Why are we here?

HISTORY OF THE UNIVERSE

Key:
- quark
- neutrino
- ion
- star
- electron
- bosons
- atom
- galaxy
- muon
- meson
- photon
- black hole

The concept for the above figure originated in a 1986 paper by Michael Turner.

Particle Data Group, LBNL © 2015

Supported by DOE
Why are we here?

Today

- ratio
  - matter - antimatter radiation
  observed
  (WMAP 2003)
  \((6.14 \pm 0.25) \times 10^{-10}\)

- galaxies, stars, planets
- Standard Model
  \(10^{-18}\)
- “empty” universe

Search for \(C\overline{P}\) violation beyond the Standard Model

Big Bang

- energy
- matter & antimatter
- symmetrie between matter & antimatter

Early Universe

Sakharov criteria:
- baryon number violation
- no thermic equilibrium
- \(C, C\overline{P}\) violation

Today

- ratio
  - matter - antimatter radiation
  observed
  (WMAP 2003)
  \((6.14 \pm 0.25) \times 10^{-10}\)

- galaxies, stars, planets
- Standard Model
  \(10^{-18}\)
- “empty” universe

Search for \(C\overline{P}\) violation beyond the Standard Model
Measurement of Electric Dipole Moments at Storage Rings

Volker Hejny
Forschungszentrum Jülich
Outline

• Electric Dipole Moments
  • What are those?
  • How can they help?
• EDM measurements using storage rings
  • Basic principles
  • Options
• R&D and first measurements at COSY

Further information: http://collaborations.fz-juelich.de/ikp/jedi
Electric Dipole Moments (EDM)

Classical definition: $\vec{d} = \sum q_i \vec{r}_i$

charge x distance

Example: water molecule

charge separation

electric dipole moment

$d \approx 4 \times 10^{-9} \text{ e cm}$
EDMs of elementary particles

\( \hat{s} \)  spin
\( \hat{d} \)  electric dipole moment
\( \hat{\mu} \)  magnetic moment

Transformations w.r.t. \( \mathcal{P}, \mathcal{T} \)

\[
H = -\mu \hat{s} \cdot \vec{B} - d \hat{\sigma} \cdot \vec{E}
\]

\( \mathcal{P} \): \( H = -\mu \hat{s} \cdot \vec{B} + d \hat{\sigma} \cdot \vec{E} \)

\( \mathcal{T} \): \( H = -\mu \hat{s} \cdot \vec{B} + d \hat{\sigma} \cdot \vec{E} \)

EDM measurements test violation of fundamental symmetries \( \mathcal{P}, \mathcal{T} \) and \( \mathcal{CP} \) (via \( \mathcal{CPT} \))
So what is the difference?

**elementary particle**

EDM violates $\mathcal{P}, \mathcal{T}$

**water molecule**

EDM allowed

degenerated ground state with mixed parity!

defined parity!
How can that help?

Reminder: excess of matter in the universe

<table>
<thead>
<tr>
<th>$\frac{n_B - n_{\bar{B}}}{n_\gamma}$</th>
<th>Standard Modell</th>
<th>Observed</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\approx 10^{-18}$</td>
<td></td>
<td>$6 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

Sakharov (1967): $CP$ violation needed for baryogenesis

New sources of $CP$ violation needed to explain this mismatch

EDMs as a probe for $CP$ violation beyond the SM
### Symmetries in the Standard Model

<table>
<thead>
<tr>
<th></th>
<th>Electro-magnetic</th>
<th>Weak</th>
<th>Strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C$</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>$P$</td>
<td>✓</td>
<td>×</td>
<td>✓</td>
</tr>
<tr>
<td>$T/CP$</td>
<td>✓</td>
<td>×</td>
<td>(✓)</td>
</tr>
</tbody>
</table>

$C$ and $P$ are maximally violated in weak interactions

($Lee, Yang, Wu$)

$CP$ violation discovered in kaon decays described by CKM-matrix in Standard Model

($Cronin,Fitch$)

$CP$ violation allowed in strong interaction but corresponding parameter $\theta_{QCD} \lesssim 10^{-10}$ (strong $CP$-problem)
### Sources of $CP$ violation

<table>
<thead>
<tr>
<th></th>
<th>Standard Model</th>
<th>beyond Standard Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>weak interaction</td>
<td>CKM matrix</td>
<td></td>
</tr>
<tr>
<td></td>
<td>unobservably small EDMs</td>
<td></td>
</tr>
<tr>
<td>strong interaction</td>
<td>$\theta_{QCD}$</td>
<td>best limit from neutron EDM $(\lesssim 10^{-10})$ “strong CP problem”</td>
</tr>
<tr>
<td></td>
<td></td>
<td>accessible by EDM measurements</td>
</tr>
</tbody>
</table>

Different sources of $CP$ violation result in a different EDM for different particle types.
Disentangling $\mathcal{CP}$ violation...

