Laboratory Search for New Spin-dependent Interaction at CAPP, IBS

Yunchang Shin[1], *Dong-Ok Kim*[2], *Yannis K. Semertzidis*[1,2]

[1]Center for Axion and Precision Physics Research, IBS, Daejeon, South Korea
[2]Department of Physics, KAIST, Daejeon, South Korea

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Axions are light pseudo-scalar particles originally proposed to explain the strong CP problem in Standard Model. Axions could also be a possible component of Dark Matter. Direct search of axions is the current experiment at Center for Axion and Precision Physics Research (CAPP). In addition, axions would mediate spin-dependent interactions in macroscopic scale. A precision experiment that detects spin-dependent interactions in long range has been recently proposed. The experiment includes polarized ^{3}He gas and a unpolarized mass to induce a monopole-dipole interaction. The experiment can look into axion mass range between 10^{-6} eV to 10^{-3} eV. We describe the experimental plan at CAPP.

1 Introduction

Axions are pseudo-scalar particles that were originally introduced to solve the so-called strong CP problem. Axions are also excellent candidates for Dark Matter if their mass is lighter than $\sim 10^{-5}$ eV. The existence of a new spin-dependent long-range interaction may be a signature of axion because theoretically such spin-dependent interaction could be mediated by light, pseudo-scalar bosons like axions [1]. This paper describes a table-top experiment to detect such interactions between matter objects. The concept of the propose experiment is based on

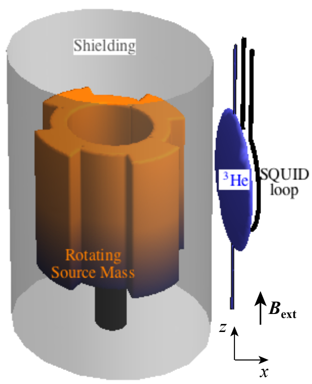

Figure 1: Schematic of experimental search for spin-dependent interaction.

the the resonant coupling between the rotational frequency of a source mass and an ensemble of polarized ^{3}He as nuclear magnetic resonance (NMR) sample with a matching spin precession frequency. In the presence of an anomalous CP-violating interaction with the source mass, the spins in the NMR material will resonantly precess off the axis of polarization. This can be measured with a superconducting quantum interference device (SQUID). There have been many experiments employing precision magnetometer technique to seek such spin-dependent long range interactions [2], [3], [4]. But this experiment is different from previous ones since the resonant effect enhances the signal to detect. With NMR technique, this experiment can look for axion mediated CP-violating forces between masses with a range between $\sim 100\,\mu$m and $\sim 10\,$cm or axion masses between $\sim 10^{-6}\,$eV and $\sim 10^{-3}\,$eV.

2 Concept of the proposed experiment

The general form of the potential caused by the exchange of axion between polarized and unpolarized matters is given as [1]:

$$U_{sp}(r) = g_s^1 g_p^2 \frac{(\hbar c)^2}{8\pi m_2 c^2} (\hat{\sigma_2} \cdot \hat{r}) \left(\frac{1}{r\lambda_a} + \frac{1}{r^2} \right) \exp(-r/\lambda_a), \tag{1}$$

where g_s^1 and g_p^2 are the relevant coupling coefficient of first object (scalar) and the second one (pseudoscalar), respectively. Their product gives the strength of the potential. m_2 and σ_2 are the mass and spin of the polarized particle, r is the distance between the particles, and $\lambda_a = \hbar/m_a c$ is the range of the interaction. The proposed experiment involves a segmented rotating cylinder mass made with high density material such as tungsten to source the axion field, and laser-polarized ^{3}He nuclei that interact with the axion field. The segment in the cylinder generates a time-varying potential at the nuclear spin precession frequency. A conceptual drawing of the experimental setup is shown in Figure 1. In the presence of an axion-mediated interaction, the nuclear spins in the hyper-polarized sample will cause a resonant precession of the axis of the polarization. This change in the magnetization can be detected by a superconducting quantum interference device (SQUID). The key advantage of this experiment is that by rotating the mass so that the segments pass by the medium at the resonant frequency, the sensitivity is enhanced by the quality factor $Q = \omega T_2$ which can be quite large. The interaction potential in Eq.1 can be expressed with axion potential $V_a(r)$ as

$$U_{sp}(r) = -\vec{\nabla} V_a(r) \cdot \hat{\sigma}_2, \tag{2}$$

where $V_a(r) = \frac{\hbar^2 g_s^1 g_p^2}{8\pi m_p} \frac{e^{-\frac{r}{\lambda_a}}}{r}$ is an axion generated potential, which acts on a nearby fermion just like an effective magnetic field of size and direction given by $\vec{B}_{\text{eff}} = \frac{\vec{\nabla} V_a(r)}{\hbar \gamma_f}$, where γ_f is the fermion gyromagnetic ratio. This effective magnetic field is, however, different from an ordinary magnetic field because it does not couple to electric charges or angular momentum. Therefore, a superconducting shielding can be placed between the source mass and detector to screen background electromagnetic field.

3 The Future Plan at CAPP

This experiment requires minimizing all environmental noise that may swamp the effective magnetic field. In this section, a couple of design features to reduce magnetic and vibrational noise and the integration of the setup at CAPP will be presented.

