid August up to the end of September (Table 4). If more time can be allocated, experimental runs with intermediate field values will be conducted or they will be postponed for the next year(s).

Table 4: Simplified planning of the OSQAR-CHASE activities at CERN for 2015.

<table>
<thead>
<tr>
<th>Anticryo. pumping tests</th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sept</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laser/CCD order &amp; tests</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>X</td>
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4.1.2. Configuration of the experiment

The experimental run will focus to the chameleon search with the set-up shown in Fig. 3 and specially developed and successfully tested at CERN [9]. In addition as described in section 3.2, the selected
aperture of the LHC dipole for OSQAR CHASE will be fitted with an anticryostat that will serve as vacuum chamber. It will be closed by two BK7 windows with antireflection coating clamped at each end. One of the key points of the experiment concerns the leak tightness of the vacuum chamber with a leak rate that shall be better than $10^{-8}$ mbar l/s at ambient temperature. Once the integrity of the vacuum chamber is obtained, the pumping can start using a turbo-molecular pump to reach a residual pressure of about $10^{-8}$ mbar. Then the cooling of the anticryostat/vacuum chamber can start by switching-off its heater. Once the anticryostat will reach about 80 K, the turbo-molecular pump will be less efficient than the cryopumping effect and can eventually be switch-off after closing the valve at the entrance of the anticryostat. The use of a sputter ion pumping group instead of the turbo-molecular one is meaningless if the leak rate is sufficiently low to not require a permanent pumping. As another remark concerning ultra-high vacuum (UHV) conditions concern pressure measurements. It is important to remind that in general, when the pressure is measured in a tube, due to the conductance limitation, the value obtained is not related directly to the quality of the vacuum achieved inside the tube but to the outgassing around the pressure gauge. Typically for a LHC dipole cooled down to 1.9 K, the magnet aperture and hence the anticryostat will reach a residual pressure that typically will be equal to the saturated vapor pressure of H$_2$ at this temperature, which is of the order of $10^{-15}$-$10^{-16}$ mbar.

For the photon source, the same Verdi V18-series CW laser as the one used for the last run of OSQAR-LSW \[5\] will be rented from Coherent GmbH. It is a diode-pumped solid-state laser delivering 18.5 W at 532 nm, \textit{i.e.} at 2.33 eV.

For the detection, the thermoelectric cooled CCD - Andor iKon-M 934 Series used for OSQAR-LSW \[5\] will be rented. The CCD sensor is composed of a 2D array of 1024 x 1024 square pixels of 13 µm size. The quantum efficiency of the CCD at 532 nm is closed to 90%, the typical readout noise at 50 kHz is equal to 3.3 e- and the dark current < 0.00047e/Pixel/s at -100°C.

4.1.3. Expected results

The GammeV-CHASE experiment set limits on photon-chameleon couplings much below collider constraints for a wide set of unexplored dark energy models \[14\]. The new OSQAR experimental set-up for chameleon search, which has been validated in 2014 is ready for operation in 2015. As a preliminary estimate from (5), exclusion limits for the di-photon coupling constant $g_{\gamma \gamma} = \beta_{\gamma} / M_{Pl} \sim B^{1} P^{-1/4} \eta^{-1/4}$ in the chameleon massless limit can be improved \textbf{by a factor of about 3-4} with respect to the present reference result of the GammeV-CHASE collaboration \[19\] assuming the increase of the magnetic field $B$ from 5 T to 9 T, the laser power $P$ from 3.5 W to 18.5 W, the detector efficient $\eta$ from 0.29 to 0.87 and the values for all other parameters unchanged. The last assumption can be justified from the value of the geometrical coefficient obtained from the simulations in section 3.3.2, which is found to be very close to the one of GammeV despite the lower reflectivity of the wall of the vacuum chamber for OSQAR-CHASE.

The magnetic field gradient at the entrance and the exit of the uniform magnetic field region were measured inside a LHC dipole. A preliminary numerical simulation of the effect of this gradient on the chameleon to photon conversion probability suggests that this is altered negligibly for chameleons of effective mass smaller than 5 meV, which includes the dark energy scale ($M_\Lambda \approx 2.4$ meV). The search of chameleons with larger mass scales, which will require the insertion of intermediate windows within the vacuum chamber, is postponed to next runs. It will prove of utmost relevance to properly proceed not only to the most accurate detection of the regenerated photons, but also to a thorough analysis of the recorded counts on the CCD detector. Appropriate Bayesian methods such as the maximum entropy one will be implemented to extract a possible signal and determine the detection level. The final data will be confronted to the power-law models $V(\phi) = g \phi^n$ of chameleon self-interaction and constant coupling $\beta_m \phi^2 / M_{Pl} + \beta_\gamma \phi / M_{Pl}$ to matter and electromagnetic fields with $n < 0$ and $n > 2$ similarly to GammeV-CHASE\[14\].

\[4\] For information, it is this way that the insulation vacuum of the LHC is achieved. As an anecdote, for the 2014 OSQAR-LSW run it was very difficult to find a pumping unit simply because all of them were used in the LHC tunnel. For 2015, no problem for finding one simply because the LHC being cold, nearly all pumping units have been removed to surface...
In a next step of analysis models with field dependent coupling will also be examined. As a bonus, the search for a possible pseudo-scalar field showing the chameleon mechanism will also be conducted, since this will amount to only change the polarization of the incoming laser beam during the production process of these hypothetical pseudo-scalar chameleons.