EDM measurements

- Neutron, Proton
- Nuclei: $^2\text{H}, ^3\text{H}, ^3\text{He}$
- Diamagnetic atoms: Hg, Xe, Ra
- Paramagnetic atoms: Tl, Cs
- Molecules: YbF, ThO, HfF$^+$
- Leptons: muon

QCD (including $\theta$-term)

- Quark EDM
- Quark chromo-EDM
- Gluon chromo-EDM
- Four-quark operators
- Lepton-quark operators
- Lepton EDM

Fundamental Theory

Graphics: J. de Vries
Current EDM limits

- proton: no direct measurement
- deuteron: no measurement

Here: EDMs of charged particles
How to measure EDMs?

Common strategy for all EDM measurements:
→ measure interaction of $\vec{d}$ with electric field $\vec{E}$

With spin:
→ precession

For charged particles:
https://www.youtube.com/watch?v=qwM4ensIA_k
by Tales Of a Musing Gator
How to measure EDMs of charged particles?

Electric field accelerates particles

→ use a storage ring

Ideal case:

\[
\frac{d\hat{S}}{dt} \propto d\vec{E} \times \hat{S}
\]

Build-up of vertical polarisation by slow precession

\[
s_\perp \propto |d|
\]
"Ad-hoc" boundary conditions

| Very slow spin precession | Long measurement times \((t \approx 1000 \text{ s})\)  
High electric fields \((E \approx 10 \text{ MV/m})\)  
High degree of polarization \((P \approx 0.8)\)  
Precise polarisation measurement  
(analysing power \(A \approx 0.6\), acc. \(f \approx 0.005\)) |
| --- | --- |
| Particle ensemble \((N \approx 4 \times 10^{10} \text{ per fill})\) | All particles must act identically  
All spins need to be aligned  
(“spin coherence time”) |
| Horizontal polarisation \(||\) momentum | Control spin motion at high precision |
| Magnetic moment causes fake rotations | High field quality  
Magnetic shielding  
Precise geometrical alignment  
Fringe fields under control |

\[
\sigma_{\text{stat}} \approx \frac{1}{\sqrt{Nf\tau PAE}} \implies \sigma_{\text{stat}}(\text{1 year}) \approx 10^{-29} \text{ecm}
\]

**Major challenge:**  
get **systematic uncertainties** to the same level!
Spin motion

Thomas-BMT equation:

\[
\frac{d\hat{S}}{dt} = \vec{\Omega} \times \hat{S} = -\frac{q}{m_0} \left\{ G\vec{B} - \frac{\gamma G}{\gamma + 1} \vec{\beta} (\vec{\beta} \cdot \vec{B}) + \left( \frac{1}{\gamma^2 - 1} - G \right) \frac{\vec{\beta} \times \vec{E}}{c} \right\} + d \frac{m_0}{q\hbar S} \left( \vec{E} - \frac{\gamma}{\gamma + 1} \vec{\beta} (\vec{\beta} \cdot \vec{B}) + c \vec{\beta} \times \vec{B} \right) \times \hat{S}
\]

\[\Omega: \text{angular precession frequency} \quad d: \text{electric dipole moment} \]
\[G: \text{anomalous magnetic moment} \quad \gamma: \text{Lorentz factor} \]

Storage rings: \(\vec{B}\) vertical, \(\vec{E}\) radial
Storage rings: general case

\[
\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m_0} \left\{ G\vec{B} + \left( \frac{1}{\gamma^2 - 1} - G \right) \frac{\vec{\beta} \times \vec{E}}{c} \right\} + d \frac{m_0}{q\hbar S} \left( \vec{E} + c\vec{\beta} \times \vec{B} \right) \times \vec{S}
\]

- magnetic moment causes fast spin precession: $\vec{s}_H \parallel \vec{p}$

- EDM
  - $\Omega$: angular precession frequency
  - $G$: anomalous magnetic moment
  - $d$: electric dipole moment
  - $\gamma$: Lorentz factor

- Lorentz force
\[
\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m_0} \left\{ G\vec{B} + \left( \frac{1}{\gamma^2 - 1} - G \right) \frac{\vec{\beta} \times \vec{E}}{c} + d \frac{m_0}{q\hbar S} \left( \vec{E} + c\vec{\beta} \times \vec{B} \right) \right\} \times \vec{S}
\]

\(\equiv 0!\)

"frozen spin" : precession vanishes at magic momentum

\[ G = \frac{1}{\gamma^2 - 1} \Rightarrow p = \frac{m}{\sqrt{G}} \]

only possible for \( G > 0 \)

