Optically Pumped Magnetometers for Particle Physics and Geoprospection/Geomagnetism

Acronym: **OPMPPG MAGLab OPMLab**
Sub-program: **Natural sciences and mathematics**
Participating SROs:

SRO	Acronym
Institute of Physics Belgrade	IPB
Faculty of Physics, University of Belgrade	FF???
School of Electrical Engineering, University of Belgrade	ETF – SEE???

Principal Investigator: **Dr Zoran D. Grujić**

Abstract

We propose to build and equip modern laboratory where main field of research will be development of optically pumped magnetometers (OPMs) and their use in wide range of applications: (I) highly accurate OPM for measurement of neutron Electrical Dipole Moment (nEDM), (II) tabletop experiment to search for hypothetical elementary particles (GNOME - The Global Network of Optical Magnetometers for Exotic physics), and (III) portable multifunctional high sensitivity and high accuracy magnetometer (PHASM) for recording/scanning geomagnetic field. Trough the abstract, marks (I), (II) and (III), will be used to refer to each of research directions.

Novelty: (I) We strive to improve sensitivity of nEDM experiment operated by international nEDM collaboration at Paul Scherrer Institute (PSI) in Switzerland. Our task within collaboration would be to design an array of highly accurate magnetometers using laser spectroscopy of cesium vapor in cells with antirelaxation coating. This implies innovative methods in high precision measurements of magnetic field module on the order of 200 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$, or better, in the main offset field of 1 μT. (II) We intend to actively participate in endeavours of international GNOME collaboration. Goal is to build high sensitivity magnetometer that will be connected to the GNOME network to detect extra-terrestrial perturbations of atomic spin. Such perturbation might be due coupling to axion, hypothetical elementary particle that is one of proposed building blocks of dark matter in Universe. (III) The PHASM would be designed using latest development in magnetometry, laser physics and electronics. With sensitivity and accuracy of 1 $\mathrm{pT}/\sqrt{\mathrm{Hz}}$ or better the PHASM would be useful in archaeology and in mapping of ore deposits. The accuracy of the device will enable reproducibility of recorded maps and long term tracking of Earth magnetic field.

Background: (I) After Big Bang, according to Standard model (SD), the same amount of matter and antimatter was produced. But in the Universe today we find antimatter only in traces. This disbalance could be explained if CP symmetry is broken in some processes. Sole existence of nEDM breaks CP symmetry and measurement of its value puts limits to numerous extensions of SD. (II) Dark matter is one of the most puzzling problems of cosmology today. Many scientists believe that weakly interacting axions are good candidate to explain huge discrepancy between mass of visible matter in galaxies and their larger disproportional gravitational pull. Idea of GNOME collaboration is to detect coupling of axion field gradient (while planet Earth passes through axion wall, axion star, axion clumps…) and atomic spin. (III) Numerous applications could be foreseen for PHASM like tracking of geomagnetic field, search for magnetic and electroconductive ore deposits, mapping of archaeological sites without of digging, finding magnetic wreckages of ships underwater, observation of biomagnetism...

Methods: (I) In special conditions free spin precession (FSP) magnetometer delivers approximately precision on the order of 200 $\mathrm{fT}/\sqrt{\mathrm{Hz}}$. We intend to investigate in detail why such magnetometers suffer from heading error. In parallel, properties and heading error of the more promising free alignment precession (FAP) based magnetometer will be put under scrutiny. (II) Lamp, or laser pumped high sensitivity magnetometer will be installed in underground space of "Low-background laboratory for nuclear physics" to benefit from magnetically calm and vibration free environment. Recorded signals will be streamed over internet to a central server for storage and correlation analysis. (III) Combine results of fundamental research from (I) and (II) in a single novel device.

Expected results: (I) Improved sensitivity of the nEDM experiment. Applications in metrology, fundamental research, and Earth magnetic field prospection. (II) Narrowing of allowed parameter space where axion-like particles could exist. (III) High sensitivity and high accuracy (1 $\mathrm{pT}/\sqrt{\mathrm{Hz}}$ or better) prototype of portable magnetometer that could be effectively used out of magnetic shielding and out of controlled laboratory environment. Possible commercialisation and patent of PHASM.

