Measuring the Electric Dipole Moment of Protons

GRK-Seminar: Mass and Symmetries after the Discovery of the Higgs Particle at the LHC

May 22nd, 2019

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In the beginning ...

tested in the lab

created matter and antimatter in equal amounts

„a million times“

... the Big Bang
Today ...

... we only find matter
Evolution of Matter

Galaxy A1689-zD1:
~700 million years after the Big Bang

Big Bang
Radiation era
~300,000 years: “Dark Ages” begin

~400 million years: Stars and nascent galaxies form

~4.5 billion years: Sun, Earth, and solar system have formed

• 13.7 billion years: Present

matter and antimatter annihilated ...

How?

... some matter survived
Baryon to Photon Ratio:

$$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 5 \cdot 10^{-10}$$

$$n_\gamma \approx 0.4/mm^3$$

$$n_B \approx 0.2/m^3$$

$$n_{\bar{B}} \approx 0$$

Standard Model fails by many orders of magnitude

... we only find matter
The Fate of Antimatter?
Content

• The Fate of antimatter – Introduction
• EDM: Experimental Method
• Electrostatic Storage Rings
• Experimental Strategy and Goals
Matter and antimatter annihilated
a tiny fraction of matter survived
(approx. 1 particle in $10^9$)
our universe
1. Baryon-Number Violation
2. CP-Violation
3. Thermal Non-Equilibrium


Necessary condition for any model
BARYON-NUMBER VIOLATION

Vacuum-energy

≈ 7 TeV

Standard Model!

Electroweak phase transition: $T \approx 100 \text{ GeV}$
But: \[ \eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} \] too small!
In equilibrium:

\[ \bar{A} \iff B \]

antimatter \iff matter

CPT ensures equal rates

Out-of equilibrium:

\[ n_B = n_{\bar{B}} \]  

(sphalerons)

Matter excess created in the walls between the phases
NON-EQUILIBRIUM
1. Baryon-Number Violation
2. CP-Violation
3. Thermal Non-Equilibrium


More CP-violation needed!
Leptogenesis started with leptons

Baryogenesis started with baryons

Leptogenesis

Baryogenesis

More CP-violation needed
Leptogenesis

Leptogenesis

- Process started with leptons
- Leptons: electron, muon, tau, electron neutrino, muon neutrino, tau neutrino

Baryogenesis

Baryogenesis

- Process started with baryons
- Baryons: up, charm, top, down, strange, bottom

Experimental search for new sources of CP-violation

Neutrino-Oscillations

Electric Dipole Moments
Electric Dipole Moment
Spin: $\hat{S}$
EDM: $\hat{d}$

EDM violates $T$
CPT $\rightarrow$ violates CP

$\langle \hat{S} \cdot \hat{d} \rangle \iff - \langle \hat{S} \cdot \hat{d} \rangle$
T-Violation in QCD: Prefer one over the other
T-Violation in QCD: Prefer one over the other
EDM at high energies

Jet Event at 2.36 TeV Collision Energy
2009-12-14, 04:30 CET, Run 142308, Event 482137
Experimental Method
DIPOLES in a FIELD

electric field
• Field exerts a torque on the spin
• Field exerts a torque on the spin
• Spin precesses around the field direction
Problem: Magnetic effect much larger!

eliminate magnetic fields
PROTONS in a FIELD

\[ F_{el} = F_Z \]

Electric field

EDM

electrostatic storage ring

No EDM

Spin

Orbit

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Thomas BMT-Equation:

\[
\vec{\omega} = \frac{e}{m_p} \left[ a \vec{B} + \left( \frac{\gamma^2}{1 - \gamma} - a_p \right) \vec{\beta} \times \frac{\vec{E}}{c} + \frac{d}{2} (\vec{E} \times \vec{B}) + \frac{d \vec{E}}{2c} \right]
\]

\[
a_p = \frac{g_p - 2}{2}
\]

If zero: magic momentum frozen spin

For protons: 700.7 MeV/c
Counter-rotating beams: Identifies false signal from B-field
Electrostatic Ring
Perfect Dipole:

\[ \vec{E} = E_0 \hat{e}_r \]
\[ \varphi(r) = \varphi_0 (r - r_0) \]