Dedicated ring for protons
Storage rings: combined ring

\[
\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m_0} \left\{ \frac{1}{\gamma^2 - 1} G \vec{B} + \left( \frac{1}{\gamma^2 - 1} - G \right) \vec{\beta} \times \vec{E} \right\} + d \frac{m_0}{q \hbar S} (\vec{E} + c \vec{\beta} \times \vec{B}) \right\} \times \vec{S} \\
\equiv 0!
\]

„frozen spin“: proper combination of \( \vec{B} \), \( \vec{E} \) and \( \gamma \) also for \( G < 0 \) (i.e. deuterons, \(^3\)He)

All-in-one ring for protons, deuterons, \(^3\)He
Storage rings: magnetic ring

\[ \frac{d \hat{S}}{dt} = \tilde{\Omega} \times \hat{S} = -\frac{q}{m_0} \left\{ G \vec{B} + \left( \frac{1}{\gamma^2 - 1} - G \right) \vec{\beta} \times \vec{E} \right\} + d \frac{m_0}{q \hbar S} (\vec{E} + c \vec{\beta} \times \vec{B}) \times \hat{S} \]

**COSY:** pure magnetic ring, polarized protons and deuterons
access to EDM via motional electric field \( \vec{\beta} \times \vec{B} \)

Ideal starting place for R&D and a proof-of-principle experiment
Pure magnetic ring

Due to fast precession longitudinal polarization component is 50% of time parallel
50% of time anti-parallel
to momentum

\[
\frac{d\vec{S}}{dt} \propto \left( G\vec{B} + d \frac{m_0c}{q\hbar S} \vec{\beta} \times \vec{B} \right) \times \vec{S}
\]

E* field in the particle rest frame tilts spin due to EDM
50% of time up and
50% of time down
→ no net EDM effect
Resonant rf Wien filter

Wien filter: Lorentz force vanishes → no effect on EDM rotation

Effect on horizontal precession:

Without WF 50 %
Static WF 50 %
(precession just faster or slower)
Resonant rf WF speed up prec. <50 %
(resonant on precession frequency) slow down prec. >50 %

net EDM effect
R&D at COSY

Thomas-BMT equation:

\[
\frac{d\vec{S}}{dt} = \vec{\Omega} \times \vec{S} = -\frac{q}{m_0} \left\{ \vec{G}\vec{B} + \left( \frac{1}{\gamma^2 - 1} - G \right) \vec{\beta} \times \vec{E} \right\} + d \frac{m_0}{q\hbar S} (\vec{E} + c\vec{\beta} \times \vec{B}) \times \vec{S}
\]

magnetic moment  

neglect EDM

study spin tune \( \nu_s = \frac{||\vec{\Omega}||}{|\omega_{cycl}|} = \gamma G \)

→ phase advance per turn

R&D with deuterons

\( p = 1 \text{ GeV/c} \)
\( G = -0.14256177(72) \)
\( \nu_s \approx -0.161 \rightarrow f \approx 120 \text{ kHz} \)
(Some) Questions to be addressed

• Precise measurement of the precession frequency (spin tune) → also time dependent within one cycle
• Maximizing the spin coherence time (goal: ≈1000 s)
• Maintaining the spin direction → keep precession frequency stable
  → match frequency and phase to Wien filter radio frequency
• Study effects of field misalignments, orbit distortions, etc.
Cooler Synchrotron COSY

COSY provides cooled & polarized protons and deuterons with $p = 0.3 - 3.7$ GeV/c
Experimental setup

1. inject and accelerate vertically polarized deuterons to $p = 1 \text{ GeV/c}$
2. bunch and (pre-)cool
3. turn spin by means of a RF solenoid into horizontal plane
4. extract beam slowly (within 100-1000 s) onto a carbon target, measure asymmetry and precisely determine spin precession

spin tune:

$$|\nu_s| = |\gamma G| = \frac{\text{spin precessions}}{\text{particle turn}} = \frac{f_{\text{prec}}}{f_{\text{rev}}} \approx \frac{120 \text{ kHz}}{750 \text{ kHz}} \approx 0.16$$
Polarimetry

- reaction: elastic d+C scattering
- up/down asymmetry $\propto P_x$ projection on x-axis
- left/right asymmetry $\propto P_y$ projection on y-axis

Asymmetry measurement

Detector signal

\[
N_{up,down} = 1 \pm PA \sin(2\pi \cdot f_{prec} t) = 1 \pm PA \sin(2\pi \cdot v_s n_{turns})
\]

P: polarisation, A: analysing power

Asymmetry

\[
\varepsilon = \frac{N_{up} - N_{down}}{N_{up} + N_{down}} = PA \sin(2\pi \cdot v_s n_{turns})
\]

