ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-WEPAB188

NEW METHOD TO SEARCH FOR AXION-LIKE PARTICLES DEMONSTRATED WITH POLARIZED BEAM AT THE COSY STORAGE RING

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on behalf of the JEDI collaboration†

Abstract

The axion was originally proposed to explain the absence size of CP violation in quantum chromodynamics. Axions or axion-like particles (ALPs), when coupled to gluons, induce an oscillating Electric Dipole Moment (EDM) along the nucleon's spin direction. At the Cooler Synchrotron COSY in Jülich, this principle was used to perform a first test experiment to search for ALPs using an in-plane polarized deuteron beam. In COSY, the beam polarization vector precesses in the horizontal plane due to the presence of magnetic fields. If the spin precession frequency equals the EDM oscillation frequency, a resonance occurs that accumulates the rotation of the polarization out of the ring plane. Such a resonance is searched for by scanning beam revolution frequency, which is directly related to the spin precession frequency. At COSY, four beam bunches with different polarization directions were used to make sure that no resonance was missed because of the unknown relative phase between the polarization precession and the EDM oscillations. We scanned a frequency window of about 1.5 kHz width around the spin precession frequency of 121 kHz. This paper describes the experiment.

INTRODUCTION

Originally, the axion was introduced to resolve the strong CP problem in quantum chromodynamics [1]. It was proposed to have low mass and weak coupling to nucleons. If sufficiently abundant, it might be a good candidate for dark matter in the universe. Axions or Axion-Like Particles (ALPs), when coupled with gluons, induce oscillations in the nuclear Electric Dipole Moment (EDM) d_n [2,3] that can be described as

$$d_n(t) = d_0 + d_1 \cos(\omega_a t + \phi_a),$$

where ω_a, the oscillation frequency, is related to the axion mass m_a by $\omega_a = m_a c^2/\hbar$ and ϕ_a is the oscillation phase.

In spring 2019, the JEDI Collaboration conducted a proof-of-principle experiment at COSY using a 0.97 GeV/c in-plane polarized deuteron beam. This search method assumes that the axion is coherent in space, causing all the particles along the ring to oscillate together; the axions are dense enough to be detected whenever we look for one; and the axion maintains coherence in time long enough for the resonance jump to be measured. Previous discussions of axion searches at COSY can be found in [4,5].

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BASIC CONCEPT

The evolution of the spin in a storage ring is given by the Thomas-BMT equation [6,7]. The beam's spin tune, $\nu_s = G\gamma$, where G is the anomalous magnetic moment and γ is the Lorentz factor, describes the number of spin rotations in the ring plane per beam revolution in the ring. The EDM of the particle, which is aligned along the spin direction, experiences a torque due to the particle-frame radial electric field which rotates the beam polarization in the vertical plane. For a static EDM d_0, the combination of this torque-induced rotation and the spin tune rotation would cause tiny oscillations of the vertical polarization which average to zero.

In the case of an oscillating EDM d_1, this cancellation fails. If the EDM oscillation frequency matches the spin tune frequency, also called the spin precession frequency, a build-up of vertical polarization occurs. As the axion-induced EDM oscillation frequency is unknown, the spin precession frequency is ramped in search of the signal for an ALP, which would be a jump in the vertical polarization. An example calculation can be seen in Fig. 1.

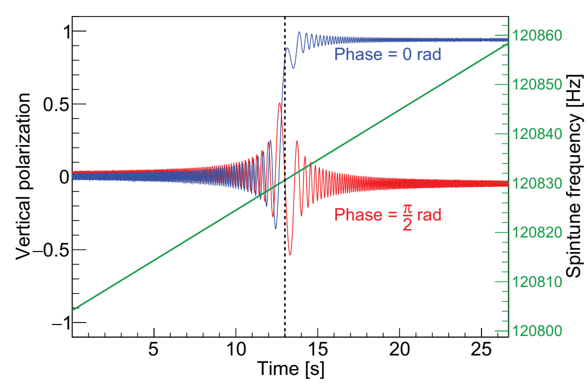

Figure 1: Example calculation where the spin precession frequency (green) was varied in search of a resonance. The signal is the jump in the vertical polarization at resonance crossing. The blue and red curves show calculations done at phases of 0 rad and $\pi/2$ rad.

