Dark Side of the Light

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Abstrakt
Tato práce popisuje pozadí vědeckého experimentu OSQAR (CERN), které spočívá v technickém zázemí a přípravě provedení experimentů. Cílem experimentu je detekce optických jevů, které jsou příznakem nových fyzikálních objevů. Experimentální metody zkoumání propojujeme s konstrukčními řešeními optického a mechanického charakteru.

Klíčová slova
Laser experiment, vakuum, axion, light, detection.

1. Introduction

Light is electromagnetic radiation perceptible with human eye. Visible light has the wavelength in the range (380; 750) nm. The light, as well as all types of radiation, is emitted in small quanta of energy – called photons. Physical behavior of the radiation features properties of waves and particles – the wave-particle duality. Main properties of the electromagnetic wave encounter its intensity, direction of propagation in space, frequency/wavelength, and polarization. Energy of a photon depends only on its wavelength:

$$E = \frac{hc}{\lambda} \tag{1}$$

Dark matter is a type of hypothetical matter expected to be the source of a large part of the total mass in the universe. We are able to observe only less than 4% of the matter in the Universe. Roughly 73% of the Universe is dark energy, and 23% consists of dark matter. One of the physical theories predicts that dark matter is formed with exotic particles like WIMPS (Weakly Interacting Massive Particles) or axions.
The axion is a hypothetical neutral weakly interacting sub-eV pseudo-scalar particle (pseudo Nambu-Goldstone boson).

2. Experimental Search

A number of experiments have attempted to detect axions. Experimental approaches are based on the concept of axions coupling with two photons.

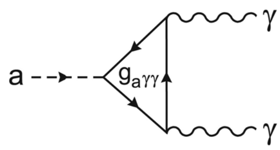

Fig. 1 *Feynman diagram of decay of the axion (a) into two photons (γ).*

One of these experiments is the OSQAR experiment in CERN. Department of Instrumentation and Control Engineering of the Faculty of Mechanical Engineering, Czech Technical University in Prague is among the collaborating members. The other competing experiments are e.g. PVLAS, CAST in CERN, ALPS, BMV, BFRT, ADMX, GammeV, which share principle, but differs in parameters. None of them has reported positive results yet.

2.1 The OSQAR Experiments

The OSQAR experiment (*O*ptical *S*earch for *Q*ED vacuum magnetic birefringence, *A*xions and photon *R*egeneration) is a laser-based experiment for search of axions and axion-like particles.

The first experiment is aimed at measuring very small vacuum magnetic birefringence for the very first time. Vacuum magnetic birefringence can be induced by magnetic field in vacuum. The Quantum Electrodynamics prediction about interaction of external magnetic field with electric field of photon gives prediction of the relative difference of vacuum refractive indices. Presence of axions can still cause sizeable deviation from this theory.

The second experiment - photon regeneration - is designed as "light shining through the wall". It tries to search for axions which are converted photons in the magnetic field.

2.2 Conversion Probability

The photon regeneration experiment looks for photon-axion conversions (see Fig. 1). Probability of photon – axion conversion in vacuum is given by

$$P_{\gamma\leftrightarrow A} = \frac{1}{4\beta\sqrt{\epsilon}} g^2 B^2 L^2 \approx \text{const. } g^2 B^2 L^2 \tag{2}$$

Weakly interacting axions can pass through optical barrier and can be reconverted back to photons at magnetic field again.

Number of detectable axions per time interval is given by

$$N_{a\text{-}p} \approx \text{const.}\, \eta \frac{P}{\lambda} g_{a\gamma\gamma}{}^4 B^4 L^4 t \tag{3}$$

These equations show the importance of key experimental parameters. The magnetic field is given and cannot be increased. Therefore the only way leading to rise of the probability of conversion is increasing the length of the laser beam propagating in the magnetic field.

2.3 Experimental Setup

In 2010 a new phase of the experiment has started. The experiment was set up in configuration displayed in Fig. 2.

