Поиск электрических дипольных моментов частиц и ядер в накопительных кольцах

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Motivation for a search for the electric dipole moments at storage rings
Electric Dipole Moments (EDMs)

Permanent EDMs violate parity $P$ and time reversal symmetry $T$

Assuming CPT to hold, combined symmetry CP violated as well.

EDMs are candidates to solve mystery of matter-antimatter asymmetry
° may explain why we are here!
CP-violation was discovered at BNL in 1964

James W. Cronin and Val L. Fitch, both then of Princeton University, proposed using Brookhaven’s AGS to verify a fundamental tenet of physics, known as CP symmetry, by showing that two different particles did not decay into the same products. They picked as their example neutral K mesons, which are routinely produced in collisions between a proton beam and a stationary metal target.

The experiment set out to show that in millions of collisions, the short-lived variety of K meson always decayed into two π mesons, while the long-lived variety never did. But to their surprise, a “suspicious-looking hump” in the data showed an unexpected result that years of subsequent experimentation and theory have been unable to explain: occasionally, the long-lived neutral K meson does decay into two π mesons. Cronin and Fitch had found an example of CP violation.

Schematic of the experimental apparatus used by Cronin and Fitch.
<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;3×10^{-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>
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<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}</td>
<td>4×10^{-29}-2.5×10^{-30}</td>
</tr>
<tr>
<td>Electron</td>
<td>&lt;8.7×10^{-29}</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Origin of EDMs

- Standard Model EDMs are due to CP violation in the quark weak mixing matrix - CKM (e.g. the $K^0/B^0$-system) but...
  - $e^-$ and quark EDM's are zero at first order
  - Need at least two "loops" to get EDM's (electron actually requires 4 loops!)
    - Thus EDM's are VERY small in standard model

Neutron EDM in Standard Model is

$\sim 10^{-32} \text{ e-cm} \quad (=10^{-19} \text{ e-fm})$

Electron EDM in Standard Model is

$< 10^{-40} \text{ e-cm}$
Physics Beyond the Standard Model

- New physics (e.g. SuperSymmetry = SUSY) has additional CP violating phases in added couplings
  - New phases: $\phi_{CP}$ should be $\sim 1$ (why not?)
- Contributions to EDMs depends on masses of new particles
  \[ d_n \propto \frac{\sin \phi_{CP}}{M_{SUSY}^2} \]
  - In MSSM (Minimal Supersymmetric Standard Model)
  \[ d_n \sim \left( \frac{200 \text{ GeV}}{M_{SUSY}} \right)^2 \times 10^{-25} \text{ e\text{\textperiodcentered}cm} \]
Search for the muon EDM in framework of $g$-2 experiments
\[ \Omega = \sqrt{\Omega_{MDM}^2 + \Omega_{EDM}^2} \]

\[ t = \frac{\pi}{2\Omega} \]

Figure 1. The contributions to the precession frequency \( \Omega \) from the magnetic dipole moment and the electric dipole moment. The resulting spin precession plane.

Muon: \( d < 1.8 \times 10^{-19} \text{ e}\cdot\text{cm} \)
Next plans for the muon EDM experiments (Fermilab and J-PARC):

Muon $d < 10^{-21}$ e·cm
Resonance methods of the storage ring EDM experiments
Resonance synchrotron oscillations

Generalized Thomas-Bargmann-Mishel-Telegdi equation of spin motion in storage rings in the cylindrical coordinate system:

\[
\Omega^{(cyl)} = -\frac{e}{m} \left\{ GB - \frac{G\gamma}{\gamma + 1} \beta (\beta \cdot B) \right. \\
+ \left( \frac{1}{\gamma^2 - 1} - G \right) (\beta \times E) + \frac{1}{\gamma} \left[ B_{||} - \frac{1}{\beta^2} (\beta \times E)_{||} \right] \\
+ \frac{\eta}{2} \left( E - \frac{\gamma}{\gamma + 1} \beta (\beta \cdot E) + \beta \times B \right) \left\} .
\]

