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A new method with minimized systematic error sources to detect axion dark matter in storage rings using an rf Wien filter

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Axion, a hypothetical pseudo-scalar particle, is a direct consequence of the Peccei-Quinn mechanism, which was proposed to solve the strong CP problem in 1977. It is also a plausible candidate for dark matter. The axion feebly interacts with the Standard Model (SM) particles, which makes it extremely challenging to detect a sign of its existence. Nevertheless, there have been many efforts to search for the axion-SM interaction, the prevailing method among which is a cavity haloscope seeking for the axion-photon interaction, more suited for axion-frequencies above 100 MHz. On the other hand, there is another branch of interaction, namely a coupling between the axion and the nuclear electric dipole moment (EDM), which induces an oscillating EDM at the axion Compton frequency. A storage ring EDM experiment provides a powerful method sensitive to a proton EDM as small as 10^{-29} $e\cdot$cm. We extend the storage ring EDM concept to measure an oscillating EDM with a comparable sensitivity by exploiting a new spin resonance scheme using a radio frequency Wien filter. The new method does away with the severe spin resonance systematic error sources by a careful combination of frequencies used. We introduce this new method from a basic working principle to a projected sensitivity on the axion-EDM coupling constant.

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1. Introduction

An axion is a hypothetical pseudoscalar particle that was proposed by Peccei and Quinn to resolve the Strong CP problem in 1977 [1]. There have been many efforts to directly or indirectly find the axion, particularly since it was pointed out that the axion is a compelling dark matter candidate [2–4]. While most experiments seek to probe the axion-photon interaction using the resonant cavity haloscope or helioscope methods, high-precision spin precession experiments can serve as a window to the axion coupling with nucleon electric dipole moment (EDM) or fermion spins [5]. The primary signature as a result of the axion-EDM coupling is an oscillating nucleon EDM at the axion Compton frequency. This paper illustrates a recently proposed, novel method to probe the oscillating EDM of a charged nucleon induced by an axion-like dark matter in storage rings, with the aid of a radio frequency (rf) Wien filter (WF) [6]. This is complementary to a method tuning the $g-2$ frequency to the axion frequency [7], which is practically more challenging than tuning the rf frequency of the WF in practice. There is existing work on introducing the WF for the storage ring EDM experiment [10], but there are two substantial differences between it and this work. First, this work aims to measure the oscillating EDM, not the conventional static EDM, which would be evidence of the axion-EDM coupling and axion dark matter. Second, one can avoid the systematic vertical spin rotation from the WF misalignment in this case by tuning the WF frequency away from the horizontal spin precession frequency. We present the analytic derivation of the spin resonance in the presence of the WF, followed by the spin tracking simulation studies for verification. Then we discuss the potential systematic effects in the following section. Finally, we show the projected sensitivity of the axion-EDM coupling with future storage ring EDM experiments.

2. Spin resonance with an rf Wien filter in storage rings

The relativistic motion of particle spin in external electric and magnetic fields is governed by Thomas-Bargmann-Michel-Telegdi equation [8, 9]:

$$\boldsymbol{\omega}_s = -\frac{q}{m}\left[\left(G+\frac{1}{\gamma}\right)\mathbf{B} - G\frac{\gamma}{\gamma+1}(\boldsymbol{\beta}\cdot\mathbf{B})\boldsymbol{\beta} - \left(G+\frac{1}{\gamma+1}\right)\frac{\boldsymbol{\beta}\times\mathbf{E}}{c} + \frac{\eta}{2}\left(\frac{\mathbf{E}}{c} - \frac{\gamma}{\gamma+1}\left(\boldsymbol{\beta}\cdot\frac{\mathbf{E}}{c}\right)\boldsymbol{\beta} + \boldsymbol{\beta}\times\mathbf{B}\right)\right], \tag{1}$$

where G is a magnetic anomaly ($G \equiv (g-2)/2$) and η is a unitless EDM term, serving a similar role as the g-factor in the magnetic moment. The spin vector is given by the differential equation: $\frac{d\mathbf{S}}{dt} = \boldsymbol{\omega}_s \times \mathbf{S}$.