Figure 1 illustrates the vertical polarization jump at the resonance crossing. Calculations for two different phases ϕ between the in-plane precession and axion-induced EDM oscillations are shown to indicate that it is not sufficient to find a resonance frequency, since the magnitude of the observed signal also strongly depends on the phase ϕ. The

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procedure used to overcome this problem is discussed in the next section.

MACHINE SETUP

One of the major requirements for this storage ring polarization experiment is an in-plane polarized beam with a long spin coherence time. To achieve this, the beam was bunched, electron cooled and sextupole-field corrected [8,9]. The polarization was recorded in the WASA detector [10]. A detailed explanation of setting up the storage ring EDM experiments can be found in [9].

A solution to the phase problem is to run the search using multiple beam bunches with different polarization directions in the storage ring simultaneously, all sensitive to the same ALP. This search used four bunches. The WASA detector rate as a function of time and location around the ring is shown in Fig. 2. The four bunches are clearly visible. An RF solenoid, operating at the frequency $(1 + G\gamma)f_{\mathrm{rev}}$, was used to rotate the beam polarization from vertical to the horizontal plane. Figure 3, which is a top down illustration of the ring, shows the polarization and particle-frame electric field direction for all four bunches that results from this procedure. Any two adjacent bunches have perpendicular spin directions with respect to the electric field and thus are together sensitive to all possible phases. The presence of all these combinations of electric field and the spin direction makes it possible to suppress systematic errors of the polarization measurement.

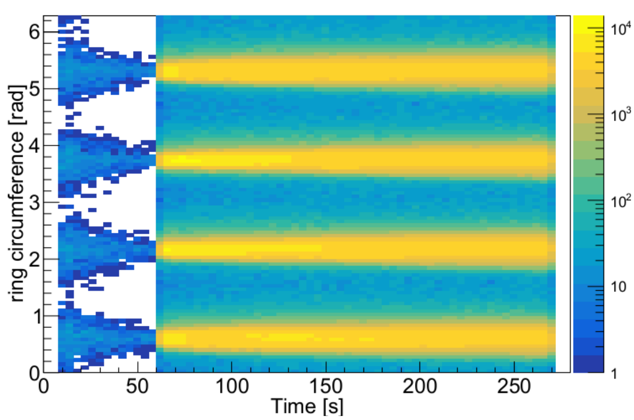

Figure 2: Detector rate as function of time within a beam store (x-axis) and position in the ring (y-axis), depicting the well separated four bunches. After beam cooling, the data acquisition starts at 60 s.

The measurement of the horizontal polarization of the bunches provides the relative polarization directions (Fig. 4). The WASA detector at its fixed location in the ring registers each bunch at different times. This produces unequally spaced relative phases that are nevertheless consistent with model predictions of the setup as shown in radians inside a red bracket pattern. This confirms the pattern of Fig. 3.

Figure 5 illustrates the scanning method used in the search for ALPs. The beam revolution frequency, and thus also

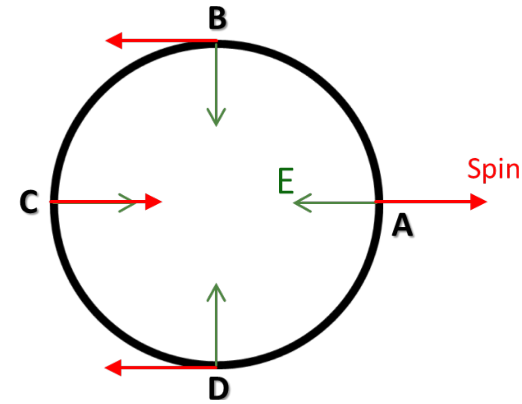

Figure 3: An illustration of a top down view of the ring at a fixed time with four bunches. The arrows show the particle-frame electric field (green) and the polarization direction (red). This pattern allows the search to be sensitive to to all phases.