4.2. Upgrade phases of OSQAR-CHASE

4.2.1. Promising directions

*Development of specific anticryostats*

Among improvements that need to be implemented it can be reminded that by reducing the distance between windows, chameleons of larger mass can be trapped and probed. To profit from this effect a clever solution has been developed by GammeV-CHASE by inserting windows within the vacuum chamber [12], [14], [15]. For OSQAR-CHASE, this implies developing a specific anticryostat fitted with windows at various locations. Teflon coating can be an option for the internal surface of the anticryostat to increase the optical reflectivity.

*Optimization of the photon source*

The possibility of using a more powerful laser is under consideration. In particular and as already announced in [5], the 200 W infrared laser of the HiLASE project is considered as a serious option and a unique opportunity.

*Optimization of the photon detection*

The optimization of the photon detection implies the improvement of the photon collection described by the geometrical factor of section 3.3.2 and the sensitivity of the detector coupled with the statistical analysis method used for treating data. Simulations based on Zemax® software will be extensively used to optimize the photon collection efficiency, to study the effect of the diameter of the vacuum chamber as well as to design the focus lens. There is still room for improvements. Efforts in research and development of specific detectors with ultra low background and high sensitivity is ongoing within the OSQAR collaboration [21], specially for the infrared domain. As this will be developed in the next section, such developments will be strengthened thanks to new collaborators willing to join OSQAR.

4.2.2. Focus on chameleon fragmentation

Quantum corrections to chameleon effective field theories have attracted increasing attention in recent years as experimental efforts have matured [22], [23], [24], [25], [26]. The quantum effect of primary concern to OSQAR-CHASE is fragmentation, which increases the number of chameleon particles in a population while decreasing the average energy per particle. Rapid fragmentation would result in a chameleon population whose kinetic energy per particle was of the order of the effective mass, strongly suppressing oscillation into photons. Although one might suspect large fragmentation rates above the typical cutoff energy of 10^{-3} eV of a chameleon dark energy model, it has been shown [25] that the fragmentation rate remains well-controlled even at energies around 1 eV characteristic of laser oscillation experiments. Furthermore, for power law potentials with $V(\phi) \propto \phi^n$ with $n < 1$, fragmentation is sub-dominant to photon regeneration, leaving the constraints of the GammeV-CHASE experiment essentially unaffected. Significant fragmentation for steeper potentials $n > 2$ could potentially be controlled by operating with lower-energy photons. One further quantum effect, a correction to the chameleon-photon phase shift arising from quantum corrections to $V(\phi)$ near the chamber walls [23], is also expected to be small. Grazing-angle wall reactions contributing to the afterglow rate are relatively insensitive to quantum corrections, and averaging over polarizations washes out any residual effect [15].

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5 Proposal for an extended collaboration by Giovanni Cantatore (INFN, Trieste, Italy), Dieter Hoffmann (TU Darmstadt, Germany), Marin Karuza (University of Rijeka, Croatia), Amol Upadhye (Argonne National Laboratory, US), and Konstantin Zioutas (University of Patras, Greece).
Since defragmentation remains an option for a coherence experiment like OSQAR-CHASE, the search for afterglow at lower energies than the initial laser energy completes the possible chameleon detection in such an experiment. It is stressed that the search for correlated photons to emerge from an optical cavity, but at lower energy than the initial LASER energy, allows to search not only for an afterglow signal, but also for a simultaneous photon emission at lower energies. This additional option in a chameleon search makes thus the extra efforts worth doing and this for the first time.

Photons in the sub-eV energy range, down to a few meV can be detected with a variety of techniques. Current technology employed in radio astronomy, based on receiver antennas and low noise current amplifiers, can reach sensitivities in detected power (in the ~100 GHz frequency range, corresponding to meV energies) down to $10^{-20}$ W. This figure can decrease by a factor 100 when cryogenic temperatures are reached. Photons having energies larger than $10^{-2}$ eV can be sensed with standard THz heterodyne detection techniques, or with Transition Edge Sensors. The latter, working at cryogenic temperatures, have an extremely low background and are capable of single-photon counting.

4.2.3. Overview of OSQAR-CHASE activities for 2015-2016

As presented in the section 4.2.2, the OSQAR collaboration will be extended with members coming from CAST to develop detector in the infrared domain and study chameleon fragmentation. Although all details are still under discussions, a preliminary planning of the OSQAR-CHASE activities is given in Table 5.

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Table 5: Simplified planning of the overall OSQAR-CHASE activities for 2015.

5. Conclusion

The OSQAR activities are now split in three main components:

- OSQAR-VMB for the Vacuum Magnetic Birefringence measurement; this part is the less advanced one, mostly for resource issues. It relies on the development of 20 m long optical cavities of high finesse.
- OSQAR-LSW, for Light Shining through Wall experiment; in 2014, this experiment has been run with an outstanding sensitivity pushing the limit of the possible existence axion and ALPs down to an unprecedented level for such a laboratory experiment.
- OSQAR-CHASE for Chameleon Afterglow Search Experiment, which will start in summer 2015 as described in this proposal and in [5].

This multipurpose experiment, focusing on some of the most important questions in Physics including Cosmology such as Dark matter and Dark Energy, has really an interesting potential at a very marginal cost for CERN.

Acknowledgements

The OSQAR collaboration warmly thanks Dr. Vincent Baglin from the CERN-TE-VAC group, in charge of vacuum studies and measurements at CERN, for his advices concerning UHV conditions and related problems.
REFERENCES


[18] Zemax® is a software that is used to design and analyze optical imaging systems such as camera lenses, as well as illumination systems. It works by ray tracing - modeling the propagation of rays through an optical system. It can model the effect of optical elements such as simple lenses, aspheric lenses, gradient index lenses, mirrors, and diffractive optical elements. It is sold by American company Radiant Zemax; https://www.zemax.com/home