3.1 Anti-vibration Platform

In the proposed experiment, the reduction of vibrational noise plays an important role to make high precision measurement possible. The constant environmental vibration from cars or trains passing near by the building where the measurement takes place has been increased as urban city has evolved. This means that the transmission of vibration from outside become significant source of noise in the precision measurement. The objective of using insulating mechanisms for experimental setup is to reduce repetitive, or sinusoidal vibrations. The task is to keep the motion of the flexibly mounted machine within permissible limits for operation. The vibration insulators selected must have sufficient dampening capacity. Anti-vibration platforms with vibration isolators will be installed in CREATION HALL at KAIST Munji campus. Seven platforms will be installed in total and one of the platforms will be designated for the experimental search of axion with spin-dependent interaction. Figure 2 shows the conceptual design of anti-vibration platform. Expected isolation efficiency of the platform that will be installed is listed in Table 1.

Frequency (Hz)	Efficiency (dB)	Ratio (%)
10	-15	75
20	-25	93
30∼100	-35	97

Table 1: The frequency dependent isolation efficiency of the anti-vibration platform.

3.2 Magnetic Shielding Room (MSR)

This experiment measuring spin-dependent interaction with high precision NMR employs the use of incredibly sensitive magnetometers, such as SQUID to pick up on low level fields induced by the precession within the ^{3}He cell. This signal, however, may be swamped by background fields unless they are properly suppressed. Therefore, the experiment requires shielding from electromagnetic fields with a magnetically shielded room (MSR). The concept for the magnetic shield of the MSR is based on conventional shielding with highly optimized material processing, design and demagnetization, characterization and passive and active compensation of fields. For the proposed experiment, CAPP will have a MSR at CREATION HALL with an extraordinary performance. This MSR will be designed to have residual field at 2 nT with field gradient at 0.5 nT. The shielded room with inside dimensions of $2.8\,\mathrm{m}\times2.5\,\mathrm{m}\times2.5\,\mathrm{m}$ cube consists of two layers of μ-metal and an electrically shielding layer of aluminum. The MSR will be eventually installed on the anti-vibration platform to maximize the shielding performance. The frequency-dependent damping factor is tabulated in Table 2.

Frequency	Shielding performance
0.01 Hz	200 times or more
0.1 Hz	300 times or more
1 Hz above	2000 times or more
10 Hz $\sim$ 400 MHz	more than 10,000 times
400 MHz $\sim$ 1000 MHz	more than 1,000 times

Table 2: The shielding performance of the proposed magnetic shielding room.

3.3 Compact ^{3}He Polarization Unit

The ^{3}He polarizing unit is specially designed to fulfill the needs of the experiment at CAPP. The unit will deliver at least 1 atm· liter of spin-polarized ^{3}He gas in the measurement cell every measurement cycle. ^{3}He from a reservoir is fed into the polarizing cell. Metastability Exchange Optical Pumping (MEOP) method will be employed to produce polarized ^{3}He gas with pressure at ∼mbar in the cell [6]. To avoid complication in the transport of the polarized ^{3}He, the magnetic field from the optical pumping unit to the measurement cell will be aligned in same direction. The pressure inside the system will be controlled by mass flow controller. The gas will be purified by means of a getter-based purifier. After the purification, the ^{3}He gas is fed into the optical pumping cells. The optical pumping cells will consists of two quartz glass tube with $\sim$ 1 m length and $\sim$ 50 mm diameter. After the optical pumping, the polarized ^{3}He gas will be compressed in a compression unit made with non-magnetic piston and will be stored in a storage volume at 1 atm pressure. All unit will be installed on three different faces of vertical triangular post [7]. Six sets of coils will be installed around the posts to provide uniform magnetic field while ^{3}He gas is polarized and transported. The integration of our compact ^{3}He polarization unit into the anti-vibration platform and MSR is shown in Figure 2. The polarization unit will be mounted at the central region of the anti-vibration platform. The ^{3}He gas will be polarized and transported directly from the polarization unit to the experimental setup. With this configuration, the polarized ^{3}He will undergo the same direction of magnetic guiding field while they are transported and one can avoid the complication of magnetic guiding field.

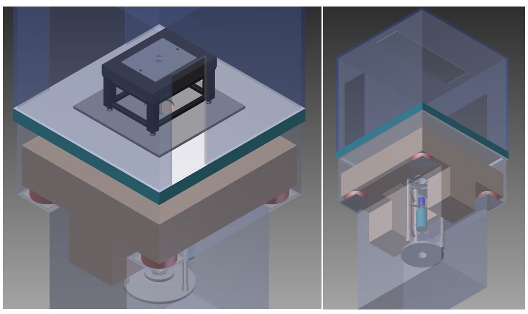

Figure 2: 3D design of the experimental platform with the polarization unit and MSR.

4 Summary

We presented a new concept in experimental search for axions from a spin-dependent interaction. The proposed experiment will be complementary to our CAPP's flagship experiment of axion search with a resonant cavity. In addition, the experimental scheme presented here, in particular, may improve the experimental constraints in respective characteristic energy ranges of axions. Most of these experimental concepts including anti-vibration platform and compact polarization unit are expected to be installed at CAPP in near future for the experimental search of axions from spin-dependent interaction.

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