PBC EDM subgroup
Yannis Semertzidis, CAPP/IBS and KAIST

Proton, deuteron, muon, $^3$He (n-equivalent)

• Storage ring p,d EDMs @ $<10^{-29}$e-cm level
• Probing New Physics $\sim 10^3$-$10^4$ TeV

• Storage ring EDMs: Great probe of New Physics AND $\theta_{QCD}$
Core members

- Mike Lamont (CERN)
- Gianluigi Arduini (CERN)
- Christian Carli (CERN)
- Mei Bai (Juelich/GSI)
- Klaus Jungman (Groningen)
- YkS (CAPP/IBS & KAIST, Korea)
- Joerg Pretz (Aachen)
- Ed Stephenson (Ind. University)
- Hans Stroeher (Juelich)
- Paolo Lenisa (Ferara)
- Themis Bowcock (Liverpool), TBC
A storage ring experiment to detect a proton electric dipole moment


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Jülich Electric Dipole Moment Investigations

≈ 100 members actual count: 126
(Aachen, Bonn, Daejeon, Dubna, Ferrara, Grenoble, Indiana, Ithaca, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St. Petersburg, Stockholm, Tbilisi, ...)
≈ 10 PhD students

Current spokespersons: Paolo Lenisa (INFN Ferrara), Jörg Pretz (FZJ)
Executive Board, PubCom, Bi-annual Collaboration Mtgs.

http://collaborations.fz-juelich.de/ikp/jedi/
JEDI

COSY at Forschungszentrum Jülich

… the only (operational) test facility for $CP$ EDM
JEDI & srEDM Collaborations

• Two very strong collaborations

Extensive experience in

• Hadronic physics, polarimeters
• Storage rings
• Muon g-2 systematic errors
• Polarized beams
• Beam/spin dynamics

Together: $CP$ EDM
Fundamental particle EDM: study of CP-violation beyond the Standard Model
Proton EDM proposal: $d=10^{-29}e\cdot cm$

- High sensitivity experiment:
- Blowing up the proton to become as large as the sun, the sensitivity to charge separation along N-S would be $r < 0.1 \mu m$!
Why is there so much matter after the Big Bang:

We see:

\[
\frac{n_B}{n} = (6.08 \pm 0.14) \times 10^{-10}
\]

From the SM:

\[
\frac{n_B}{n} = 10^{18}
\]
# Storage Ring Electric Dipole Moments

<table>
<thead>
<tr>
<th>Fields</th>
<th>Example</th>
<th>EDM term</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dipole magnetic field ($B$)</td>
<td>Muon g-2</td>
<td>Tilt of the spin precession plane. (Limited sensitivity due to spin precession)</td>
<td>Eventually limited by geometrical alignment. Requires CW and CCW injection to eliminate systematic errors</td>
</tr>
</tbody>
</table>
| Combination of electric and magnetic fields ($E$, $B$) | Deuteron, $^3$He, proton, etc. | Mainly: \[
\frac{d\vec{s}}{dt} = \vec{d} \times (\vec{v} \times \vec{B})
\] | Most powerful. Small ring. Need to build combined B and E-field system. Reduce vertical E-field. |
| Radial Electric field ($E$) | Proton, etc. | \[
\frac{d\vec{s}}{dt} = \vec{d} \times \vec{E}
\] | Large ring, CW & CCW storage. Simplest to achieve. Reduce radial B-field. |
What has been accomplished?

✓ Polarimeter systematic errors (with beams at KVI, and stored beams at COSY).
✓ Precision beam/spin dynamics tracking.
✓ Stable lattice, IBS lifetime: $\sim 10^4$ s (Lebedev, FNAL)
✓ Spin coherence time $10^3$ s; role of sextupoles understood (using stored beams at COSY).
✓ Feasibility of required electric field strength $>10$ MV/m, 3cm plate separation (JLab)
✓ Analytic estimation of electric fringe fields and precision beam/spin dynamics tracking. Stable!
Finishing up

• SQUID-based beam position monitors

• Magnetic field shielding: develop a cost effective mu-metal shielding

• Define the B and E-field specifications (geometrical phases)

• High efficiency precision beam/spin dynamics simulations
In 2014 we have received the P5 endorsement for the proton EDM experiment under all funding scenarios!
Possible candidate particles

• Proton EDM ($\theta_{QCD}$, quark-gluon EDM)
• Deuteron EDM (T-odd nuclear forces)

• $^3$He (equivalent to nEDM)
• Electron EDM?
• Muon EDM?
Storage ring EDM program

• Proton, Deuteron and neutron (or $^3$He) together can help pin-point the source of CP-violation should one is found to be non-zero!

• Possible sources: $\theta_{\text{QCD}}$ or (e.g., SUSY-like) New Physics or (most likely) a combination.

