SEARCH FOR ELECTRIC DIPOLE MOMENTS AT COSY IN JÜLICH
Closed-orbit and spin tracking simulations

19.03.2018 I VERA SCHMIDT on behalf of the JEDI collaboration
CONTENT

- Motivation
- Electric dipole moments (EDM)
- Quadrupole misalignments
- Invariant spin axis
- Summary & Outlook
BARYOGENESIS

Big Bang
Matter-Antimatter Symmetry

Early Universe
Sakharov conditions:
1. Baryon number violation
2. Non thermal equilibrium
3. Violation of $C$ and $CP$ symmetry

Annihilation

Today
Only matter observed

Baryon-to-photon density ratio

<table>
<thead>
<tr>
<th></th>
<th>Measured</th>
<th>Theory</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$(6.14 \pm 0.25) \cdot 10^{-10}$</td>
<td>$10^{-18}$</td>
</tr>
</tbody>
</table>
**ELECTRIC DIPOLE MOMENTS (EDMS)**

\[
\mathcal{H} = -\vec{\mu} \cdot \vec{B} - \vec{d} \cdot \vec{E}
\]

\[
P: \mathcal{H} = -\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}
\]

\[
T: \mathcal{H} = -\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E}
\]

- Permanent EDMs of light hadrons are \(T\) and \(P\)-violating
  \(\Rightarrow\) \(CPT\) theorem \(\Rightarrow\) \(CP\) violation
- Measuring EDMs of charged particles in storage rings

**EDM**

<table>
<thead>
<tr>
<th></th>
<th>Classical</th>
<th>Water molecule</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\vec{d})</td>
<td>(\sum_i q_i \cdot \vec{r}_i)</td>
<td>(d \approx 4 \cdot 10^{-9} e \cdot cm)</td>
</tr>
<tr>
<td>QM</td>
<td>(\vec{d} = \eta \cdot \frac{q}{2mc} \vec{S})</td>
<td>Neutron (d &lt; 3 \cdot 10^{-26} e \cdot cm)</td>
</tr>
</tbody>
</table>
EDM MEASUREMENTS IN STORAGE RINGS

EDM experiments

- Different methods possible: E-field, B-field, combined
- Pictured: pure E-field method
- Interaction of EDM $\vec{d}$ and electric field $\vec{E}$
  $\Rightarrow$ spin rotation
- Charged particles: Lorentz force
- Storage ring as particle trap

Basic idea:

- Inject particles with $\vec{p} \parallel \vec{S}$
- Apply radial electric field
- For $\vec{d} \neq 0$: spin rotates out of horizontal plane
- Measure: build-up of vertical polarization ($\phi \propto |\vec{d}|$)
Polarized protons & deuterons

Current experiments with deuterons at $p = 970$ MeV/c

RF Wien filter for EDM measurement

Measuring polarization with a polarimeter
**RESONANT WIEN FILTER METHOD**

\[
\frac{d\hat{S}}{dt} = (\hat{\Omega}_{MDM} + \hat{\Omega}_{EDM}) \times \hat{S} = \left(\frac{q}{m} G \vec{B} + \frac{q\eta}{2m} \vec{p} \times \vec{B}\right) \times \hat{S}
\]

- Vertical fields
- \(\hat{S} \parallel \vec{p}\)
- Spin rotates in horizontal plane
- \(\vec{d} \neq 0\): vertical spin build-up

→ No net EDM effect
RESONANT WIEN FILTER METHOD

- RF device used to accumulate the EDM signal:
  - Radial electric field: \( E_x \sim \cos(\omega t + \varphi) \)
  - Vertical magnetic field: \( B_y \sim \cos(\omega t + \varphi) \)

- Wien filter: Lorentz force vanishes → no beam perturbation
- RF frequency tuned to horizontal spin precession (\( \nu_s \approx -0.161 \))

\[ S_y \]

EDM signal

\[ \text{turns in a.u.} \]

→ Net EDM effect
MISALIGNMENT OF QUADRUPOLES

- Disturbed closed-orbit due to QP misalignment
- Spin sees radial magnetic field
- Radial magnetic fields lead to vertical spin build-up
\[ \eta = 0 \] (no EDM)

One QP vertically shifted by 1 mm

\[ S_x, S_y, S_z \]
**SPIN MOTION AND QP MISALIGMENTS**

\[ \eta = 0.0001 \]
\[ (d \approx 1.5 \cdot 10^{-19} e \cdot cm) \]

\[ \eta = 0 + \text{random QP misalignments} \]
\[ (\mu = 0 \text{ mm and } \sigma = 1 \text{ mm (} \sigma = 1 \text{ mrad)} ) \]

Vertical spin build-up due to EDM and QP misalignments!
INVARIANT SPIN AXIS

- Gaussian distributed QP misalignments with \( \mu = 0 \) mm \((\mu = 0 \text{ mrad})\) and \( \sigma = 1 \) mm \((\sigma = 1 \text{ mrad})\)

- Reference particle with initial coordinates \( x = y = z = 0 \)
Invariant spin field: \( \hat{n}(\vec{z}, \theta + 2\pi) = \hat{n}(\vec{z}, \theta) \)

\[ R(\vec{z}_i, \theta)\hat{n}(\vec{z}_i, \theta) = \hat{n}(\vec{z}_f, \theta), \quad R: \text{one turn spin map} \]

→ Determine **best-fit plane** and find **average spin rotation axis**
IN Variant Spin Axis

300 sets of random QP misalignments

\[ \text{RMS}_{n_z} \approx 0.001 \rightarrow \sigma_{EDM} = 3 \times 10^{-18} \text{ e cm} \]
SUMMARY & OUTLOOK

- EDMs as candidate for physics beyond the Standard Model
- Measure EDM at COSY with RF Wien filter method
- Quadrupol misalignments lead to disturbed closed-orbit and vertical spin build-up
- Time dependent spin rotation axis → averaging over many turns lead to average rotation axis for a fixed set of QP misalignments

- Implementation of measured magnet misalignments at COSY
- Use CW and CCW beams to overcome systematic effects due to misaligned magnets