EDMs violate $P$ and $T$ symmetries, test CP-violation. Any observation might illuminate the matter/anti-matter asymmetry of the universe.

Storage ring search for an Electric Dipole Moment (EDM)

Beam polarization measurement and preservation in a storage ring search for an electric dipole moment

Edward J. Stephenson
Indiana University
(Forschungszentrum Jülich)
(KAIST-CAPP)
The EDM Experiment:

Whether electric or magnetic, all storage rings have a radial inward electric field in the particle frame. For a beam polarized along the velocity, an EDM creates a rotation of the polarization, which we see as a changing vertical component.

Spin polarization will be measured by an asymmetric scattering from carbon. Keep polarization along velocity with extra E fields. For proton, only E field.

Requirements

- Polarimeter: Efficiency ~ 1%, Analyzing power ~ 0.6. (done)
- Control geometry and rate systematic errors.
  Must be able to measure a difference of one part per million.
- Extend horizontal polarization lifetime (unstable) to $10^3$ s.
- Control polarization direction with active feedback.

Sensitivity goal: $10^{-29}$ e·cm in one year of running.
Deuteron-carbon analyzing powers are large at forward angles (optical model spin-orbit force).

Inelastic and \((d,p)\) are similar, and should be included.

Simplest polarimeter is absorber/detector:

\[ \text{FOM} = \sigma A^2 \]

Azimuthal angles yield two asymmetries:

\[ \varepsilon_{\text{EDM}} = \frac{L - R}{L + R} \]

\[ \varepsilon_{g-2} = \frac{D - U}{D + U} \]

Polarimeter Study

COSY storage ring
polarized deuterons, 0.97 GeV/c

17 mm C target

double-hit extraction?: deflect at (1), then oscillate to (2)
How to manage systematic errors:
(measuring left-right asymmetry)

Usual tricks: Locate detectors on both sides of the beam (L and R).
Repeat experiment with up and down polarization.
Cancel effects in formula for asymmetry (cross-ratio).

\[
pA = \varepsilon = \frac{r - 1}{r + 1}
\]
\[
r^2 = \frac{L(+)R(-)}{L(-)R(+)}
\]

But this fails at second order in the errors.

From experiments with large induced errors make a model of those errors:

Using the data itself, devise parameters:

\[
\phi = \frac{s - 1}{s + 1}
\]
\[
s^2 = \frac{L(+)L(-)}{R(+)R(-)}
\]

and rate \( W = L + R \)

Calibrate polarimeter derivatives and correct (real time):

\[
\varepsilon_{CR,corr} = \frac{r - 1}{r + 1} - \left( \frac{\partial \varepsilon_{CR}}{\partial \phi} \right)_{MODEL} \Delta \phi - \left( \frac{\partial \varepsilon_{CR}}{\partial W} \right)_{MODEL} \Delta W
\]

Create a model. Will this work? for both \( X \) and \( \theta \)?
Geometry model

Parameters we know we need to include:

**EDDA Analyzing power:**  
\[ A_y \text{ and } A_T = \frac{\sqrt{6}T_{22}}{\sqrt{8 - p_T T_{20}}} \]

**Polarizations:**  
\( p_V \) and \( p_T \) for the states V+, V−, T+, T−

There is some information available from the COSY Low Energy Polarimeter.

**Logarithmic derivatives:**  
\[ \frac{\sigma'}{\sigma}, \quad \frac{\sigma''}{\sigma}, \quad \frac{A_y'}{A_y}, \quad \frac{A_y''}{A_y}, \quad \frac{A_T'}{A_T}, \quad \frac{A_T''}{A_T} \]

**Solid angle ratios:**  
L/R  \quad D/U  \quad (D+U)/(L+R)

Total so far: 19 parameters
Parameters we found we needed (peculiar to COSY detector):

Rotation of Down/Up detector (sensitive to vertical polarization): \( \theta_{\text{rot}} \)

\( X - Y \) and \( \theta_X - \theta_Y \) coupling (makes D/U sensitive to horizontal errors): \( C_X, C_\theta \)

Ratio of position and angle effects (effective distance to the detector): \( X/\theta = R \)

Tail fraction: multiple-scattered, spin-independent, lower-momentum flux that is recorded only by the “right” detector (to inside of ring)

\( F = \text{fraction} \quad F_X, F_\theta \text{ sensitivities to position and angle shifts} \)

Total so far: 26

Rate model

Linear correction based on rate for each polarization observable (5)

Total parameters: 31
Changes to beam position/angle produced effects that calibrate the polarimeter for errors.

Slopes given by:

\[
\frac{\sigma'}{\sigma} = -0.02562(9) \quad \frac{A'}{A} = 0.0055(3) \quad \frac{1}{\text{mrad}}
\]

Induced error in position (mm) or angle (mrad)

\(X/\theta = 52.4(8)\) cm

Position change (mm)
Slope change (mrad)

Zero level set by L/R solid angle ratio and tail fraction

Shifts measure vector asymmetry

Changes to beam position/angle produced effects that calibrate the polarimeter for errors.
Changes to beam position/angle produced effects that calibrate the polarimeter for errors.

Application to data with errors shows correction in real time.

![Graph showing left-right asymmetry](image)

**Graph: LEFT-RIGHT ASYMMETRY**

<table>
<thead>
<tr>
<th>V-</th>
<th>V+</th>
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<tbody>
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**This works!**

Slope difference measures "effective" distance to detector

\[X/\theta = 52.4(8) \text{ cm}\]
Field correction study

Learn to measure horizontal polarization as it rotates at 120 kHz (deuterons). Can sextupole corrections remove second-order contributions to decoherence.