The sign \( \parallel \) means a horizontal projection for any vector.

\[ E = 0, \quad \beta = \beta_0 \cos(\Omega t + \phi). \]

However, a nonlinearity of beam oscillations brings radial oscillations which result in an oscillating radial magnetic field acting on the magnetic dipole moment. Thus, this experiment cannot be successful due to large systematic errors.
Resonance spin flippers. RF Wien filter

One can also use a resonance radial electric field

$$\mathbf{E} = E_0 \cos \left( \Omega t + \phi \right),$$

because the vector $\beta \times E$ is vertical and does not create any resonance effect:

$$\Omega^{(cyl)} = -\frac{e}{m} \left\{ GB - \frac{G \gamma}{\gamma + 1} \beta (\beta \cdot B) \\
+ \left( \frac{1}{\gamma^2 - 1} - G \right) (\beta \times E) + \frac{1}{\gamma} \left[ B_{\parallel} - \frac{1}{\beta^2} (\beta \times E)_{\parallel} \right] \\
+ \frac{\eta}{2} \left( E - \frac{\gamma}{\gamma + 1} \beta (\beta \cdot E) + \beta \times B \right) \right\}.$$  

However, this field negatively influences beam dynamics.
The better possibility is the use of the radio-frequency Wien filter.
Lorentz force compensation

Providing minimal integral Lorentz force requires careful shaping of electrodes and all other components.

RF Wien filter

\[ \vec{F}_L = q(\vec{E} + \vec{v} \times \vec{B}) \]

Lorentz force integral with \( \vec{v} \) along Wien filter axis

\[
\frac{q}{\ell} \int_{-\ell/2}^{\ell/2} \begin{pmatrix} E_x - c\beta B_y \\ E_y + c\beta B_x \\ E_z \end{pmatrix} \, dz = \begin{pmatrix} 5.97 \times 10^{-3} \\ 7.97 \times 10^{-3} \\ 1.27 \times 10^{-21} \end{pmatrix} \text{ eV/m}
\]

\[
\int_{-\ell/2}^{\ell/2} \vec{B} \, dz = \begin{pmatrix} 2.73 \times 10^{-9} \\ 0.047 \\ 6.96 \times 10^{-7} \end{pmatrix} \text{ T mm}
\]

Continued work on RF driving circuit → to reach \( \int B \, dl \sim 0.2 \text{ T mm} \) seems possible.
Important distinguishing features of storage ring EDM experiments are also a simultaneous influence of external fields on the electric and magnetic dipole moments and the existence of a resonance effect even when the stimulating torque acting on the EDM is equal to zero.

There is not a resonance field acting on the EDM!
1. ``Resonance” stimulated by the oscillating vertical magnetic field in the storage ring with the main magnetic field $B_0$

$$B(\Phi) \cos (\omega't + \chi) = B_{0}^{(osc)} \sum_{n=-\infty}^{\infty} a_n \cos [(\omega' + n\omega_c)t + \chi]$$

The angular velocity of the spin rotation in the cylindrical coordinates is given by ($\beta = \beta e_\phi$)

$$\Omega^{(cyl)} = \omega_0 \left[ 1 + b_z \cos (\omega t + \chi) \right] e_z - \frac{e\eta}{2m} \beta B_0 \left[ 1 + b_r \cos (\omega t + \chi) \right] e_r,$$

$$\omega_0 = -\frac{eG}{m} B_0.$$ 

In the considered case,

$$b_r = b_r^{(m)} = b_z = b_z^{(m)} = \frac{a_n B_0^{(osc)}}{B_0}.$$
Evidently, the constant and oscillating parts of the vector $\Omega^{(cyl)}$ are collinear. This vector forms the small angle with the $z$ axis.

$$\vartheta = \sin \vartheta = -\frac{e\eta}{2m\omega_0}\beta B_0 = \frac{\eta\beta}{2G}$$

