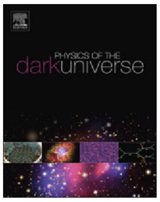
Physics of the Dark Universe 19 (2018) 27–35

Contents lists available at ScienceDirect

Physics of the Dark Universe

journal homepage: www.elsevier.com/locate/dark



Application of spin-exchange relaxation-free magnetometry to the Cosmic Axion Spin Precession Experiment

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ARTICLE INFO

Article history:
Received 15 February 2017
Received in revised form 13 September 2017
Accepted 13 November 2017

MSC 2010:
00-01
99-00

Keywords:
Axion dark matter
Atomic magnetometer
Spin-exchange relaxation-free

ABSTRACT

The Cosmic Axion Spin Precession Experiment (CASPEr) seeks to measure oscillating torques on nuclear spins caused by axion or axion-like-particle (ALP) dark matter via nuclear magnetic resonance (NMR) techniques. A sample spin-polarized along a leading magnetic field experiences a resonance when the Larmor frequency matches the axion/ALP Compton frequency, generating precessing transverse nuclear magnetization. Here we demonstrate a Spin-Exchange Relaxation-Free (SERF) magnetometer with sensitivity $\approx$ 1 fT/$\sqrt{\text{Hz}}$ and an effective sensing volume of 0.1 cm^3 that may be useful for NMR detection in CASPEr. A potential drawback of SERF-magnetometer-based NMR detection is the SERF's limited dynamic range. Use of a magnetic flux transformer to suppress the leading magnetic field is considered as a potential method to expand the SERF's dynamic range in order to probe higher axion/ALP Compton frequencies.

1. Introduction

Dark matter and dark energy are the most abundant yet mysterious substances in the Universe. Axions and axion-like particles (ALPs; we do not distinguish between axions and ALPs in the following) have emerged as theoretically well-motivated dark-matter candidates [1–7]. The Cosmic Axion Spin Precession Experiment (CASPEr) experiment searches for a time-varying axion field by using Nuclear Magnetic Resonance (NMR) techniques [8–11]. CAPSEr is projected to realize a sensitivity to axions and ALPs beyond the current astrophysical and laboratory limits [9].

As discussed in [8,9], a dark-matter ALP field can cause oscillating torques on nuclear spins either by generating an oscillating nuclear electric dipole moment (EDM) that interacts with a static electric field or through an oscillating "ALP wind" that acts as a pseudo-magnetic field along the relative velocity vector between the sample and the dark matter. The oscillation frequency of the torque is given by the ALP Compton frequency ω_a. In CASPEr, a sample of nuclear spins is polarized along a leading magnetic field, and if the Larmor frequency matches ω_a, a resonance occurs and precessing transverse magnetization is generated. The initial plan for CASPEr employs Superconducting Quantum Interference Device (SQUID) magnetometers to search frequencies $\lesssim$ 1 MHz (roughly corresponding to an applied magnetic field below 0.1 T depending on the sample), and inductive detection using an LC circuit for frequencies $\gtrsim$ 1 MHz.

Another possibility for NMR detection is the use of an optical atomic magnetometer [12]. In particular, a state-of-the-art Spin-Exchange Relaxation-Free (SERF) magnetometer has realized a sensitivity of 160 aT/$\sqrt{\text{Hz}}$ in a gradiometer arrangement, and its quantum noise limit is 50 aT/$\sqrt{\text{Hz}}$, which is the most sensitive magnetometer in the low-frequency region [13]. This motivates consideration of SERF magnetometers for NMR detection in CASPEr [8]. SERF magnetometers are applied in fundamental symmetry tests [12,14–17]; they have better sensitivity than Superconducting Quantum Interference Devices (SQUIDs) in the low-field regime [13,18], which could in principle improve the sensitivity of