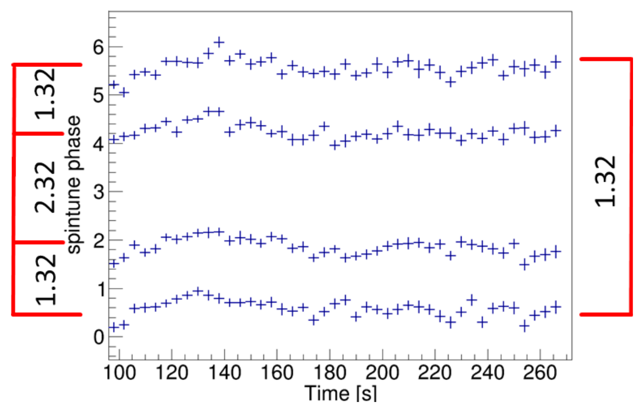

Figure 4: Relative horizontal polarization phase in radians of the four beam bunches as seen at the polarimeter (see text).

the spin precession frequency, is slowly varied in search of the resonance. Each scan is repeated multiple times and consecutive scans are deliberately overlapped by 10% so as to not miss an axion near either end of the scan. The operation of the RF solenoid, which makes use of a spin resonance, requires the revolution frequency to be at the same value for every scan. Hence after the RF solenoid is switched off, a frequency jump was made to the starting value of each individual scan as shown by the first jump in frequency in Fig. 5.

A total of 106 scans were performed covering a frequency width of 1.5 kHz ranging from 119 997 Hz to 121 457 Hz. The corresponding ALP mass range is from 4.95×10^{-9} eV to 5.02×10^{-9} eV.

TEST USING RF WIEN FILTER

To verify that the setup was capable of detecting an axion-like resonance, a test signal was made using an RF Wien filter with a radial magnetic field. Information on the RF Wien filter is given in ref. [11]. The RF Wien filter in this configura-

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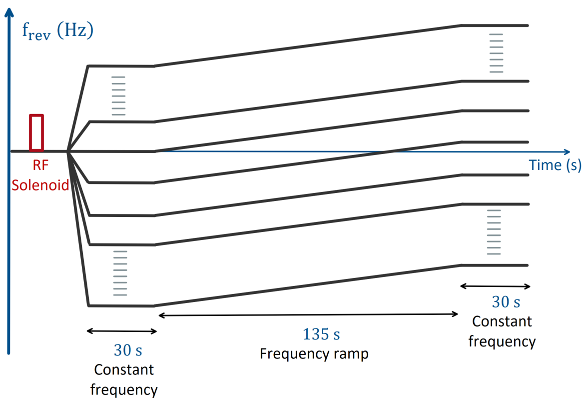

Figure 5: Schematic diagram of the scanning process (see text). The horizontal axis is time and vertical axis is the revolution frequency of the machine. The red rectangle marks the time of the RF solenoid operation.

tion produces driven oscillations in the vertical polarization when tuned to the resonance frequency $(1 - G\gamma)f_{\text{rev}}$. When this resonance is crossed by varying the machine frequency, jumps are created in the polarizations of the four bunches. An example is shown in Fig. 6.

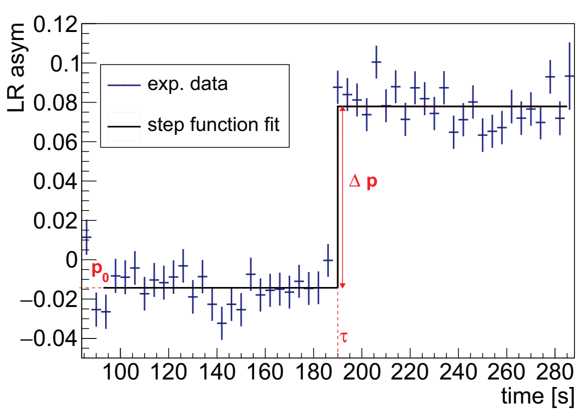

Figure 6: Polarization jump seen at resonance crossing in the case of the RF Wien filter scan. Also shown is the step function fit used to calculate the jump magnitude at resonance crossing.