Any resonance effect does not exist:

$$\Omega^{(cyl)} = \omega_0 [1 + b_z \cos (\omega t + \chi)] e_\vartheta,$$

$$e_\vartheta = e_z + \vartheta e_r.$$

$$\Omega^{(cyl)} = \Omega^{(0)} + \Omega^{(1)}$$

**constant part**

$$\Omega^{(0)} = \omega_0 e_\vartheta,$$

$$\Omega^{(1)} = \omega_0 b_z \cos (\omega t + \chi) e_\vartheta.$$
Figure 1. Magnetic-field "flipper".

\[ \Omega^{(cyl)} = \Omega^{(0)} + \Omega^{(1)} \]

constant part \hspace{1cm} oscillating part

\[ \Omega^{(0)} = \omega_0 e_g, \]

\[ \Omega^{(1)} = \omega_0 b_z \cos(\omega t + \chi) e_g. \]
2. Resonance stimulated by the oscillating radial electric field in the storage ring with the main magnetic field $B_0$

\[ E_0 = E_0 e_r, \quad b_r = b_r^{(e)} = \frac{a_n E_0}{\beta B_0}, \quad b_z = b_z^{(e)} = -\frac{\beta a_n E_0}{GB_0} \left( \frac{1}{\gamma^2 - 1} - G \right) \]

It is very convenient to switch to the new axes, $e_\zeta = e_r - \vartheta e_z$, $e_\phi$ and $e_\vartheta$

\[ \Omega^{(cyl)} = \omega_0 \left[ 1 + b_z \cos (\omega t + \chi) \right] e_\vartheta + \omega_0 \vartheta (b_r - b_z) \cos (\omega t + \chi) e_\zeta. \]

\[ b_r^{(e)} - b_z^{(e)} = \frac{a_n E_0}{\beta B_0} \cdot \frac{G + 1}{G \gamma^2} = -\frac{e\eta a_n E_0}{2m \beta \gamma^2 \omega_0}. \]

The horizontal spin polarization at the initial vertical spin direction is given by

\[ P_x(t) = \mathcal{E} t \sin (\omega t + \chi), \]

\[ P_y(t) = -\mathcal{E} t \cos (\omega t + \chi) \]

\[ \mathcal{E} = \frac{1}{2} \omega_0 \vartheta \left( b_r^{(e)} - b_z^{(e)} \right) = -\frac{e\eta}{4m} \cdot \frac{G + 1}{G \gamma^2} a_n E_0. \]
For the E-field flipper,

\[ \Omega^{(cyl)} = \Omega^{(0)} + \Omega^{(1)}, \]

\[ \Omega^{(0)} = \omega_0 e_\varphi, \]

\[ \Omega^{(1)} = \omega_0 b_z^{(e)} \cos(\omega t + \chi) e_\varphi \]

\[ + \omega_0 \varphi \left( b_r^{(e)} - b_z^{(e)} \right) \cos(\omega t + \chi) e_\zeta. \]
3. Resonance stimulated by the rf Wien filter in the storage ring with the main magnetic field $B_0$

There is not any oscillating force acting on a particle:

$$B_0^{(osc)} + \beta E_0 = 0.$$ 

Oscillating fields should be synchronized:

$$E = E_0 \cos(\omega t + \chi), \quad B^{(osc)} = B_0^{(osc)} \cos(\omega t + \chi).$$

The angular velocity of the spin rotation takes the form

$$\Omega^{(cyl)} = \omega_0 \left[1 + (b_z^{(e)} + b_z^{(m)}) \cos(\omega t + \chi)\right] e_z + \omega_0 \vartheta e_r.$$ 

There is not a resonance field acting on the EDM!