Nominal field: 10 MV/m
(+/- 200 kV over 4 cm)
Finite Element Analysis

Poisson’s equation: \( \nabla^2 \varphi(x, y) = \frac{\rho}{\varepsilon_0} \)

Plates: metallic surfaces with const. potential (boundary condition)
Finite Element Analysis

Poisson's equation:

\[ \nabla^2 \varphi(x, y) = \frac{\rho}{\varepsilon_0} \]

Plates: Metallic surfaces with constant potential (boundary condition)

\[ \varphi(x, y) \]
Finite Element Analysis

Poisson’s equation:

\[ \Delta \varphi(x, y) = \frac{\rho}{\varepsilon_0} \]

Plates: metallic surfaces with constant potential (boundary condition)

\[ E_x(x, y) \]

\[ E_y(x, y) \]

\[ \vec{E} = -\nabla \varphi \]

-15...+15 MV/m

0...15 MV/m

0 V
\( \varphi(x, y) \)  

Simple Capacitor  

Field Cage
$\varphi_{Q}(\vec{r}) = 2U_{Q} \frac{x^2 - y^2}{d^2} \quad (x, y, 0)$

$\vec{E}_{Q}(\vec{r}) = \frac{4U_{Q}}{d^2} (-x, y, 0)$
Electric field fixed by potential:

$$\vec{E} = -\nabla \varphi(\vec{r})$$

Potential can be fixed by metal strips

$$\varphi(\vec{r}_i) = U_i$$

Advantage:
- Arbitrary shape of field cage

Disadvantage:
- Need many different voltages
- Finite granularity of field strips
\( \varphi(x, y) \)
$E_x(x, y)$

$E_y(x, y)$
Poisson’s equation is linear: \( \nabla \cdot \vec{E} = \frac{\rho}{\epsilon_0} \)

\( \rightarrow \) potential and electric fields super-impose

**Combined Function:**

\( \vec{E}_{c.f.} = \vec{E}_{\text{Dipole}} + \vec{E}_{\text{Quadrupole}} + \cdots \)

\( \rightarrow \) strips: \( U_{\text{strip}} = U_{\text{Dipole}} + U_{\text{Quadrupole}} + \cdots \)
Combined Function: $\vec{E}_{c.f.} = \vec{E}_{\text{Dipole}} + \vec{E}_{\text{Quadrupole}} + \ldots$

\[\varphi = \frac{U_D}{2} \quad \varphi = -\frac{U_D}{2}\]

\[\Rightarrow \text{strips: } U_{\text{strip}} = U_{\text{Dipole}} + U_{\text{Quadrupole}} + \ldots\]
\[ \varphi(x, y) \]

\[ U_{\text{Dipole}} = 2 \times 157.5 \text{ kV} \]
\[ U_{\text{Quadrupole}} = 2 \times 50 \text{ kV} \]
Dipole

Quadrupole

fringe fields!
Combined Function

Dipole

Quadrupole

Dipole

Quadrupole
Combined Function
Strategy and Goals
EXPERIMENTAL STRATEGY: 3 STEPS

Precursor @ COSY Forschungszentrum Jülich
- Magnetic storage ring
- Limited E-field in RF Wien filter

Prototype Ring Forschungszentrum Jülich
- Could start soon
  - Electrostatic storage ring
  - $p \approx 35$ MeV/c (non-magic)
  - Counterrotating beams or frozen spin

Magic Ring Open Site
- Final step
  - Electrostatic storage ring
  - Magic momentum
  - Counterrotating beams and frozen spin

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Scientific Motivation

- Fate of Antimatter
- $\theta$-puzzle of QCD
  $$-\theta \frac{n_f g^2}{32\pi^2} G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \quad \theta < 10^{-10} ?$$
- Dark Matter: Oscillation EDMs from axion fields
Scientific Motivation

- Fate of Antimatter
- $\theta$-puzzle of QCD
  
  $$-\theta \frac{n_f g^2}{32\pi^2} G_{\mu\nu}^{\alpha} \tilde{G}^{\alpha,\mu\nu} \theta < 10^{-10}?$$

- Dark Matter:
  Oscillation EDMs from axion fields
Precursor @ COSY
COoler SYnchrotron (COSY) at Forschungszentrum Jülich (Germany)
- Cyclotron as injector
- 45 MeV H\(^-\), 76 MeV D\(^-\) via stripping injection
- \(\sim 10^{11}\) protons/deuterons per injection
- Polarized (p,d) beams up to 3.7 GeV/c
- 100 keV and 2 MeV electron cooler
- Stochastic cooling
- RF spin manipulation
- Internal and external target places at COSY and injector cyclotron

→ Worldwide unique facility for spin physics
PRECURSOR EXPERIMENT
\[ \tau_{SC\text{T}} = (782 \pm 117) \text{ s} \]
ELECTRIC FIELD IN COSY
(a) $\varepsilon^{\text{EDM}}$ for $d = 10^{-20}$ e cm.