• Which one first? To be decided by the experimental working group. Both is a must!
EDM status

• The EDM experiments are gearing up, getting ready:
  
• $^{199}\text{Hg}$ EDM $<10^{-29}$ e-cm sensitivity

• nEDM at PSI $10^{-26}$ e-cm sensitivity, 2015 - 2017

• nEDM at PSI $10^{-27}$ e-cm sensitivity, 2018 - …

• nEDM at SNS $\sim 2 \times 10^{-28}$ e-cm starting data taking 2021
EDM status (cont’d)

- ThO, current limit on eEDM: $10^{-28}$ e-cm, next $\times 10$ improvement.

- TUM nEDM effort, making progress in B-field shielding, met B-field specs. It moves to ILL in 2015, goal: $10^{-28}$ e-cm, staged approach, starting in 2016.

- $^{225}$Ra EDM, $\sim 5 \times 10^{-22}$ e-cm now, $\sim 3 \times 10^{-28}$ e-cm w/ FRIB

- Storage ring EDM: p,dEDM goals $\sim 10^{-29}$ e-cm Strength: statistics. Proton w/ upgrade $\sim 10^{-30}$ e-cm
Generic Physics Reach of $d_p \sim 10^{-29} \text{e- cm}$

\[ d_p \sim 0.01 \left( \frac{m_p}{\Lambda_{NP}} \right)^2 \tan \phi^{NP} e / 2m_p \]
\[ \sim 10^{-22} \left( \frac{1 \text{TeV}}{\Lambda_{NP}} \right)^2 \tan \phi^{NP} e \text{- cm} \]

If $\phi^{NP}$ is of $O(1)$, $\Lambda_{NP} \sim 3000 \text{TeV}$ Probed!
If $\Lambda_{NP} \sim O(1 \text{TeV})$, $\phi_{NP} \sim 10^{-7}$ Probed!

Unique Capabilities!
Sensitivity to Rule on Several New Models

If found it could explain Baryogenesis (p, d, n, $^3$He)

Electron EDM new physics reach: 1-3 TeV

Much higher physics reach than LHC; complementary

1st upgrade

Gray: Neutron
Red: Electron

n current
p, d target
e target

Electron EDM new physics reach: 1-3 TeV

Statistics limited

Electron EDM new physics reach: 1-3 TeV

Much higher physics reach than LHC; complementary

Axion mediated long range forces

Together with ARIADNE: test axion physics!

Current nEDM limit

EW CPV phase, $\vartheta \sim 10^{-16}$
Summary

• Storage ring EDM effort is timely.

• Ultimate sensitivity for p,dEDM < $10^{-29}$ e-cm

• Great probe of New Physics AND $\theta_{QCD}$
Extra slides
The proton EDM ring (alternate gradient)

Straight sections are instrumented with quads, BPMs, polarimeters, injection points, etc, as needed.

Requirements:
Weak vertical focusing (B-field sensitivity)
Below transition (reduce IBS)
Technically driven pEDM timeline

- Research and systems development (R&D); CDR; final ring design, TDR, installation
- CDR by fall of 2018
- Proposal to a lab: fall 2018
Expected reach

PQ Axion $f_a$ in GeV

Experimental Bounds

Astrophysical and Experimental Bounds

Setup in this proposal

$T_\phi = 1$ sec

$T_\phi = 1000$ sec

nEDM Limit: $d_n \sim 3 \times 10^{-26}$ e·cm

pEDM Limit: $d_p \sim 10^{-30}$ e·cm

Force Range in cm
Proton Statistical Error (230MeV):

\[
\sigma_d = \frac{2\hbar}{E_R PA \sqrt{N_c f \tau_p T_{tot}}}
\]

\(\tau_p : 10^3 \text{s}\)  Polarization Lifetime (Spin Coherence Time)

\(A : 0.6\)  Left/right asymmetry observed by the polarimeter

\(P : 0.8\)  Beam polarization

\(N_c : 10^{11} \text{p/cycle}\)  Total number of stored particles per cycle

\(T_{tot} : 10^7 \text{s}\)  Total running time per year

\(f : 1\%\)  Useful event rate fraction (efficiency for EDM)

\(E_R : 7 \text{MV/m}\)  Average radial electric field strength

\[\sigma_d = 1.0 \times 10^{-29} \text{ e-cm / year}\]
Electric Dipole Moments in Magnetic Storage Rings

\[ \frac{ds}{dt} = \vec{d} \times (\vec{v} \times \vec{B}) \]

E.g. 1 T corresponds to 300 MV/m for relativistic particles

Yannis Semertzidis
Indirect Muon EDM limit from the g-2 Experiment

\[
\vec{\omega} = \frac{e}{m} \left\{ a\vec{B} + \frac{\eta}{2c} \left( \vec{v} \times \vec{B} \right) \right\}
\]

\[
\vec{\omega} = \vec{\omega}_a + \vec{\omega}_{edm}
\]

\[
\tan \theta = \frac{\omega_{edm}}{\omega_a}
\]

Ron McNabb’s Thesis 2003:

\(< 2.7 \times 10^{-19} \text{ e} \cdot \text{cm} \) 95% C.L.