The rf WF fields are radial rf electric field and vertical rf magnetic field, where their magnitudes are given to cancel the Lorentz force on particles with specific momentum.

$$\begin{aligned} \mathbf{E}_{\text{WF}} &= E_0^{\text{WF}}\cos(\omega_{\text{WF}}t + \phi_{\text{WF}})\hat{e}_x, \\ \mathbf{B}_{\text{WF}} &= \frac{E_0^{\text{WF}}}{\beta c}\cos(\omega_{\text{WF}}t + \phi_{\text{WF}})\hat{e}_y \end{aligned} \tag{2}$$

It turns out that when the WF frequency is tuned to one of the sidebands of the axion and $g-2$ frequency, $\omega_{\text{WF}} = \omega_{g-2} \pm \omega_{\text{axion}}$, it leads to the spin resonance such that the spin rotates vertically [6].

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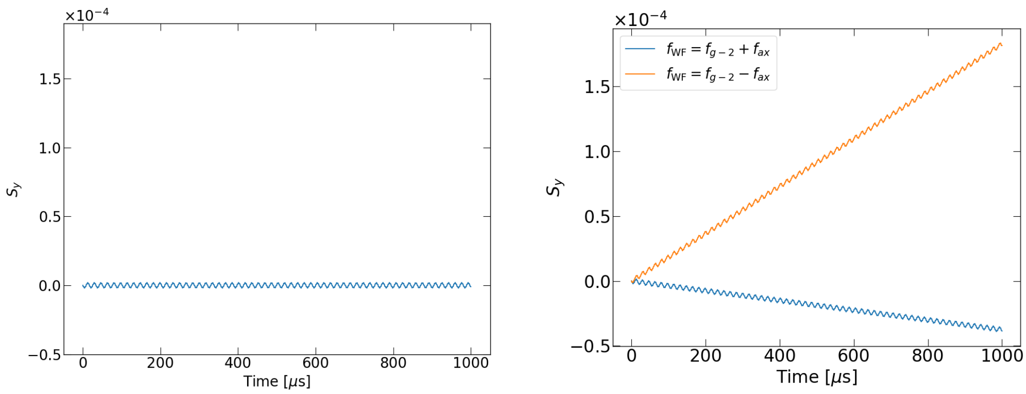
The vertical precession rate is specifically given as

$$\omega_d = -\frac{d_{\text{ac}}}{2S} E^* J_1 \left(\frac{a_{\text{WF}}}{\omega_{\text{WF}}} \right), \tag{3}$$

where $E^* = E - vB$ is the effective electric field of the storage ring, J_1 is the Bessel function of the first kind, and $a_{\text{WF}} \equiv \frac{q}{m} \frac{G+1}{\gamma^2} \frac{E_0^{\text{WF}}}{\beta c}$ is a scaled WF amplitude in a unit of angular frequency.



(a) Without the Wien filter.

(b) With the Wien filer at resonance.

Figure 1: Simulated vertical polarization of a proton in the presence of the axion-EDM coupling.

Figure 1 shows the vertical spin component as a function of time with and without the WF at resonance condition, obtained by the high precision spin tracking simulation. The vertical spin component has no average slope without the WF, whereas it linearly increases/decreases in the presence of the WF. The slopes differ at each sideband because the precession rate depends on the sign and magnitude of the sideband frequency, which can be seen in Eq. (3).

3. Potential systematic effects

A major systematic effect can arise when there are field errors. One potential source of the errors is the misalignment of the WF. For instance, there could be a small vertical electric field and radial magnetic field when the WF is tilted by a small angle, as illustrated in Fig. 2 (a). However, by tuning the WF frequency away from the horizontal spin precession frequency (also called $g-2$ frequency) targeting the same axion frequency, one can avoid the systematic false signal. This is shown in Fig. 2 (b), where the average slope does not change regardless of the size of the WF misalignment.