However, $e_\vartheta$ and $e_z$ are not collinear
To determine the resonance effect, it is convenient to pass to the axes $\mathbf{e}_\vartheta$ and $\mathbf{e}_\zeta$:

$$
\mathbf{e}_\vartheta = \mathbf{e}_z + \mathbf{\mathcal{R}} \mathbf{e}_r, \quad \mathbf{e}_\zeta = \mathbf{e}_r - \mathbf{\mathcal{R}} \mathbf{e}_z.
$$

In this case,

$$
\Omega^{(cyl)} = \omega_0 \left[ 1 + \delta \cos (\omega t + \chi) \right] \mathbf{e}_\vartheta - \omega_0 \mathcal{R} \delta \cos (\omega t + \chi) \mathbf{e}_\zeta,
$$

where

$$
\delta = b_z^{(e)} + b_z^{(m)} = -b_r^{(e)} + b_z^{(e)} = -\frac{a_n E_0}{\beta B_0} \cdot \frac{G + 1}{G \gamma^2}.
$$

The resonance EDM effect is provided by the oscillating torque acting on the MDM.
For the rf Wien filter,

\[ \Omega^{(cyl)} = \Omega^{(0)} + \Omega^{(1)}, \]

\[ \Omega^{(0)} = \omega_0 e_\varrho, \]

\[ \Omega^{(1)} = -\omega_0 \left( b_r^{(e)} - b_z^{(e)} \right) \cos(\omega t + \chi) e_\varrho \]

\[ + \omega_0 \vartheta \left( b_r^{(e)} - b_z^{(e)} \right) \cos(\omega t + \chi) e_\zeta. \]
Buildup of $P_y(t)$ using RF Wien filter for deuterons

A simple model calculation with parameters:

- Beam energy: $T_d = 50$ MeV,
- Length of device: $L_{RF} = 1$ m.
- Assumed deuteron EDM: $d = 10^{-24}$ e cm.
- Electric RF field: $30$ kV cm$^{-1}$.

EDM effect accumulates in $P_y \propto d$ [1, 2].
Frozen spin method of the storage ring EDM experiments
A Proposal to Measure the Proton Electric Dipole Moment with $10^{-29} e\cdot cm$ Sensitivity by the Storage Ring EDM Collaboration

Storage Ring EDM Collaboration

Combined electric and magnetic fields

Frozen spin method: \[ \vec{\omega}_a = \frac{e}{m} \left[ a\vec{B} + \left( a - \left( \frac{m}{p} \right)^2 \right) \vec{\beta} \times \vec{E} \right] \]

Use a radial \( E_r \)-field to cancel the \( g-2 \) precession

New Method of Measuring Electric Dipole Moments in Storage Rings

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A new highly sensitive method of looking for electric dipole moments of charged particles in storage rings is described. The major systematic errors inherent in the method are addressed and ways to minimize them are suggested. It seems possible to measure the muon EDM to levels that test speculative theories beyond the standard model.

Muon \( d < 10^{-24} \) e\( \cdot \)cm
EDM at COSY – COoler SYnchrotron

Cooler and storage ring for (polarized) protons and deuterons

\[ p = 0.3 - 3.7 \text{ GeV/c} \]

Phase space cooled internal & extracted beams

... the spin-physics machine for hadron physics

Injector cyclotron

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Precursor experiments to search for EDMs at COSY
When the radial electric and vertical magnetic fields are combined, the connection between them is given by

\[ E = \frac{G B c \beta \gamma^2}{1 - G \beta^2 \gamma^2} \approx G B c \beta \gamma^2. \]

A *magic* storage ring for protons (electrostatic), deuterons, …

<table>
<thead>
<tr>
<th>particle</th>
<th>( p ) (MeV/c)</th>
<th>( T ) (MeV)</th>
<th>( E ) (MV/m)</th>
<th>( B ) (T)</th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>701</td>
<td>232.8</td>
<td>16.789</td>
<td>0.000</td>
</tr>
<tr>
<td>deuteron</td>
<td>1000</td>
<td>249.9</td>
<td>−3.983</td>
<td>0.160</td>
</tr>
<tr>
<td>(^3)He</td>
<td>1285</td>
<td>280.0</td>
<td>17.158</td>
<td>−0.051</td>
</tr>
</tbody>
</table>

Possible to measure \( p, d, \(^3\)He\) using one machine with \( r \sim 25 \) m
All-electric storage ring for the proton EDM experiment

Freezing the horizontal spin precession

\[ \vec{\omega}_a = \frac{e}{m} \left( a - \left( \frac{m}{p} \right)^2 \right) \vec{\beta} \times \vec{E} \]

The spin precession is zero at “magic” momentum (0.7 GeV/c for protons, 3.1 GeV/c for muons, …)

\[ p = \frac{m}{\sqrt{a}}, \quad \text{with} \quad a = \frac{g - 2}{2} \]
Is the polarimeter analyzing power good at $P_{\text{magic}}$? YES!