Yannis Semertzidis
The proton EDM ring evaluation  Val Lebedev (Fermilab)

Beam intensity $10^{11}$ protons limited by IBS

<table>
<thead>
<tr>
<th></th>
<th>Soft focusing</th>
<th>Strong focusing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circumference, m</td>
<td>263</td>
<td>300</td>
</tr>
<tr>
<td>$Q_x/Q_y$</td>
<td>1.229/0.456</td>
<td>2.32/0.31</td>
</tr>
<tr>
<td>Particle per bunch</td>
<td>1.5-10^8</td>
<td>7·10^8</td>
</tr>
<tr>
<td>Coulomb tune shifts, $\Delta Q_x/\Delta Q_y$</td>
<td>0.0046/0.0066</td>
<td>0.0146/0.0265</td>
</tr>
<tr>
<td>Rms emittances, x/y, norm, $\mu$ m</td>
<td>0.56/1.52</td>
<td>0.31/2.16</td>
</tr>
<tr>
<td>Rms momentum spread</td>
<td>1.1·10^{-4}</td>
<td>2.9·10^{-4}</td>
</tr>
<tr>
<td>IBS growth times, x/y/s, s</td>
<td>300/(-1400)/250</td>
<td>7500</td>
</tr>
<tr>
<td>RF voltage, kV</td>
<td>13</td>
<td>10.3</td>
</tr>
<tr>
<td>Synchrotron tune</td>
<td>0.02</td>
<td>0.006</td>
</tr>
</tbody>
</table>
Storage ring proton EDM method

• All-electric storage ring. Strong radial E-field to confine protons with “magic” momentum. The spin vector is aligned with momentum horizontally.

• High intensity, polarized proton beams are injected Clockwise and Counter-clockwise with positive and negative helicities. Great for systematics (e.g., geometrical phases).

• Great statistics: up to $\sim 10^{11}$ particles with primary proton beams and small phase-space parameters.
<table>
<thead>
<tr>
<th>System</th>
<th>Current limit [e cm]</th>
<th>Future goal</th>
<th>Neutron equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neutron</td>
<td>&lt;1.6 × 10^{-26}</td>
<td>~10^{-28}</td>
<td>10^{-28}</td>
</tr>
<tr>
<td>$^{199}$Hg atom</td>
<td>&lt;10^{-29}</td>
<td></td>
<td>10^{-25}-10^{-26}</td>
</tr>
<tr>
<td>$^{129}$Xe atom</td>
<td>&lt;6 × 10^{-27}</td>
<td>~10^{-30}-10^{-33}</td>
<td>10^{-26}-10^{-29}</td>
</tr>
<tr>
<td>Deuteron nucleus</td>
<td></td>
<td>~10^{-29}</td>
<td>3 × 10^{-29}-5 × 10^{-31}</td>
</tr>
<tr>
<td>Proton nucleus</td>
<td>&lt;7 × 10^{-25}</td>
<td>~10^{-29}-10^{-30}</td>
<td>10^{-29}-10^{-30}</td>
</tr>
</tbody>
</table>
CP-violation phase from Higgs

EDMs will eventually be discovered: d_e, d_n, d_p... d_D
Magnitudes of ≈ -10^{-28} expected for Baryogenesis
Atomic, Molecular, Neutron, **Storage Ring** (All important)

CP violation phase in: **Hee, H_{\gamma\gamma}, H_{tt}, 2HD Model**...
Uniquely explored by 2 loop edms! Barr-Zee effect
May be our only window to Hee, Huu and Hdd couplings
Guided by experiment: H \rightarrow \gamma\gamma \quad (H \rightarrow \tau^+\tau^-, \mu^+\mu^-) etc.

*Updates Anxiously Anticipated!*

*The Higgs may be central to our existence!*
Anomalous magnetic moment factors

\[
\frac{1}{\gamma^2 - 1} - G = 0 \rightarrow \gamma = \sqrt{\frac{1}{G}} + 1
\]

→ \( G > 0 \) for \( \gamma > 1 \), if only electric fields are applied

\[
\gamma = \sqrt{\frac{1}{G}} + 1 \iff p = \frac{m}{\sqrt{G}}
\]

\[
\mu_p / \mu_N = 2.792 \, 847 \, 356 \, (23) \quad \rightarrow \quad G_p = 1.7928473565
\]
\[
\mu_d / \mu_N = 0.857 \, 438 \, 2308 \, (72) \quad \rightarrow \quad G_d = -0.14298727202
\]
\[
\mu_{He-3} / \mu_N = -2.127 \, 497 \, 718 \, (25) \quad \rightarrow \quad G_{3He} = -4.1839627399
\]

Nuclear magneton: \( \mu_N = e\hbar / (2m_p c) = 5.050 \, 783 \, 24 \, (13) \cdot 10^{-27} \, J \, T^{-1} \)

→ Magic momentum for protons: \( p = 700.74 \) MeV/c

→ Deuterons, He-3:

\[
E_r = \frac{GBc\beta\gamma^2}{1 - G\beta^2\gamma^2} \approx GBc\beta\gamma^2
\]