Characterization of the CAPP magnetometer for GNOME

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The **G**lobal **N**etwork of **O**ptical **M**agnetometers to search for **E**xotic physics (GNOME) is an experiment to search for transient events of axion domain walls based on a novel scheme: synchronous measurements of high precision optical magnetometer signals from multiple stations around the Earth. This collaboration now consists of more than 10 magnetometer stations located geographically well apart from each other. One of them at the Center for Axion and Precision Physics (CAPP) is a newly joined station in Daejeon, South Korea and expects to start the operation of an optical magnetometer for GNOME by the end of 2017. We present initial setup and characterization of the atomic magnetometer at CAPP station.

1 Introduction

Optically pumped atomic magnetometers offer high level of performance and fundamental sensitivity in terms of delicate magnetic field measurement and they have been employed in various applications that require a high sensitive magnetic probe[1]. The inherent high sensitivity of optical magnetometers to spin dynamics may also allow other types of spin interaction from non-magnetic ones[2]. Especially optical magnetometer could be sensitive enough to detect new types of interaction between spin and hypothetical fields postulated by many theories beyond Standard Model[3],[4].

There have been a series of experiments utilizing atomic magnetometers to search for atypical spin-dependent interactions. The basic concept of such experiments is to look for anomalous shift of magnetic field caused by interaction with exotic fields rather than conventional electromagnetic fields. For example, there are experimental searches for short range spin-dependent interactions between polarized species and locally sourced mass[5]. Those experiments normally monitor the interaction between local masses.

The **G**lobal **N**etwork of **O**ptical **M**agnetometers to search for **E**xotic physics (GNOME) is an experiment to search for *transient events* of axion domain walls based on novel scheme : synchronous measurements of high precision magnetometer signals from multiple stations around the Earth. The domain walls of pseudoscalar fields are appearing in various models with spontaneously broken discrete symmetries. Such fields are predicted by many other Standard Model extensions to be made up of a significant fraction of cold dark matter. When the Earth passes through such a pseudoscalar domain wall, the gradient of the pseudoscalar field at the domain wall would exert a brief torque on atomic spins that could be detected by the highly sensitive atomic magnetometers.

The GNOME consists of $\sim$ 10 dedicated atomic magnetometers located at geographically separated stations on Earth. The target magnetometric sensitivity and bandwidth of each GNOME sensors are to be better than $\sim$ 1pT/$\sqrt{\text{Hz}}$ and a bandwidth on the order of 100Hz. Each magnetometer is located within a multi-layer magnetic shield to exclude the ambient magnetic noise. The signals from the magnetometers are recorded with accurate timing provided by Global Positioning System (GPS) using a custom GPS-disciplined data acquisition system. The GNOME is designed to characterize such transient events while avoiding erroneous detections by constructing an array of magnetometers in geographically well separated locations among them. In this paper, the principal scheme of magnetometer at the Center for Axion and Precision Physics (CAPP) as a local station of GNOME is discussed.

2 Parameterization

Axion is a hypothetical particle suggested from Peccei-Quinn (PQ) mechanism as a solution of the strong CP problem in Quantum Chromodynamics (QCD). The phenomenological searches indicate that axions are invisible due to the weak coupling with matter which is suppressed by $1/f_a$. This invisibleness is realized by two different models, one is the KSVZ and the other is the DFSZ. The astonishing feature of these axion models is that they predict the formation of topological defects in the early Universe called "domain walls", a finite region in the space where the density vanishes[6],[7].

During the inflation of the early Universe, axions might acquire quantum fluctuations which extend beyond the Hubble horizon one the condition that their masses were lighter than the Hubble parameter. If the quantum fluctuations were large enough, some of the N vacua might be populated in the axion potential and it might eventually lead to the formation of domain walls after the inflation. If one assumes the axion domain walls are the predominant contribution to the cold dark matter, the domain wall may have a quasi-Maxwellian velocity distribution in the galactic reference frame with characteristic virial velocity $v \approx 10^{-3}c$ where c is the speed of light. We assume the rate of encounter with domain wall to be larger than at least once per year to make the experiment feasible. In that case, the accessible parameter space is $L \leq 10^{-3}$ly. The thickness of the such domain wall is assumed as to be on the order of Compton wavelength as

$$d \approx \frac{2\hbar}{m_a c} \approx 400\text{m} \times \frac{1\text{neV}}{m_a c^2}. \tag{1}$$

From Eq.1, one can estimate the duration of the transient signal τ as

$$\tau \approx \frac{d}{v} \approx 1\text{ms} \times \frac{1\text{neV}}{m_a c^2}. \tag{2}$$