Impact: (I)(II) Contribute towards solving most puzzling problems of modern physics. (III) Effect on culture trough archaeology and on mining operations.

Total budget: **300`000.00 EUR**

Project Description − Part A

Each research direction (RD) of the proposal has its own objectives, methods, …, and impact. To avoid confusion trough the text we will use following labels within angular brackets:

- [nEDM] - neutron Electrical Dipole Moment,
- [GNOME] - The Global Network of Optical Magnetometers for Exotic physics,
- [NV-BIO] – Use of nitrogen vacancies (NV) in diamond for observation of bio-magnetism at micro scale.

1. Excellence

1.1. Objectives

[nEDM] Upper limit of neutron Electrical Dipole Moment (nEDM) sets important boundary to new theories beyond standard model (SM) in particle physics. Sole existence of nEDM breaks fundamental symmetries like CP (charge parity). Violated CP symmetry could explain where antimatter disappeared after Big Bang. The nEDM collaboration, based at Paul Scherrer Institute (PSI) in Switzerland, recently published the most sensitive up to date limit for nEDM $dn = (0.0 \pm 1.1\mathrm{stat} \pm 0.2\mathrm{sys}) \times 10^{-26}$ e·cm. Now they are in process of assembling an impressive second generation of the experiment (n2EDM). Many aspects of the set-up have been significantly improved. Control and measurement of magnetic field properties, its value, homogeneity, and gradient in experimental volume is of vital importance for sensitivity of the measurement. Gradients of magnetic field reduce spin coherence time of neutrons and of mercury atoms in comagnetometer contributing to experimental uncertainties due gravitational shift. Our objective is to improve accuracy and/or precision of approximately 100 cesium magnetometers that will be installed.
[GNOME] Optically pumped magnetometers (OPMs) are based on highly precise observation of atomic spin to magnetic field coupling. Due their nature it is expected that OPMs might be sensitive to other vector fields, like gradient of axion field, where axion is hypothetical pseudoscalar elementary particle. High sensitivity OPMs are normally operated inside a magnetic shield to reduce ambient magnetic noise below magnetometer sensitivity. But large magnetic perturbations still do pass through even best shielding thus making distinction of local versus axion perturbations impossible. In other hand probability that two distant OPMs will observe local perturbations of same nature is greatly suppressed. Thus, extension from few to network of OPMs is the main idea of GNOME collaboration with goal to detect propagation of planet Earth trough theoretically proposed gigantic objects like axion walls, axion stars, axion clumps, etc. In scope of the project we intend to build, install and continuously operate GNOME station in underground space of "Low-background laboratory for nuclear physics" to benefit from magnetically calm and vibration free environment.
[NV-BIO]

Describe the specific objectives for the Project, which should be clear, measurable, realistic and achievable within the duration of the Project. Objectives should be consistent with the expected exploitation and impact of the Project (see Section 2).

1.2. Concept and methodology

- Describe and explain the overall scientific concepts and methodology underpinning the Project. Describe the main ideas, methods, models and assumptions involved. Identify any trans-disciplinary considerations.
- If applicable, describe how the proposed Project is related to other Projects in which the PI, the members of the project team and their SRO(s) have been involved.

1.2.1. Data usage[1]

- Elaborate on data usage in the proposed Project. Provide answers to all questions that apply to your Project.
    - What types of data will the Project generate/collect?
    - What significant datasets are needed for the Project implementation? Specify data types and data size. Specify primary or secondary usage of data.
    - Do you already have access to stated data, or will the data be obtained during Project implementation? If the data is to be obtained during Project implementation, please specify so.
    - How will the data be stored and accessed? What measures will be taken to ensure secure data storage and usage, including data security?
    - Who will have access to the data during Project implementation?
    - How will the data be used with reference to the research field?
    - How will the costs of data curation and preservation be covered?

[1] Make sure to budget all data usage costs related to the Project proposal. All costs and justification thereof need to be entered in the Budget document (provided in the excel form).