(b) Contour plot of (a).
(c) $\varepsilon^{\text{EDM}}$ for $d = 10^{-18}$ e cm.

(d) Contour plot of (c).
(e) Simulated $\varepsilon^{\text{EDM}}$ for $d = 10^{-20}$ e cm.

(f) First $9 + 9 + 14$ data points on 3 maps ($\approx 2$ weeks)

Data: Nov./Dec. 2018
work in progress!
Outlook

- First limit on d-EDM ($10^{-20} \, e \cdot cm$ ?)
- First measurement of oscillating EDM
- Work with protons

(e) Simulated $\varepsilon_{\text{EDM}}$ for $d = 10^{-20} \, e\cdot cm$

(f) First $9 + 9 + 14$ data points on 3 maps ($\approx 2$ weeks)
ProEDM

Circumference = 100 m

8 m

29 m
- Small ring (~ 100 m circumference)
- All-electric ring
- Counter-rotating beams
- Frozen spin
- Measurement of p-EDM

\[ E_{\text{kin}} = 30 \text{ MeV} \]

\[ E_{\text{kin}} = 45 \text{ MeV} \]
30 MeV all-electric p ring

- Storage time
- CW/CCW operation
- Spin coherence time
- Polarimetry
- Phase space cooling
- $\mu_p$ effects

Option: add B-field, 45 MeV

- pEDM measurement
Table 1: Basic beam parameters.

<table>
<thead>
<tr>
<th></th>
<th>$E$ only</th>
<th>$E \times B$</th>
<th>unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>kinetic energy</td>
<td>30</td>
<td>45</td>
<td>MeV</td>
</tr>
<tr>
<td>$\beta = v/c$</td>
<td>0.247</td>
<td>0.299</td>
<td></td>
</tr>
<tr>
<td>momentum</td>
<td>239</td>
<td>294</td>
<td>MeV/c</td>
</tr>
<tr>
<td>magnetic rigidity $B\rho$</td>
<td>0.798</td>
<td>0.981</td>
<td>T-m</td>
</tr>
<tr>
<td>electric rigidity $E\rho$</td>
<td>59.071</td>
<td>87.941</td>
<td>MV</td>
</tr>
<tr>
<td>$\gamma$ (kinetic)</td>
<td>1.032</td>
<td>1.048</td>
<td></td>
</tr>
<tr>
<td>emittance $\varepsilon_x = \varepsilon_y$</td>
<td>1.0</td>
<td>1.0</td>
<td>mm-mrad</td>
</tr>
<tr>
<td>acceptance $a_x = a_y$</td>
<td>1.0</td>
<td>10.0</td>
<td>mm-mrad</td>
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</table>

<table>
<thead>
<tr>
<th>units</th>
<th></th>
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<tbody>
<tr>
<td># B-E deflectors</td>
<td>8</td>
</tr>
<tr>
<td># arc D quads</td>
<td>4</td>
</tr>
<tr>
<td># arc F quads</td>
<td>8</td>
</tr>
<tr>
<td># straigh quads</td>
<td>4</td>
</tr>
<tr>
<td>quad length</td>
<td>0.400</td>
</tr>
<tr>
<td>straight length</td>
<td>8.000</td>
</tr>
<tr>
<td>bending radius</td>
<td>8.861</td>
</tr>
<tr>
<td>electric plate length</td>
<td>6.959</td>
</tr>
<tr>
<td>arc length (45°)</td>
<td>15.718</td>
</tr>
<tr>
<td>circumference total</td>
<td>100.473</td>
</tr>
</tbody>
</table>
Magic Ring
Magic momentum:
\[ p = 701 \text{ MeV/c} \quad E_{\text{kin}} = 233 \text{ MeV} \]