Figure 6 also illustrates how data from a scan is analysed to search for a resonance crossing by varying the time of crossing τ while looking for the largest jump Δp based on the overall best fit. This type of scan is free of systematic errors due to the distribution of the bunch polarizations.

CONCLUSION

This paper discusses the first experiment performed to search for axion-like particles using a storage ring by scanning the machine frequency for resonance between the axion-induced oscillating EDM frequency and spin precession frequency. A frequency window of about a 1.5 kHz width around 121 kHz was scanned. No axion or axion-like particle were observed. The analysis to calculate the upper limit of the strength of the oscillating EDM is still ongoing.

REFERENCES

[1] R. D. Peccei and H. R. Quinn, "CP conservation in the presence of pseudoparticles", *Phys. Rev. Lett.*, vol. 38, pp. 1440–1443, Jun. 1977. doi:10.1103/PhysRevLett.38.1440

[2] P. W. Graham and S. Rajendran, "Axion dark matter detection with cold molecules", *Phys. Rev. D*, vol. 84, p. 055013, Sep. 2011. doi:10.1103/PhysRevD.84.055013

[3] P. W. Graham and S. Rajendran, "New observables for direct detection of axion dark matter", *Phys. Rev. D*, vol. 88, p. 035023, Aug. 2013. doi:10.1103/PhysRevD.88.035023

[4] S. P. Chang, S. Hacıömeroğlu, O. Kim, S. Lee, S. Park, and Y. K. Semertzidis, "Axionlike dark matter search using the storage ring edm method", *Phys. Rev. D*, vol. 99, p. 083002, Apr. 2019. doi:10.1103/PhysRevD.99.083002

[5] J. Pretz *et al.*, "Statistical sensitivity estimates for oscillating electric dipole moment measurements in storage rings", *Eur. Phys. J. C*, vol. 80, no. 2, p. 107, Feb. 2020. doi:10.1140/epjc/s10052-020-7664-9

[6] V. Bargmann, L. Michel, and V. L. Telegdi, "Precession of the polarization of particles moving in a homogeneous electromagnetic field", *Phys. Rev. Lett.*, vol. 2, pp. 435–436, May 1959. doi:10.1103/PhysRevLett.2.435

[7] T. Fukuyama and A. J. Silenko, "Derivation of generalized THOMAS–BARGMANN–MICHEL–TELEGDI equation for a particle with electric dipole moment", *Int. J. Mod. Phys. A*, vol. 28, no. 29, p. 1350147, Nov. 2013. doi:10.1142/s0217751x13501479

[8] G. Guidoboni *et al.*, "How to reach a thousand-second inplane polarization lifetime with 0 97-GeV/c deuterons in a storage ring", *Phys. Rev. Lett.*, vol. 117, p. 054801, Jul. 2016. doi:10.1103/PhysRevLett.117.054801

[9] G. Guidoboni *et al.*, "Connection between zero chromaticity and long in-plane polarization lifetime in a magnetic storage ring", *Phys. Rev. Accel. Beams*, vol. 21, p. 024201, Feb. 2018. doi:10.1103/PhysRevAccelBeams.21.024201

[10] F. Müller *et al.*, "Measurement of deuteron carbon vector analyzing powers in the kinetic energy range 170–380 MeV", *Eur. Phys. J.*, vol. 56, no. 8, p. 211, Aug. 2020. doi:10.1140/epja/s10050-020-00215-8

[11] J. Slim *et al.*, "Electromagnetic simulation and design of a novel waveguide RF wien filter for electric dipole moment measurements of protons and deuterons", *Nucl. Instrum. Methods Phys. Res., Sect. A*, vol. 828, pp. 116–124, Aug. 2016. doi:10.1016/j.nima.2016.05.012