Three sextupole magnet families:

- MXS (large $\beta_x$)
- MXL (large $\beta_y$)
- MXG (large D)
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

distribution of turn number fraction yields beam distribution
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

magnitude gives horizontal polarization

Correcting phase slip from one bin to the next adjusts the spin tune
**Sample data**

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

**POLARIMETER EVENT RATE**

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

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

- 760 $\pm$ 230 $\sim$ 140 s
- 140 $\pm$ 5 s

\[ \epsilon = 21.8 \pm 0.8 \text{ s} \]

Times are exponential decay rates.

Program searches for highest amplitude in a narrow range. To get maximum asymmetry stationary in one angle bin, spin tune must be accurate to $< 1 \times 10^{-6}$. Normal scatter is usually $< 1 \times 10^{-7}$.

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

Downward slope means spin tune wrong by $3 \times 10^{-8}$ ($\delta \sim 10\%$). EDM ring requirement is $1 \times 10^{-9}$ from feedback.

Phase in a single store with fixed spin tune
Expected sensitivity of polarization lifetime (inverse) to sextupole strength

\[
\frac{1}{\tau_{\text{SCT}}} = |A + a_1 S + a_2 L + a_3 G|\theta_X^2 \\
+ |B + b_1 S + b_2 L + b_3 G|\theta_Y^2 \\
+ |C + c_1 S + c_2 L + c_3 G|\sigma_P^2
\]

drivers: emittance, sync. osc.

natural value

sensitivities

sextupole currents (MXS, MXL, MXG)

1. Set chromaticities to zero (X and Y). Make horizontally wide beam.
2. Measure initial polarization slopes.
3. Repeat for changing MXG.

Make linear fit to early part.

\[\varepsilon = a_0 + a_1 t\]

\[\text{SCT} = -\frac{a_0}{a_1}\]
Can we maximize the polarization lifetime using all 3 sextupole families?

Use two machine setups to separately check:
[1] horizontal emittance. E-cool and bunch together, then heat with white noise.

Extraction onto polarimeter target uses vertical white noise (always present).

Chromaticity in MXG x MXS plane. MXL = $-2.0\%$.

Note the overlap of the two dotted lines that represent the places where the chromaticities vanish.

Sextupole magnet settings are in percent of power supply full scale.
Make scans in 2D MXS x MXG space with MXL = −1.45%

- Horizontal heating (large X emittance)
- Cool, then bunch (large synchrotron orbits)

Both transverse (X) and longitudinal spreads of the beam produce decoherence; both are canceled at places of zero chromaticity.

Errors less than the size of the symbols.

The longest polarization lifetimes are found near the middle of this range.

lines of zero chromaticity (X or Y) in this plane – errors ~ 1 %

Scales are in percent of power supply full range.

Results from run completed in August, 2014.
Longest horizontal polarization lifetime:
Electron pre-cooling time 75 s. No cooling afterward…

Smooth template based on Gaussian distribution of betatron amplitudes.

Half-life = 1173 ± 172 s
Requirements on polarization control:

Maintain polarization within some limited angular range on either side of the velocity for ~ 1000 s. From beginning to end, $10^{-9}$ precision is needed.

Periodically rotate sideways and hold for a check of the polarization. (For tensor polarized deuterons, this is possible in place.)
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Make 2 kinds of corrections:

1. \( \Delta f \) to choose a new spin tune regulate spin tune

2. \( \Delta f \) for \( \Delta t \) to go to a new phase (new direction)
Calibration of feedback to RF cavity

\[
\frac{\Delta \nu_S}{\nu_S} = \frac{\Delta \gamma}{\gamma} = \beta^2 \frac{\Delta p}{p} = \beta^2 \frac{\Delta f}{f}
\]

Spin tune \( \nu_S \)

Revolution frequency \( \nu \)

for the deuteron beam:

\[ p = 0.97 \text{ GeV} / c \]

\[ \beta = 0.456 \]

\[ \eta = 0.58 \]

\( \Delta f \) is adjustable in steps of 3.7 mHz, or \( \frac{\Delta \nu_S}{\nu_S} = 2 \times 10^{-9} \)

\( \nu_S = \nu_0 + \frac{\partial \phi}{\partial t} \)

Initial slope is mismatch between real spin tune and reference spin tune.

Slope match is excellent.

This tests case 1.
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Recapture of polarization
(working demonstration for use with RF Wien filter, etc.)

RF solenoid

feedback on

vertical polarization

horizontal polarization

Asymmetry Left-Right SpinStates 01/02/15
AsylR_01

Slope1=6.02e-03±1.6e-04
Slope2=3.29e-03±1.2e-04

Asymmetry Left-Right SpinStates 01/02/15
AsylR_01

Slope1=-5.51e-03±1.3e-04
Slope2=-3.40e-03±1.1e-04

\( \phi \)

\( \phi + \pi \)
Recapture of polarization
(working demonstration for use with RF Wien filter, etc.)

Plot of initial slope as a function of the target phase for the feedback circuit.

Completes requirement for the precursor and EDM experiments.
Results:

A long solid target may be employed at the edge of the stored beam and still maintain efficiency.

The analyzing power is large.

Once calibrated, systematic rate and geometric errors may be compensated using information available in the data set. (A test works on a part in $10^5$.)

It is possible to build a clock readout that allows us to unfold deuteron polarization precession in the ring plane and provide information on the magnitude of the polarization.

Sextupole field may be used in a magnetic ring to lengthen the polarization lifetime for a horizontally polarized beam.

Polarization lifetimes near 1000 s were seen.

Feedback from polarimeter can correct the spin tune or spin tune phase (samples once per second).