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https://doi.org/10.1016/j.dark.2017.11.003

the search for axion dark matter, but SERF magnetometers have a disadvantage of a smaller bandwidth than SQUIDs [19,20]. With a magnetically shielded room, a SQUID magnetometer operated inside a LOw Intrinsic NOise Dewar (LINOD) could reach a noise level of about 260 aT/$\sqrt{\text{Hz}}$ below 100 Hz, and achieve a noise level of 150 aT/$\sqrt{\text{Hz}}$ between 20 kHz and 2.5 MHz [21]. SERF magnetometers have demonstrated comparable magnetic-field sensitivities to those of SQUID magnetometers; however, they have certain advantages that may be important in specific applications. First and foremost, SERF magnetometers do not require cryogenics, they generally have the 1/f knee at lower frequencies, and they are robust with respect to electromagnetic transients. There are also disadvantages such as generally lower dynamic range, bandwidth, the necessity to heat the sensor cells, larger sensor size, and the absence of the elegant gradiometric arrangements possible with SQUIDs.

In Section 2, CASPEr is summarized and the corresponding estimates for the axion induced signal shown. We then explore the potential of SERF magnetometry in CASPEr where an experimental arrangement is proposed and various sources of noise are considered. In Section 3, we introduce a modification to the quantum noise equations to account for position dependent atomic absorption by the pump beam. We then present a 1 fT/$\sqrt{\text{Hz}}$ magnetometer and demonstrate a measurement of the modified noise described by the equations. A possible technique to significantly expand the bandwidth of the SERF axion search is also explored.

2. SERF magnetometers for spin precession detection in CASPEr

The CASPEr research program encompasses experiments employing established technology to search for an oscillating nuclear electric dipole moment (EDM) induced by axions or ALPs (CASPEr Electric) and search for direct interaction of nuclear spins with an oscillating axion/ALP field (axion wind; CASPEr Wind). The CASPEr-Wind and the CASPEr-Electric experiments have a lot of features in common. The proposal to use a SERF magnetometer for detection of spin precession may be applicable to both CASPEr-Wind and CASPEr-Electric although in the following we focus on CASPEr-Electric. The axion field can be treated as a fictitious AC-magnetic field acting on nuclear spins in an electrically polarized material [8]

$$B_a(t) = \frac{\epsilon_S E^* d_n}{\mu} \sin(\omega_a t)\,, \tag{1}$$

where ϵ_S is the Schiff factor [2], E^* is the effective static electric field acting on the atoms containing the nuclear spins of interest, μ is the nuclear magnetic moment, $\omega_a = m_a/\hbar$ is the frequency of the axion (we set $c = 1$ in the paper), and m_a is the mass of the axion. Note that the field oscillates at the Compton frequency of the axion. The nuclear electric dipole moment (d_n) generated by the axion dark matter can be written as [9]

$$d_n \approx (10^{-25} e \cdot \text{cm})(\frac{\text{eV}}{m_a})(g_d \times \text{GeV}^2). \tag{2}$$

where g_d is the EDM coupling.

In the CASPEr experiment, the nuclear spins in a solid sample are prepolarized by either a several tesla magnetic field generated by superconducting coils or optical polarization via transient paramagnetic centers. The experiment is then carried out in a leading magnetic field B_0; the effective electric field E^* inside the sample is perpendicular to B_0 as shown in Fig. 1. The time-varying moments induced by axion dark matter are collinear with nuclear spin. In the rotating frame, if there is a nucleon electric dipole moment, the nuclear spins will precess around the electric field, and this will induce a transverse magnetization, which can be measured with a sensitive magnetometer. The first generation CASPEr-Electric experiment will most likely employ a ferroelectric sample containing Pb as the active element. As mentioned in [8], ^{207}Pb (nuclear spin $I = 1/2$) has a nonzero magnetic dipole moment, and has a large atomic number (Z), which means it has a large Schiff factor (since the effect produced by the Schiff moment increases faster than Z^2) [22,23]. The transverse magnetization of the ferroelectric samples caused by the axion field can be written as [8,24]

