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Spin of protons in NICA and PTR storage rings as an axion antenna

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Axions, first proposed by Peccei and Quinn in 1977 [1] as a solution to strong CP-violation in QCD, are widely discussed as a plausible candidate for the dark matter. One of manifestations of the cold galactic halo axions will be a NMR-like resonant rotation of the spin in the oscillationg axion field [2–6]. Here the spin serves as an axion antenna and the experimental search by the JEDI collaboration of the axion signal with polarized deuterons in the storage ring COSY is in progress [7]. Inherent to the JEDI technique of a buildup of the vertical polarization from the in-plane one is a need for a long coherence time of the in-plane precessing spin and it is not applicable to protons with arguably short spin coherence time [8].

In this communication we suggest the alternative scheme which is free of these limitations and looks preferred one for searches for axions at the Nuclotron, NICA [9] and PTR [10] storage rings. We also comment on exclusive features of the spin frequency scan in hybrid rings with concurrent electric and magnetic bending, the PRT storage ring proposed by the CPEDM collaboration being a good example.

A detailed introduction into axions is found in reviews [4, 11–13], here we only mention the principal points. The amplitude of the classical axion field $a(x) = a_0 \cos(\omega_a t - \mathbf{k}_a \cdot \mathbf{x})$ can be inferred from the local density of the dark matter [2, 14]. Weinberg's gradient interaction of axions with fermions [15],

$$L_{a\bar{\psi}\psi} = -\frac{1}{2f_a}\, g_f\, \overline{\psi}\gamma^\mu\gamma_5\psi\, \partial_\mu a(x)\,, \qquad (1)$$

can be reinterpreted as an interaction of fermion's spin with the pseudomagnetic field [16]. Still another manifestation of axions is the oscillating contribution to the electric dipole moment (EDM) of nucleons [2, 17], $d_N^{\rm ax}(x) = (a(x)/f_a)\cdot(\mu_N/c)\cdot\kappa_a$, where μ_N is the nuclear magneton and the small factor $\kappa_a \sim (m_d m_u/(\Lambda_{QCD}(m_d+m_u)) \approx 10^{-2}$ describes the chiral suppression of the EDM by small masses of light quarks [18, 19].

We start with all magnetic storage rings, $\mathbf{E} = 0$, when the spin tune $\nu_s = G\gamma$. The effect of the axion field induced EDM is tantamount to that of the radiofrequency Wien filter [20]. Secondly, spin interacts with the oscillating pseudomagnetic field, proportional to the particle velocity and the time derivative $\partial_t a(x)$ [16, 20], which is tangential to the particle orbit and acts as a radiofreqency solenoid. Note that the velocity of particles in a storage ring, v, is of the order of the velocity of light and $v \approx 10^3 v_a$, where $v_a \sim 250$ km/s is the velocity of Earth's motion in Galaxy. At the axion resonance, $\omega_a = \nu_s\Omega_c$, the instantaneous angular velocity of the axion-driven resonant spin rotation takes the form [21]

$$\mathbf{\Omega}_{\rm res} = \frac{a_0}{f_a}\left(g_f\omega_a \sin(\omega_a t)\frac{\mathbf{v}}{c} - \kappa_a\gamma\cos(\omega_a t)\left[\frac{\mathbf{v}}{c}\times\mathbf{\Omega}_c\right]\right). \qquad (2)$$

Upon solving the BMT equations by the Bogoliubov–Krylov averaging [22, 23], one finds the angular velocity of the resonant up-down rotation of the spin envelope

$$\Omega_{\rm res} = \frac{a_0}{2f_a}\,\frac{\gamma v}{c}\,\mid g_f G - \kappa_a \mid \Omega_c. \qquad (3)$$

A strong enhancement of the contribution from the pseudomagnetic field by the factor $g_f G/\kappa_a \gg 1$ was missed in the early discussion [7], and the actual sensitivity of the JEDI experiment was greatly underestimated.

As the axion mass is unknown, one is bound to scanning the spin angular velocity as $\Omega_s(t) = \omega_a + 2\Omega_t^2 t$, where $2\Omega_t^2 = d\Omega_s/dt$. In our convention a scan starts at large negative time $t = -t_0$ and the exact resonance takes place at $t = 0$. The spin phase during the scan varies as $\theta_s(t) = \omega_a t + \Omega_t^2 t^2$. A derivation of the axion-driven small in-plane polarization envelope P_{xz} gives

$$P_{xz}(t) = P_y\Omega_{\rm res}\int_{-t_0}^{t} d\tau \exp\left[-\Gamma(t-\tau)\right]\cos(\Omega_t^2\tau^2). \qquad (4)$$

In the usually discussed scheme with the in-plane initial polarization [6, 7, 24, 25], the axion signal will be proportional to $\sin\Delta$ [22, 26], where Δ is an entirely unknown difference of the spin presession and axion oscillation phases. In contrast to that, a buildup of the in-plane polarization from the initial vertical one is free of this phase ambiguity.

In the limit of large spin coherence time, $\Gamma \ll \Omega_t$, the envelope P_{xz} will exhibit a jump of temporal width

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$t_1 \sim 1/\Omega_t$ and the amplitude $P_{xz}^{\max} \sim P_y\Omega_{\rm res}/\Omega_t$. The opposite limiting case of $\Gamma \gg \Omega_t$, is of special interest for protons with short spin coherence time [8], and here emerges a new time scale $t_2 \sim \Gamma/(\Omega_t^2)$. At $-t_2 < t < t_2$ the envelope P_{xz} will oscillate as

$$P_{x,z} \approx \frac{\Omega_{res}}{\Gamma} P_y \cos(\Omega_t^2 \tau^2), \tag{5}$$

and fits to the well specified function (5) will facilitate identification of the axion signal.

We note that in all magnetic fields the resonance condition entails $\omega_a = p/(R\gamma m)$, where R is the ring radius and p is the particle momentum. Consequently, in all magnetic rings the attainable axion masses are bounded from below by the minimal momentum the storage ring can run at.

The hybrid ring with concurrent magnetic and electric bendings are much more versatile compared to all magnetic rings. An example is provided by the prototype test ring PTR proposed by the CPEDM collaboration [9]. With the radial electric field $E_0 = 7\times 10^6\,\mathrm{V/m}$ complemented by the vertical magnetic field $B_0 = 0.0327\,\mathrm{T}$, PTR will provide the frozen spin of protons, $\mathbf{\Omega}_s^{\rm mdm} = 0$, i.e., $\nu_s = 0$. Beyond this point, the electric and magnetic fields must be varied synchronously to preserve the injection energy, the orbit radius and the cyclotron frequency, and the spin tune will vary as $\nu_s = -G_p\gamma\Delta E/E_0$. The axion resonance will take place at $\omega_a = -G_p\gamma\Omega_c\Delta E/E_0$, and the resulting angular velocity of the axion-driven spin rotation will be given by

$$\Omega_{\rm res} = \frac{a_0}{2f_{(a)}}\,\frac{\gamma v}{c}\,|\,g_f G\frac{\Delta E}{E_0} + \kappa_{(a)}\,|\,\Omega_c. \tag{6}$$

To summarize, we demonstrated how the spin of polarized protons can be used as an axion antenna in spite of the short spin coherence time of the in-plane polarization of protons. The key point is to look for a buildup of the idly precessing in-plane polarization starting from the stable verical one. Hybrid prototype rings emerge as a promising proton spin antenna sensitive to axions with small masses up to few $\mathrm{neV/c^2}$. These observations suggest new options for the experimental searches for axions at NICA in Dubna, COSY in Juelich, planned PTR and elsewhere.

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