SEARCH FOR ELECTRIC DIPOLE MOMENTS AT COSY IN JÜLICH
Spin tracking simulations using Bmad

19.03.2019  I  VERA PONCZA on behalf of the JEDI collaboration
CONTENT

▪ Electric dipole moments (EDM)

▪ Measurement method

▪ Simulation results and comparison to measurement

▪ Summary & Outlook
MATTER ANTIMATTER ASYMMETRY

Big Bang

Equal amount of matter & antimatter

Early Universe

Preference of matter

Sakharov criteria:
• Baryon number violation
• No thermic equilibrium
• $C, CP$ violation

Today

Only matter

Observed:
$6.14 \pm 0.25 \cdot 10^{-10}$

Standard Model:
$10^{-18}$

Search for $CP$ violation beyond the Standard Model
**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:** \[ \mathcal{H} = -\vec{\mu} \cdot \vec{B} + \vec{d} \cdot \vec{E} \]

- **EDM:** a permanent separation of positive and negative charge (vector along spin direction)
- Fundamental property of particles (like mass, charge, magnetic moment)
- Existence of EDM only possible if violation of time reversal and parity symmetry

What are we talking about?

Neutron: \( d < 3 \cdot 10^{-26} \text{ e \cdot cm} \)
Example: pure electric ring

**Basic idea:**
- Inject particles with $\vec{S} \parallel \vec{p}$
- Use storage ring as particle trap
- Interaction of EDM with electromagnetic fields
- For $\vec{d} \neq 0$: spin rotates out of horizontal plane
- Measure: build-up of **vertical polarization** ($\phi \propto |\vec{d}|$)
- Different methods possible: pure E-field, pure B-field, combined versions

\[ \frac{d\vec{S}}{dt} \propto \vec{d} \cdot \left( \vec{E} + c\vec{\beta} \times \vec{B} - A \vec{\beta} \left( \vec{\beta} \cdot \vec{E} \right) \right) \times \vec{S} \]
Cyclotron
Wien filter
Dipoles
Quadrupoles
Polarimeter
Circumference: 184 m
Sextupoles
Solenoid 1
Solenoid 2
Steerer
Circumference: 184 m

Polarized protons & deuterons
Current experiments with deuterons at $p = 970$ MeV/c
Measuring polarization with a polarimeter
Special device necessary in order to measure the EDM: RF Wien filter

▪ Polarized protons & deuterons
▪ Current experiments with deuterons at $p = 970$ MeV/c
▪ Measuring polarization with a polarimeter
▪ Special device necessary in order to measure the EDM: RF Wien filter
\[
\frac{d\vec{S}}{dt} = (\vec{\Omega}_{MDM} + \vec{\Omega}_{EDM}) \times \vec{S} = \left( \frac{q}{m} \vec{G} \vec{B} + \frac{q \eta}{2m} \vec{\beta} \times \vec{B} \right) \times \vec{S} \quad \text{with} \quad \vec{d} = \eta \cdot \frac{q}{2mc} \vec{S}
\]

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

build-up

\[ S_y \times 10^{-3} \]

No net EDM effect
RESONANT WIEN FILTER METHOD

- **Aim**: prevent averaging out of EDM signal
- **RF device** used to accumulate the EDM signal:
  - ✓ Radial electric field: $E_x \sim \cos(\omega t + \phi)$
  - ✓ Vertical magnetic field: $B_y \sim \cos(\omega t + \phi)$
- Additional time dependent phase advance each turn
- **Wien filter mode**: Lorentz force vanishes
  - $\rightarrow$ no beam perturbation
- **RF frequency** tuned to horizontal spin precession frequency ($\nu_s \approx -0.161/\text{turn}$)

$\Rightarrow$ Net EDM effect
**SYSTEMATIC EFFECTS**

- **Systematic effects** in the ring lead to EDM-like signals
- **Invariant spin axis tilts** due to radial and longitudinal magnetic fields
- Especially **radial B-fields** lead to vertical spin build-up
- **Simulations needed** to separate systematic effects from real EDM signal

\[
\eta = 0.0001 \quad (d \approx 5 \cdot 10^{-19} e \cdot \text{cm})
\]

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

**EDM resonance strength**

\[
\varepsilon_{\text{EDM}} = \frac{\Omega_P}{\Omega_{\text{rev}}} \quad \text{and} \quad \varepsilon_{\text{EDM}}^2 \propto A(\phi_{WF} - \phi_0)^2 + B(\chi_{\text{Sol1}} + \chi_0)^2
\]

- \(\Omega_P\): Angular frequency of vertical polarization oscillation
- \(\Omega_{\text{rev}}\): Orbital angular frequency
- \(\phi_{WF}\): Wien Filter rotation angle
- \(\chi_{\text{Sol1}}\): Spin rotation angle of Solenoid 1

**Basic idea:**

- Manipulating the spin by
  1. rotating the Wien filter (\(\phi_{WF}\))
  2. longitudinal B-field of a Solenoid (\(\chi_{\text{Sol1}}\))
- Fitting point of minimal resonance strength (\(\phi_0, \chi_0\))
- Fit parameter \(\phi_0\) is a measure of the EDM magnitude + **systematic effects**
SIMULATION INCLUDING MAGNET MISALIGNMENTS

Spin tracking simulations using Bmad Software Library

Ideal lattice, $\eta = 0.0002$

\[
\begin{align*}
\phi^\text{fit}_0 &= -0.32531 \pm 0.01764 \text{ mrad} \\
\phi^\text{theo}_0 &= -0.32127 \text{ mrad}
\end{align*}
\]

magnet misalignments, $\eta = 0.0$

\[
\begin{align*}
\phi^\text{fit}_0 &= 0.15328 \pm 0.01764 \text{ mrad} \\
\phi^\text{measured}_0 &= -3.42 \pm 0.28 \text{ mrad}
\end{align*}
\]
SUMMARY

- EDMs as candidate for physics beyond the Standard Model
- RF device was developed and is already installed and under test
- Systematic effects have to be investigated by simulations (Bmad software library + extensions)
- Simulations so far include magnet misalignments
- The results can not fully explain the measurement

OUTLOOK

- Additional systematic effects have to be considered and implemented
- Take measurement and position uncertainties of magnet positions into account
- Build a realistic simulation model in order to support the data analysis
THANK YOU