We also investigated more generic random field errors that could interfere with both the orbital and spin angular motions. In particular, one can set the random magnetic field errors as follows:

$$B_x(x, y, s) = \sum_{k=1,N=1} b_{k,N} \, \Im \left(\frac{x+iy}{r_a} \right)^{k-1} \cos\left(N\frac{s}{R} + \phi_N \right), \tag{4}$$

$$B_y(x, y, s) = \sum_{k=1,N=1} b_{k,N} \, \Re \left(\frac{x+iy}{r_a} \right)^{k-1} \cos\left(N\frac{s}{R} + \phi_N \right), \tag{5}$$

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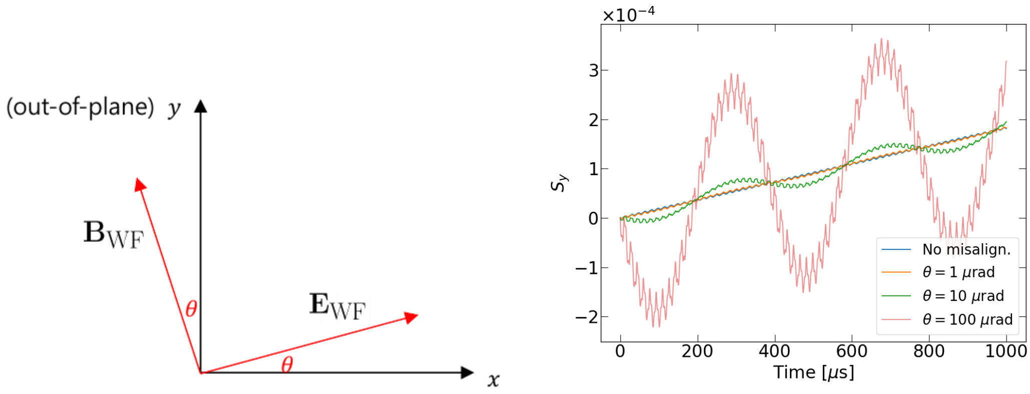

(a) An illustration of the Wien filter misalignment. The vertical magnetic field and the horizontal electric field are tilted by an angle θ.

(b) Simulated vertical polarization with the Wien filter at resonance. Different colors indicate the different sizes of the misalignment up to 100 microradians.

Figure 2: Systematic effect from the Wien filter misalignment.

where R is the radius of the storage ring and r_a is the beam acceptance excursion. We find the average slope still does not vary much from the ideal case, even when the magnitude of the random field errors is as high as 5 parts per million of the main magnetic field of the storage ring, as verified in Fig. 3.

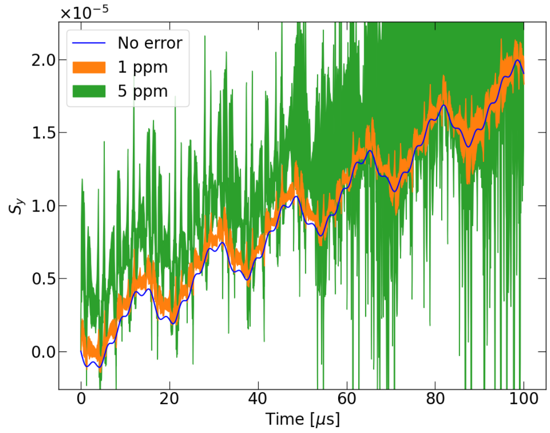

Figure 3: The fluctuations of the vertical spin component versus time in the presence of random field errors. The blue curve is the reference plot without the field errors, where the orange and green curves show maximum and minimum excursions of many simulations in the presence of 1 ppm and 5 ppm or field errors, respectively.