$$M_a(t) \approx n_{Pb} p \mu \gamma_{Pb} \frac{1/T_b}{(1/T_b)^2 + (\omega_0 - m_a/\hbar)^2} B_a(t), \tag{3}$$

where n_{Pb} is the number density of nuclear spins of ^{207}Pb, p is the spin polarization of ^{207}Pb, $\mu = 0.584\mu_N$ is the nuclear magnetic moment of ^{207}Pb, γ_{Pb} is the gyromagnetic ratio of ^{207}Pb, ω_0 is the spin-precession frequency in the applied magnetic field, we define $T_b = min\{T_2, \tau_a\}$ as the "signal bandwidth time", T_2 is the transverse relaxation time of the nuclear spins, and $\tau_a = 10^6 h/m_a$ is the axion coherence time [9], which varies from 4×10^5 to 4×10^{-3} s over the range of the axion masses from $10^{-14} - 10^{-6}$ eV.

CASPEr searches for axion dark matter corresponding to axions of different masses by sweeping the applied magnetic field from zero to several T or higher, which in turn scans the NMR resonance frequency and sets the axion Compton frequency to which the apparatus is sensitive. Much of the interesting parameter space corresponds to field values that exceed the magnetic field limit of the SERF magnetometer. The large DC field problem can be solved using a flux transformer as shown in Fig. 1, which acts as a "DC magnetic filter" reducing the static magnetic field to keep the alkali metal atoms in the SERF regime. The flux transformer only picks up the time-varying component of the magnetic flux through the enclosed area.

A SERF magnetometer has a narrow bandwidth of a few Hz [25]; by applying a constant magnetic field along the pump-beam direction, the SERF magnetometer can be tuned to resonate at a higher frequency, which increases the detectable frequency range of the SERF magnetometer up to 200 Hz [26] or higher. The LOngitudinal Detection scheme (LOD) discussed in [27,28] can, in principle, fully remedy the disadvantage of the SERF magnetometer's limited bandwidth, which is discussed in Appendix.

The alkali cell of the SERF magnetometer is heated to 373 K-473 K in order to increase the alkali vapor density to improve the sensitivity. However, the ferroelectric sample is cooled down to a low temperature to increase the longitudinal relaxation time and the spin polarization of the sample [29,8]. Again a flux transformer [30,31] is a potential solution to this problem where, as shown in Fig. 1, the SERF magnetometer can be placed in a warm bore of a superconducting system containing the transformer coils and magnetic shields.

The magnetic flux through the primary coil can be written as [9,32]

$$\Phi_p = \mu_0 \mu_r g N_p M_a A_p, \tag{4}$$

where μ_r is the relative permeability of the ferroelectric sample, $\mu_r \approx 1$ for PbTiO$_3$, $g \approx 1$ is the geometric demagnetizing factor [32], A_p is the cross-section of the cylindrical sample, and N_p is the number of turns of the primary coil.

The flux transformer has an enhancement factor ($k_{FT} = B_s/B_p$), where B_s is the magnetic field in the secondary coil, B_p is the magnetic field in the primary coil, which can be calculated as

$$k_{FT} = \frac{N_p A_p B_s}{\Phi_p} = \frac{N_p A_p}{\Phi_p} \frac{\mu_0 N_s}{l_s} \frac{\Phi_p}{L_s + L_p} = \frac{\mu_0 N_s}{l_s} \frac{N_p A_p}{L_s + L_p}, \tag{5}$$

where N_s is the number of turns of the secondary coil, l_s is the coil length of the secondary coil, L_p and L_s are the inductances of the primary and the secondary coil, respectively. Inductances of multi-turn long solenoid coil can be written as

$$L_p \approx \frac{\mu_0 N_p^2 A_p}{l_p}, L_s \approx \frac{\mu_0 N_s^2 A_s}{l_s}, \tag{6}$$