Laser-based Particle/Astroparticle Physics Experiments at CERN
To probe the Low Energy Frontier...

OSQAR Status & Plans
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Outline

• Introduction

• OSQAR-CHASE (CHameleon Afterglow Search Experiment)
  - Experimental
  - Data analysis
  - Preliminary exclusion plots

• OSQAR-LSW (Light Shinning through Wall)
  - From past results to optimisation of data analysis & Future R&D plans towards JURA

• OSQAR-VMB (Vacuum Magnetic Birefringence)
  - Preparatory phase & Perspectives towards VMB@CERN

• Conclusion & Outlook
To measure for the 1st time the QED Vacuum Magnetic Birefringence (VMB) (Heisenberg & Euler, Weisskopf, 1936) i.e. the vacuum magnetic “anomaly” of the refraction index “n-1” ~ 10^{-22} in 9.5 T

“Exploring a new territory with a precision instrument is the key to discovery”, Prof. S.C.C. Ting

To explore the Physics at the Low Energy Frontier (sub-eV)
- Axion & Axion Like Particles i.e. solution to the strong CP problem (Weinberg, Wilczek, 1978) & Non-SUSY Dark Matter candidates (Abbott & Sikivie; Preskill, Wise & Wilczek, 1983)
- Paraphotons (Georgi, Glashow & Ginsparg, 1983), Milli-charged Fermions
- Chameleons (Khoury & Weltman, 2004) Dark Energy candidate
- The Unknown ... SERENDIPITY, “Why not an abundance of ultralight particles ?”

A complementary way of doing Particle Physics based on the Laser beam interaction with magnetic fields

Spin-offs in the domain of the metrology of electric & magnetic fields
- Spin-off : Start-up created in 2009 by Prof. L. Duvillaret
  https://www.kapteos.com/
Introduction to Chameleons

• Chameleon: Hypothetical scalar particle with a variable effective mass, which is an increasing function of the ambient energy density [J. Khoury and A. Weltman, Phys. Rev. D 69, 044026 (2004)].

• New kind of particle providing a phenomenological explanation of dark energy as a scalar field evolving in an effective potential, the minimum of which depends on the local matter density in such a way that the experimental constraints of 5th force and violation of equivalence principle are relaxed.

• Based on the coupling to photons, chameleons can manifest through an afterglow signal or a magneto-phosphorescence of the quantum vacuum, i.e. a remaining luminescence after the lighting is switched off.
Phase 1: Filling the “jar” with chameleons produced from the interaction of real photons with virtual ones (Primakoff effect)

\[ P_{\gamma \to \phi} = \frac{4 \omega^2 g_{\gamma}^2 B^2}{m_{\phi}^2} \sin^2 \left( \frac{m_{\phi}^2 L}{4\omega} \right) \]

Phase 2: Emptying the “jar” and detection of “afterglow” regenerated photons (inverse Primakoff effect)

\[ \dot{N}_{afterglow}(t) = \frac{\eta P_{esc} f_{vol} P_{\gamma \to \phi}^2 c}{\omega L_{total}} \left( 1 - e^{-\Gamma dt} \right) e^{-\Gamma t} \]

Successful Experimental Run in 2017

- Typical durations of phases 1&2: ¼ - 11 h
- Measured switching time between phases 1&2: 6-20 s

For Low Energy Laser-based Particle/Astroparticle Physics
Definition of the ROI with a diffuse light source (CCD sensitive area of $13 \times 13 \text{ mm}^2$) used for data reduction (Detection efficiency & noise characterisation)

- Afterglow signal observed but non-magnetic as it dissapear after background substraction recorded with exactly the same configuration and protocole without magnetic field
- Negative results also obtained for pseudo-scalar search
- The quantitative analysis to define exclusion plots is not straightforward and more complex than anticipated with several Chameleon potentiels to consider

https://doi.org/10.1016/j.nima.2018.11.065
https://hal.ird.fr/INPG/hal-01991788
Phase 2, *i.e.* Afterglow photon emission, in the 2-point path approximation, *i.e.* 3D axisymmetry path

The flux of afterglow photons as a function of time can be modeled as:

\[ S_{AFT} (t) = \eta \frac{F_\gamma P_{\phi \leftrightarrow \gamma} \Gamma_{AFT}}{\Gamma_{DEC}} (1 - e^{-\Gamma_{DEC} \tau_{Prod}}) e^{-\Gamma_{DEC} t} \]

\( \eta = 0.65 \) is the overall detection efficiency

\[ \Gamma_{DEC} = \frac{1}{4\pi} \int \int d\Sigma \int d\Omega P_{DEC} \frac{\cos \theta}{L_T} \]

with

\[ P_{DEC} = P_{ABS}^{AFT} + |\tilde{\psi}_{\gamma}^{Bexit}|^2 \]

and

\[ P_{AFT} = \left( |(\tilde{\psi}_{\gamma}^{Bexit} \cdot \hat{S}) A_{S}^{N-N} |^2 + |(\tilde{\psi}_{\gamma}^{Bexit} \cdot \hat{P}) A_{P}^{N-N} |^2 \right) P_{DET} \]

Exclusion limits in the parameter space (chameleon mass $m_\phi$, chameleon-photon coupling $\beta_\gamma$), 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 $\xi_\phi$ 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 $V = M_\Lambda^4[1 + e^{-\kappa \phi/M_\Lambda}]$. 

\[ \xi_\phi = \frac{\pi}{n-2} \] for $V = g \phi^n$, $\xi_\phi = \frac{\pi}{n+2}$ for $V = g \phi^n$, $\xi_\phi = \pi$ for $V = M_\Lambda^4[1 + e^{-\kappa \phi/M_\Lambda}]$. 