4. Sensitivity

We finally turn our attention to the projected sensitivity on the axion-EDM coupling parameter. Assuming the axion-like particle makes up all of the local dark matter with a density $\rho_{\rm DM} \approx$

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0.3 GeV/cm^3, the nucleon EDM is given by [5]

$$d_n \approx \left(1.4 \times 10^{-25}\ e \cdot \mathrm{cm}\right)\left(\frac{\mathrm{eV}}{m_a}\right)\left(\frac{g_d}{\mathrm{GeV}^{-2}}\right)\cos(m_a t). \tag{6}$$

According to the feasible EDM sensitivity proposed by the storage ring EDM collaboration [11, 12], it corresponds to what is shown in Fig. 4.

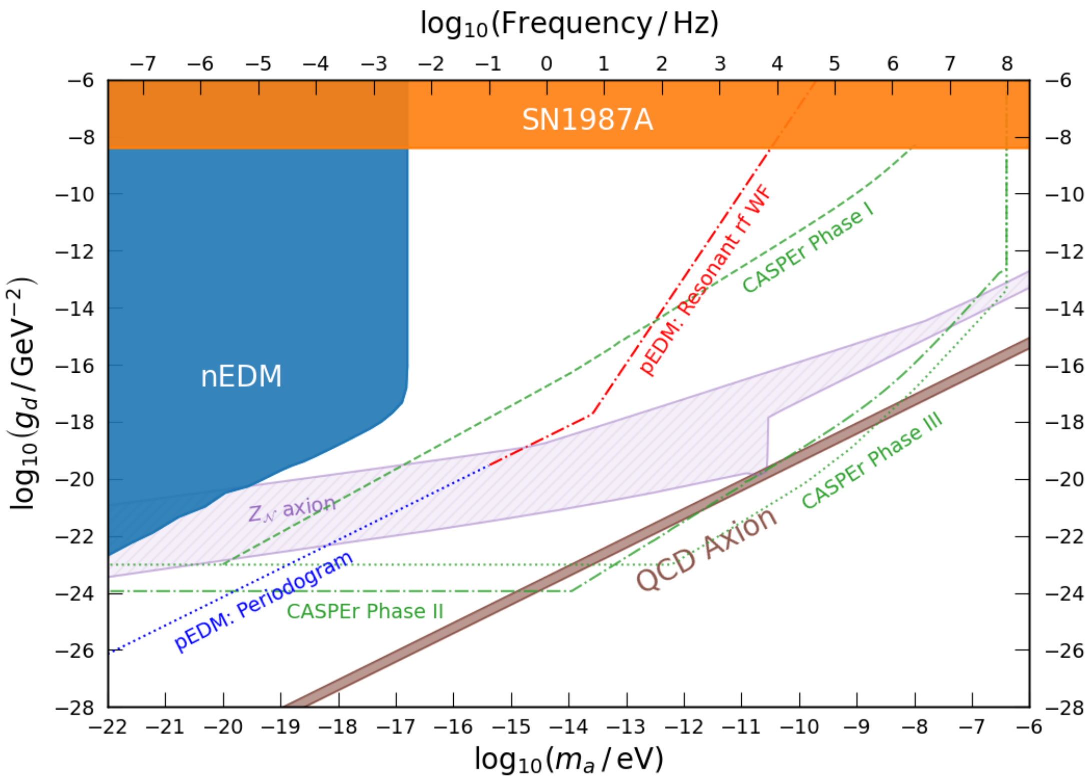

Figure 4: The projected sensitivity of the axion-EDM coupling g_d, shown in the blue-dotted line for the parasitic measurement using periodogram analysis and in the red-dashed-dotted line for the dedicated measurement with resonant rf Wien filter. The direct laboratory constraint from the neutron EDM experiment is shown in the blue-filled region [13]. There are other projected sensitivities from the CASPEr experiments [14–16]. One theoretical model above the QCD axion, $\mathcal{Z}_N$ axions, is introduced here for reference [17].

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