A Search for Axion-like Particles with a Horizontally Polarized Beam in a Storage Ring

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Axions proposed to explain the lack of CP violation. Electric dipole moments (EDMs) did not appear.

Axions are a candidate for interstellar dark matter.

One characteristic is the ability to induce oscillating EDM.

\[ d = d_0 + d_1 \cos(\omega t + \varphi) \]

Oscillation frequency connected to axion mass. At the time of observation, the phase is unknown.

Idea: create an oscillating polarization, look for resonance at \( \omega \).
Description of the axion search (demonstration)

We start from a known COSY setup: polarized deuterons at 0.97 GeV/c. Beam is electron (pre-)cooled with long, in-plane polarization lifetime.

Standard picture of frozen spin EDM experiment:

For deuteron in COSY

In the axion search:

(in the axion search: (spin is not frozen))

After ~3 revolutions

polarization reversed

but EDM has flipped

combination allows signal accumulation

EDM accumulation depends on $v \parallel p$.

Axion accumulation is automatic if the frequency is right.

But phase is unknown.
The frequency is unknown. So scan for it.

You may be lucky enough to cross the axion frequency.

Flat regions allow for a precise before-after comparison.

Then you will measure:

\[ \Delta p = -0.75 \]
\[ \text{ramp} = 0.5 \text{ Hz/s} \]

Critical assumptions:

> The axion is coherent in space. All particles oscillate together. The axion is present in all of COSY. Axions are dense.
> The axion is coherent in time. It takes a few seconds to pass COSY. (only slow axions stay in galaxy, \( v[esc] \sim 550 \text{ km/s} \))
Electron cooling and adjustment of sextupole fields are essential for a long horizontal polarization lifetime.
Modified WASA setup

Carbon block target

Range Hodoscope:
3 x 24 elements (10cm)
2 x 24 elements (15cm)
pizza shaped

Veto Hodoscope:
1 x 24 elements (20mm)
vertical bars
double-sided readout

Window Counter:
2 x 24 elements (3mm)
pizza shaped

Straw Tubes:
4 x 4 layers
0°, 90°, 45°, -45°

Trigger Hodoscope:
1 x 48 elements (5mm)
pizza shaped
New data acquisition procedure – time stamp every event

- Count turn number (bunched beam)
- Compute total spin precession angle
- Bin by phase around the circle
- Compute asymmetry in each bin

\[ \text{distribution of turn number} \]
\[ \text{fraction yields beam distribution} \]
\[ \text{based on integral part of turn number} \]

smooth curves through phase bin asymmetries

these curves determined by asymmetry measurements for 9 angle bins

As the polarization rotates the down-up asymmetry reflects the sideways projection of the polarization.
**Sample data**

Distribution of beam around the ring as a function of time in the store.

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**Sample measurements of horizontal polarization loss (corrected for positive bias)**

\[
\varepsilon = \frac{3}{2} p_y A_y
\]

Times are exponential decay rates.

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Program searches for highest amplitude in a narrow range. To get maximum asymmetry stationary in one angle bin, spin tune must be accurate to < 1e-6. Normal scatter is usually < 1e-7.

Best error in phase is \( \sim 3^\circ /s \).

Downward slope means spin tune wrong by \( 3e-8 (\delta \sim 10\%) \).

EDM ring requirement is 1e-9 from feedback.

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Phase in a single store with fixed spin tune.

- e-cool + bunch
- prep
- observation time

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Contents below 5 events/bin suppressed.
Problem: Axion phase is unknown.
Conduct search simultaneously with beams having perpendicular polarizations. Combine results for better signal.

Plan: Use 4 bunches...

Operate RF solenoid at
\[ f_{\text{REV}}(1+G\gamma) = 629771.9 \text{ Hz} \]

verification
Calibration based on tracking through rotational history

Calculation shows size of jump as a function of oscillating EDM size.

Red – axion in phase (0°)
Magenta – phase = 90°
Black – sum in quadrature

Ramp rate = 10 Hz/s
(most data taken at 0.1 or 0.05 Hz/s)

For any other ramp rate, scale by $1/\sqrt{r}$.

$\epsilon$ is the EDM rotation (rad/turn), so $\omega_{EDM} = f_{REV} \epsilon$.

Electric dipole:

$$d = (6.242 \times 10^{20}) \frac{\hbar \omega_{EDM}(2\pi R)}{v(B\rho)}$$

conversion to e·cm
Run a series of scans in frequency

RF sol.

expected signal

Machine acceptance

Test calibration

A system test was made using an RF Wien filter to generate signals similar to an axion. The signal response was also used to calibrate the polarization jump.
Check against Wien filter:

Frequency at maximum power level produces average \( \varepsilon = 1.42 \times 10^{-7} \)

Scale for ramp rate

- predicted for 0.1 Hz/s \( \Delta p = 0.736 \)
- predicted for 0.05 Hz/s \( \Delta p = 0.915 \)
In practice, random phase distributions resulted in a spread of jumps. We want the maximum.

Values in figures are the length of the diagonals.

Typical jumps averaged over all cases:

\[ 0.1 \text{ Hz/s} \rightarrow \Delta(pA) = 0.0948 \]

\[ 0.05 \text{ Hz/s} \rightarrow \Delta(pA) = 0.1163 \]
At 190 s average horizontal polarization is 0.13.

Scales polarizations to 0.73 and 0.90

The Wien filter test confirms the calibration from the rotation model.
Anticipated limit achievable using:

- Deuteron/proton beams
- Combined electric/magnetic ring
- Parasitic analysis using all-electric ring

see S.P. Chang et al., PRD 99, 083002 (2019)