Challenges

- precession frequency \( f_{prec} \approx 120 \text{ kHz} \)
- \( v_s \approx -0.16 \) → 6 turns / precession
- event rate \( \approx 5000 \text{ s}^{-1} \) → 1 hit / 25 precessions
  -> no direct fit of the rates
Asymmetry measurement

single reference clock

COSY rf → beam revolutions: counting turn number \( n \)
detector events → assign turn number \( n \) → phase advance \( \varphi_s = 2\pi \nu_s n \)

for intervals of \( \Delta n = 10^6 \) turns: \( \varphi_s \rightarrow \varphi_s \mod 2\pi \)

scan \( \nu_s \) in some interval around \( \nu_s = \gamma G \)

see: “Measuring the polarization of a rapidly precessing deuteron beam”

Phys.Rev. STAB 17, 052803 (2014)
Spin Coherence Time (SCT)

Ensemble of \( \approx 10^9 \) deuterons: coherent precession needed!

Ideal case:
- all particles have exactly the same momentum \( \text{no} \)
- all particles travel the same path (orbit) in the ring \( \text{no} \)
- all particles see the same fields \( \text{no} \)

Example:

\[
\frac{\Delta \gamma}{\gamma} = \beta^2 \frac{\Delta p}{p} \approx 10^{-4} = \frac{\Delta \nu}{\nu}
\]

\[
\Delta \nu \approx 10^{-4} \cdot 0.16 \approx 10^{-5}
\]

\[
\Delta \varphi = 2\pi \cdot 10^{-5} \cdot 10^6 \text{s}^{-1} \approx 60 \text{ rad/s}
\]

revolution frequency
Spin Coherence Time (SCT)

- unbunched beam: $\frac{\Delta \gamma}{\gamma} \approx 10^{-5} \implies$ decoherence in $<$ 1s
- bunching: eliminate effects on $\frac{\Delta p}{p}$ in 1st order $\implies \tau \approx 20$ s
- correcting higher order effects using sextupoles and (pre-) cooling $\implies \tau \approx 1000$ s

Precise determination of spin tune

Monitoring phase of asymmetry ($v_s$ fixed):

\[ v_s = v_{s,\text{true}} + \delta v_s \]

\[ \Delta v_s \approx 10^{-10} \]

Application: precise determination of $v_s$

- Spin tune $v_s$ can be determined to $\sigma_{v_s} \approx 10^{-8}$ in $\Delta t \approx 2s$
- Average $\overline{v_s}$ in 1 cycle ($\approx 100s$) determined to $\sigma_{v_s} \approx 10^{-10}$
- Tool for: study long term stability of the ring
dedicated online feedback systems
probing ring/field imperfections

Spin tune: feedback system

Challenges:
- maintain resonance frequency and phase between spin precession and Wien filter
- maintain frozen spin condition in a future dedicated ring

Test at COSY:
- control spin tune via COSY rf:
  \[
  \frac{\Delta \nu_s}{\nu_s} = \frac{\Delta \gamma}{\gamma} = \beta^2 \frac{\Delta p}{p} = \frac{\beta^2}{\eta} \frac{\Delta f}{f}
  \]
- control phase to external frequency
- by accelerating/decelerating spin precession

Success!
Spin tune: probing field imperfections

$\Delta v_s = 3.01072(66) \cdot 10^{-6}$
Outlook: Polarimeter development

Status:

- EDDA is in operation since about 20 years
- acceptance limits polarimeter efficiency

Outlook: Polarimeter development

\[ \sigma \cdot A^2 \]

Current range

Desired range


crucial for feedback system
Outlook: Polarimeter development

• „database“ measurements: pC, dC analyzing powers at various beam momenta using the WASA-at-COSY forward detector

• development of a dedicated polarimeter for high precision EDM measurements

LYSO + PMT + divider

modular design
Summary

• EDMs sensitive to new sources of \( \mathcal{CP} \) violation
• Mechanism for \( \mathcal{CP} \) violation: EDMs of charged hadrons needed
• Observable: spin precession in electric fields in storage rings
• **COSY**: ideal starting point for R&D and a pre-cursor experiment

Outlook

• pre-cursor experiment at COSY: proof of principle with lower sensitivity
• dedicated storage ring: different option are currently under investigation
goal: conceptual design report
Jülich Electric Dipole Moment Investigations:

• ≈ 100 members:
  Aachen, Daejeon, Dubna, Ferrara, Grenoble, Indiana, Ithaca, Jülich, Krakau, Michigan, Minsk, Novosibirsk, St. Petersburg, Stockholm, Tbilisi, ...

• see
  http://collaborations.fz-juelich.de/ikp/jedi