If the bandwidth of GNOME magnetometer is set to be $\sim$ 100Hz, it is sensitive to the axion mass $m_a \leq 0.1$neV. The coupling of the pseudoscalar field gradient to the atomic spin $\mathbf{S}$ of particle i can be expressed through the interaction Hamiltonian as

$$H_a = \frac{\hbar c}{f_i}\mathbf{S} \cdot \nabla a(\mathbf{r}); \tag{3}$$

where $\mathbf{S}$ is in the unit of $\hbar$ and the f_i is a coupling constant for the considered particle i. This leads to estimates for the energy shift or torques experienced by the spins of fermion i which is induced from the interaction with axion domain wall as,

$$\Delta E(i) \approx \frac{\hbar c^2}{4 f_i} \sqrt{\rho_{\rm DM} m_a L}. \tag{4}$$

The more sensitive a GNOME magnetometer is to torque or energy shift, the larger the value of f_i that can be probed. From the basic concept of GNOME, one can estimate characteristics and potential sensitivity for the domain wall search with GNOME. First, the sensitivity of GNOME magnetometer, δB interpreted as energy sensitivity via

$$\delta E = g_F \mu_B \delta B, \tag{5}$$

where g_F is the Lande factor and μ_B is the Bohr magneton. With $g_F = 1/3$, energy shift becomes

$$\delta E \approx 10^{-18} {\rm eV}/\sqrt{\rm Hz} \times \frac{\delta E}{100{\rm fT}/\sqrt{\rm Hz}}. \tag{6}$$

The actual energy uncertainty scales with the square root of the duration of signal, which in turn is inversely proportional to m_a as follow:

$$\Delta E \approx 10^{-18} {\rm eV} \times \frac{\delta B}{100{\rm fT}/\sqrt{\rm Hz}} \times \sqrt{\frac{m_a c^2}{10^{-12}{\rm eV}}} \tag{7}$$

where the parameterization of the mass relative to 10^{-12}eV corresponding to the signal duration ~ 1s.

3 Optical magnetometer at CAPP

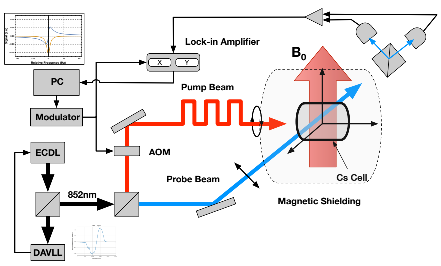

Figure 1: Schematics of CAPP magnetometer.

The magnetometer at CAPP station is a amplitude modulated nonlinear magneto-optical rotation (AM NMOR) magnetometer. The pump beam and probe beam are fed from a single external cavity diode laser (ECDL) from MOGLabs and resonant with Cs D2 transition line at 852nm. The Cs atoms are contained in a cylindrical disk cell with 6 cm in diameter and 3 cm in length. The inner surface of the cell is coated with paraffin for anti-relaxation. The cell is located within a four-layers of cylindrical magnetic shielding made by Twinleaf (MS-2). The shielding consists of three layers of Mu-metal and one inner most layer made with Ferrite. Total eight sets of integrated coil system provide uniform magnetic field along three orthogonal axes as well as first order gradient field to compensate any residual field gradient.

The laser beam from ECDL is stabilized by a laser frequency stabilization loop with Dichroic Atomic Vapor Lase Lock (DAVLL) scheme. The pump beam is amplitude modulated at $\Omega_{\rm mod} = 2\pi \times 1.5$kHz by using AOM (acousto-optics modulator) and is circularly polarized and propagating in the $\hat{\rm x}$ direction. The probe beam is linearly polarized at $\approx 45°$ to the $\hat{\rm z}$ axis and propagates in the $\hat{\rm y}$ direction. The pump beam has a diameter of $\approx$ 5mm and the probe beam has a diameter of $\approx$ 2mm. The probe beam is directed into a balance photodiode after it leaves the vapor cell. The schematics of our experimental setup is shown in Fig.1.

To characterize the magnetometer from the setup, we estimated the sensitivity and the bandwidth that provide the lowest magnetic field and response time one can measure with our system. In order to measure the bandwidth, an harmonic excitation from 0.1Hz up to the frequency at which the response cannot be resolved was applied while the amplitude of the response was monitored. RF coil was added on the cell holder to provide such resonant field in addition to the main holding field. The sensitivity of the magnetometer was estimated by measuring minimum noise level which is noise equivalent magnetic field. The noise level depends on the frequency. Fig.2 shows the measured bandwidth and sensitivity of the magnetometer.

4 Summary

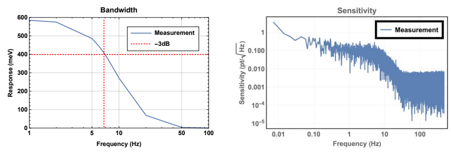

Figure 2: Bandwidth and sensitivity of the magnetometer.

The GNOME has been initiated to look for transient events of axion domain walls. One of stations at CAPP in Daejeon, South Korea is being installed and will be join the network operation of magnetometers around the world. A Cs based optical magnetometer has been adapted and characterized at CAPP to be worked as a local station for the GNOME experiment. The bandwidth and sensitivity of the magnetometer sensor have met all requirements needed as a local station. The network operation of the CAPP station along with other stations around the world will be started soon.

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