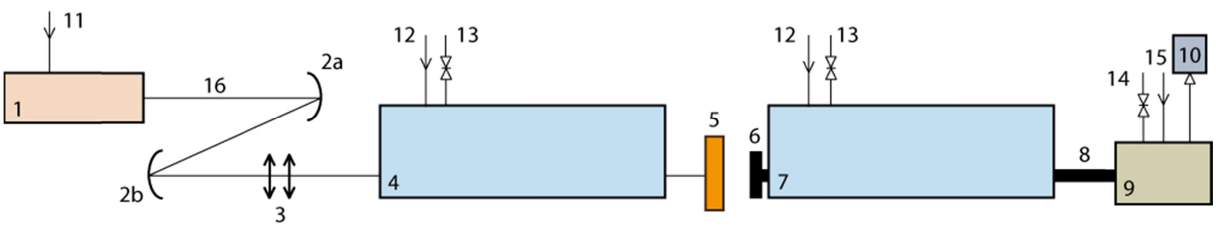

Fig. 2 *Layout of the experiment.*

1. source of photons - laser
2. a, b – adjustable mirrors
3. beam expander
4. first LHC magnet
5. light trap
6. optical filters
7. second LHC magnet
8. dark chamber
9. CCD camera
10. data acquisition - PC
11. cooling (H_2O)
12. cooling (liquid Helium, T = 1.9 K)
13. vacuum pump (p = 10^{-6} - 10^{-7} mbar)
14. vacuum pump
15. cooling (LN2)
16. laser beam

Magnetic field interferes with linearly polarized laser light and thus converts photons to axions. The magnetic field of 9T over 14.3 m length is provided by two spare superconducting dipole magnets of the Large Hadron Collider. The dipole magnets are cooled down to 1.9 K with superfluid Helium.

Source of the photons was an Ar^+ laser with approximately 4W at 514 nm. The laser beam profile can be fitted with a Gaussian curve. λ/2 wave plates were used to control polarization of the beam with respect to the transverse magnetic field.

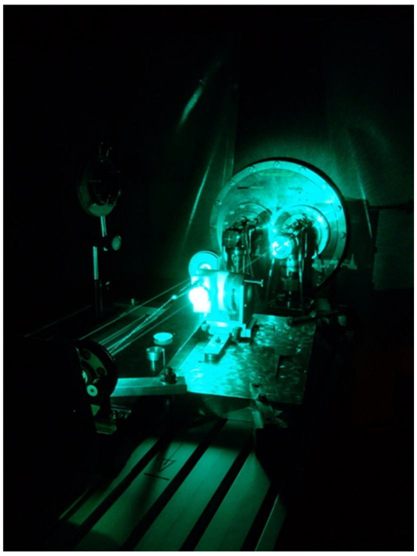

Fig. 3 *Laser injection into the dipole magnet*

Photons, which are not converted into axion in the first magnet, are absorbed in a light trap. Weakly interacting axions pass through the light trap without alteration. In the second light tight magnet the axions are converted back to photons and detected by camera. The expected signal on the camera should inherit the same profile as the incident laser beam.

In 2011, also the vacuum magnetic birefringence experiment was measured together with measurement of laser beam deflection in magnetic field. In 2012, two new spare LHC dipoles have been assigned to OSQAR, installed and aligned on the dedicated horizontal cryogenic benches B1 and E2 in the SM18 hall. The optical path has been rectified and prepared for measurement of vacuum magnetic birefringence.

In all of the experimental runs, the team from Czech Technical University has provided technical support on site including adjustment and rectification of the optical components delivering the laser beam, as well as measurement of the beam deflection, or detecting the axion-like-particles. Simultaneously to these experiments, design work has been done at the Czech Technical University. We might say the three year measurement have exploited most of the possibilities that can be explored with existing instrumentation. Transition to new phase of the experiment is being prepared.

The experiment can be improved in quality and quantity. Quality factor is being raised by better detecting camera, better focalization of the laser beam, or better stability of the whole system. As equation (2) shows, the quantity factor can be improved by increasing the length of the optical path in magnetic field. Therefore the advance workings for the run in 2013 focus on building a resonator cavity.

2.4 Result of Research and Development

The laser system had to be adjusted from square one several times. The adjustment procedure was time demanding. We have implemented several techniques helping to adjust the laser beam in much shorter time. One of them involved establishment of lowcost remote sensing system via internet, based on PC with a videocamera. All procedures were described in internal handbook which serves as a reference material for newcomer students.

Measured signal of the „shining through the wall“ experiment is a convolution of real signal with background noise, interfering with cosmic rays. Before we started the experiment, we made sequential acquisitions of background signal for 24 hours. This way we get information about the time stability of the system. Measured data were evaluated using various statistical methods.

Obtained results of the experimental measurement were published and can be found in [2] and [9].