- All-electric
- Counter-rotating beams
- Frozen spin
- Measurement of p-EDM (static and oscillating)

- Design in progress (systematic limitations!)
- Many new ideas
- Site-open studies
- Ultimate sensitivity!
Conclusions

- EDM: Window to CP-Violation
- Proton: longterm improvements
- Interesting experimental challenges

New collaborators welcome
Backup
inner strip
2mm x 200μm

glass plate
1mm

outer strip
2mm x 1mm

+157.5 kV

-157.5 kV

\[ \frac{16}{15} U_d \]

\[ \frac{14}{15} U_d \]
Impact of imperfections on the field

Mechanical precision: better than 0.1 mm
Voltages better than 10^{-3}

<table>
<thead>
<tr>
<th></th>
<th>$\Delta E_x$ \n/ $E_x(0, 0)$</th>
<th>$\Delta E_x(5mm)/E_x$</th>
<th>$E_y/E_x$ \n(5mm, 5mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>nom</td>
<td>0.000 %</td>
<td>-0.024 %</td>
<td>-5500 V/m</td>
</tr>
<tr>
<td>A</td>
<td>0.058 %</td>
<td>-0.045 %</td>
<td>-7000 V/m</td>
</tr>
<tr>
<td>B</td>
<td>0.001 %</td>
<td>-0.022 %</td>
<td>+6500 V/m</td>
</tr>
<tr>
<td>C</td>
<td>-0.045%</td>
<td>-0.028 %</td>
<td>-5700 V/m</td>
</tr>
<tr>
<td>D</td>
<td>0.003 %</td>
<td>-0.020 %</td>
<td>+6800 V/m</td>
</tr>
</tbody>
</table>
$E_x(x)$

$\Delta \frac{E}{E} = 10^{-4}$

nominal field:
10.5 MV/m

$y = 0 \text{ mm}$

$-66.3 \text{ kV/m}$

$-68.1 \text{ kV/m}$

$-5 \text{ mm} \quad -3 \text{ mm} \quad +3 \text{ mm} \quad +5 \text{ mm}$
\[ E_x(x) \]

\[ \frac{\Delta E}{E} = 10^{-4} \]

\[ E_x(x = 0) \]

\[ y = 0 \text{ mm} \quad -66.3 \text{ kV/m} \]

\[ y = 5 \text{ mm} \quad -62.0 \text{ kV/m} \]

nominal field: 10.5 MV/m

\[ -5 \text{ mm} \quad -3 \text{ mm} \quad +3 \text{ mm} \quad +5 \text{ mm} \]
$E_y(x)$

$\frac{E_y}{E_x} = +2 \cdot 10^{-4}$

$\frac{E_y}{E_x} = -2 \cdot 10^{-4}$

nominal field: 0

4.5 kV/m

$y = 5 \text{ mm}$

-5 mm -3 mm +3 mm +5 mm
Steel disks every 10 cm (?) electrodes glued into stiff plates might need stiffeners inside plates
DEFLECTORS

BPM  HV  prism

alignment sensor

positioning

positioning

HV

BPM

alignment sensor

/=2m

20° deflection
MECHANICAL POSITIONING
Piezo-Actuators?

- Travel ranges 50 to 1800 μm
- Resolution to 0.1 nm
- Linearity error 0.02 %
- Direct metrology with capacitive sensors
- X, XY, Z, XYZ versions
Laser alignment system used for example in CMS (Stefan Schael)
• IR-Laser (amplitude modulated)
• Si-strip detectors detect beam
• Metal layers removed for transmission of IR-beam
Beam pipe
- Steel pipe
- ID 15 cm
Beam pipe
- Steel pipe
- ID 15 cm
MAGNETIC SHIELDING

High Temperature Superconductor

Liquid N2 (-196°C)

High Temperature Superconductor
Polyurethane foam
15 cm shown
(LNG cargo uses 25 cm)
FINEMET Nanocrystalline Soft Magnetic Material

\[ \mu_r = 30000 \ldots 100000 \]
Systematics

Absolute average change of the vertical spin component $\Delta S_y$ per turn for different $\Delta y_{RMS}$ and an initial Wien filter phase $0^\circ$. Wien filter magnetic field $10^{-4}$ mT (0.8 m length) and...