The OSQAR Experiments @ CERN For Low Energy Laser-based Particle/Astroparticle Physics
Focus on chameleon – photon vs. chameleon – matter coupling for the inverse power law chameleon dynamic potential

\[ V(\phi) = M_\Lambda^4 \left(1 + \kappa M_\Lambda^2 / \phi^n\right) \]
\[ (\kappa = 1, n = 1) \]
\[ M_\Lambda = \rho^{1/4}_{DE} = 2.41 \times 10^{-3} \text{ eV} \]
What was not taken into account in the present analysis?

- Complex propagation not inscribed in a plane \( i.e. \) full 3D in general --> Beyond the 3D axisymmetry geometry
  - Assessment required especially for large \( \beta_m \)
- Non-specular reflection of photons, \( i.e. \) the diffuse one not considered
- Spatial distribution of the signal on the CCD detector to get more accurate exclusion limits through matched filtering of the data.

- Chameleon fragmentation the possibility of which is expected for chameleon potentials with high exponents (\( n = -3, -4, \ldots \) or 3, 4, \ldots)

All this can be achieved through Monte-Carlo simulations of the afterglow signal.
Light Shining through a Wall experiment (LSW)

Present state-of-the-art for LSW Experiments

\[
\frac{dN}{dt} = \frac{P}{\eta} \left( P_{\text{ALP}} \right)^2
\]

\[P_{\text{ALP}} = \frac{1}{4} \left( g_{\gamma \gamma} BL \right)^2 \left( \frac{2}{qL} \sin \frac{qL}{2} \right)^2 \frac{\omega}{\sqrt{\omega^2 - m_A^2}}\]

with \( q = |k_y - k_A| \), \( k_y = \omega \) and \( k_A = \sqrt{\omega^2 - m_A^2} \)

\( \omega \) : photon energy - \( m_A \) : ALP mass
in units of LH system \((h = c = \mu_0 = \varepsilon_0 = 1)\)

K. van Biber et al., PRL 59 (1987) 759


@ 95% Confidence Limit deduced from model independent Bayesian analysis,
ALPs-diphoton coupling < 3.2 \cdot 10^{-8} \text{ GeV}^{-1} (for m_A < 0.2 \text{ meV})
• Ongoing ALPs-II at DESY (12 + 12 straightened 5 T Hera dipoles with ambitious optical scheme)

~ 2 x 120 m

• Longer term future for LSW experiments with JURA (Joint Undertaken Research for Axion/ALPs), possibly with say 15 + 15 spare 9 T LHC dipoles (~ 2 x 225 m) with the same or alternative optical scheme (?)

→ At present, JURA = OSQAR + ALPs + (UF?)...

→ Ambitious proposal, R&D needs to start NOW...

• Low divergent structured beam (patent: WO2019211391 (A1), EP3564734 (A1))

• Optimisation of data analysis with matched filter (similar to Ligo & Virgo)
  - At present OSQAR-LSW sensitivity can be improved by x 3, further progress possible?

• Alternative optical scheme under consideration
  - Interferrometry approach, cf. https://cds.cern.ch/record/2641609
  - Amplification by resonant atomic transition (cf. arXiv:1803.09388v2)
The birth of a meta-collaboration, Remaining on a Human scale

Letter of Intent to measure Vacuum Magnetic Birefringence: the VMB@CERN experiment

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Discuss for the 1st time within PBC in May 2017 (slide 17)
& also presented to the SPSC-127

Proposed modulation scheme of VMB@CERN (SPSC-I-249)

L1,2 : rotating half-wave-plates
PDE : Extinction Photodiode
PDT : Transmission Photodiode.

With a single LHC dipole at 9.5 T, VMB should be detected with SNR = 1 in less than 1 day of integration.

Improvements of the OSQAR initial proposal SPSC-P-331, see also P. Pugnat, L. Duvillaret et al., Czech. J. Phys. 55 (2005) A389

See also G. Zavattini et al. https://arxiv.org/abs/2110.03943

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Conclusion & Outlook

- OSQAR-CHASE
  - Détailed data analysis of the 2017 run for scalar and pseudoscalar Chameleon search is more complex and demanding than anticipated.
  - New exclusion limits is being rigously defined from no magnetic afterglow signal observed; they are significantly better than those anticipated in the OSQAR-CHASE proposal.
  - Robusness of the analysis (beyond 3D axisymmetry, diffuse reflection) as well complementary search (chameleon fragmentation) still need to be performed.

- OSQAR-LSW
  - JURA will be the next postALPS-II LSW experiment requiring preparatory activities, which are starting within OSQAR collaboration, including:
    - Control of the laser beam divergence on long lengths (patent on structured beam);
    - Optimisation of the data analysis with matched filter;
    - Investigation of new type of experiments linked to other scientific fields such as atomic physics.

- OSQAR-VMB
  - Activities are pursued within the scope of the VMB@CERN future proposal in preparation.
  - Synergy between VMB@CERN and BabyJURA is looked at to minimise requirements asked to CERN, specially regarding the future need of LHC dipoles in the SM18 hall.