2.5 Laser Laboratory

A new laser laboratory was established at the Department of Instrumentation and Control Engineering at the beginning of 2013. This laboratory has replaced previous one that was shared with other projects. This laboratory is solely dedicated to work on resonator cavity and testing of the prototype.

It is equipped with large cast iron optical table; obtained from the Astronomical Institute of the Academy of Sciences of the Czech Republic. Two steel 0.5x1 m optical tables were placed on the top of the cast iron table. Next it was equipped with a 50mW He-Ne laser, highly reflective custom mirrors, optical components (beam splitter, λ/2 plates), mechatronic parts (piezo actuators) and instrumentation (Shack-Hartmann wavefront sensor, high speed camera, powermeter, piezo controllers).

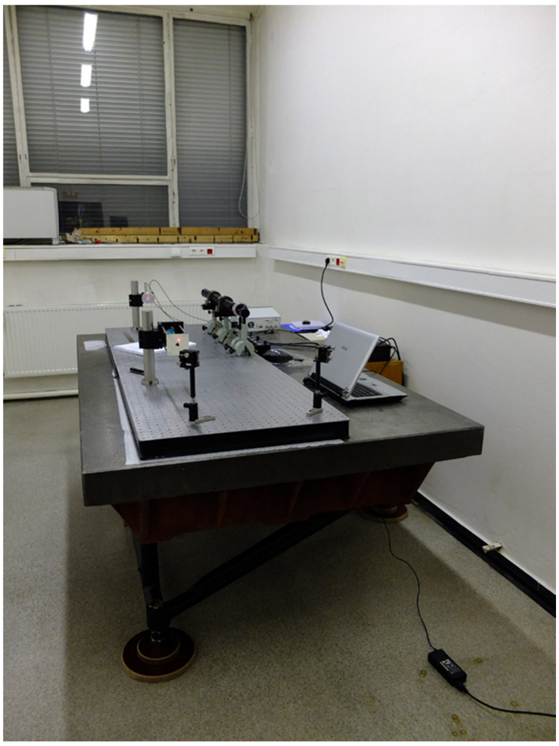

Fig. 4 *Equipment of the new laser laboratory.*

Work on the resonator cavity is under development. A 1-m prototype has been build. We have made several custom mechanical parts, like a mirror mount and easels. The work continues with experimental verification of adjustment methods, optimizing the opto-mechanical parts for use in vacuum.

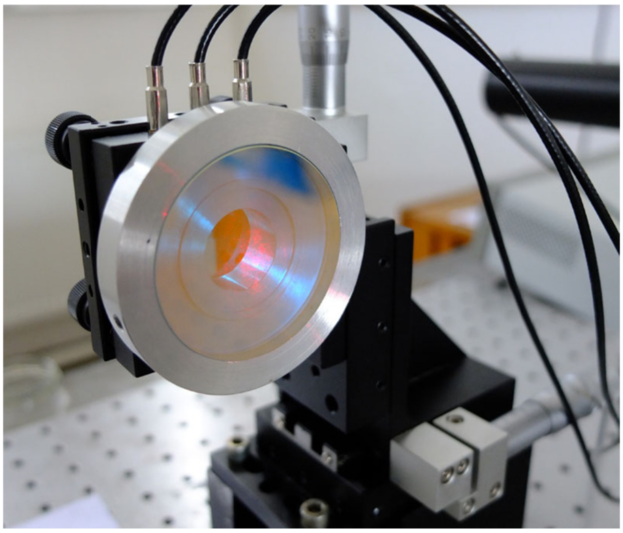

Fig. 5 *Cavity mirror holder.*

3. Conclusion

A brief description of development on the OSQAR experiment during last three years was presented. First results of the OSQAR experiment were obtained from laser beam propagating in vacuum in strong magnetic field. The vacuum magnetic birefringence measurement and search for axion experiments continue in following years. The development focuses on building a resonant cavity which is a very promising instrument. It will enable to reach higher axion-photon conversion probability factor and therefore increases the chance to extend the current exclusion limits for axions and axion-like particles.

Acknowledgement

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List of symbols

λ	wavelength	(nm)
c	speed of the light in vacuum	(ms^{-1})
h	Planck´s constant	(Js)
P	optical power	(W)
η	detector efficiency	(-)
$g_{a\gamma\gamma}$	coupling constant	(ms^{-2})
B	magnetic field	(T)
L	length of the optical beam in magnetic field	(m)
t	time	(s)

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