Analyzing power can be further optimized (E. Stephenson)

Fig. 4. Angle-averaged effective analyzing power. Curves show our fits. Points are the data included in the fits. Errors are statistical only.

Fig. 4. The angle averaged effective analyzing power as a function of the proton kinetic energy. The magic momentum of 0.7GeV/c corresponds to 232MeV.
Spin Coherence Time

\[ \vec{\omega}_a = \frac{e}{m} \left( a - \left( \frac{m}{p} \right)^2 \right) \vec{\beta} \times \vec{E} \]

\[ d\omega_a \approx \left( \frac{dP}{P} \right)^2 \times 10^7 \text{ rad/s} \]

- Due to beam momentum spread \( \frac{dP}{P} \) there is spread in the horizontal spin precession.
- The linear part of the spread is canceled by using RF-cavity. The quadratic part is canceled by using compensating sextupole magnets.
Cancelling the 2\(^{nd}\) order effects with sextupoles

\[ \Delta \omega_a \approx a_x A_x^2 + a_y A_y^2 + a_p \left( \frac{dP}{P} \right)_{\text{max}}^2 \]

Strategically placed sextupoles around the ring will cancel the effect from \(\text{dp}/p\), horizontal and vertical betatron oscillations. Method applied at Novosibirsk. Our case is analyzed by Y. Orlov who estimated SCT of \(10^3\)s should be possible.
Proton Statistical Error (230MeV):

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

\[ \begin{align*}
\tau_p : 10^3 s & \quad \text{Polarization Lifetime (Spin Coherence Time)} \\
A : 0.6 & \quad \text{Left/right asymmetry observed by the polarimeter} \\
P : 0.8 & \quad \text{Beam polarization} \\
N_c : 2 \times 10^{10} \text{p/cycle} & \quad \text{Total number of stored particles per cycle} \\
T_{Tot} : 10^7 s & \quad \text{Total running time per year} \\
f : 0.5\% & \quad \text{Useful event rate fraction (efficiency for EDM)} \\
E_R : 17 \text{ MV/m} & \quad \text{Radial electric field strength (65\% azim. cov.)} \\
\end{align*} \]

\[ \sigma_d = 1.6 \times 10^{-29} \text{e} \cdot \text{cm/year for uniform counting rate and} \]
\[ \sigma_d = 1.1 \times 10^{-29} \text{e} \cdot \text{cm/year for variable counting rate} \]
Summary

- Large EDMs can demonstrate an existence of new physics.
- Search for the muon EDM will be performed in framework of the $g$-2 experiments. The expected sensitivity is of the order of $10^{-21}$ e·cm.
- Search for the EDMs of the proton, deuteron, and helion ($^3$He nucleus) will be carried out at COSY, Jülich by the resonance method. The expected sensitivity is of the order of $10^{-24}$ e·cm.
- Stimulation of resonance synchrotron oscillations is not appropriate due to large systematic errors.
- The highest sensitivity of the order of $10^{-29}$ e·cm can be reached with the frozen spin method. The experiments can be performed in storage rings with combined electric and magnetic fields (proton, deuteron, and helion) and in an all-electric storage ring (proton).
Thank you for your attention
Magnetic focusing

The magnetic field components are given by

\[ B_x = g y \]  \hspace{1cm} (1) \]

for the radial B-field dependence and

\[ B_y = B_0 + gx - g \frac{y^2}{2R_0} \]  \hspace{1cm} (2) \]

For the vertical field component, with

\[ g = -n \frac{B_0}{R_0} \]  \hspace{1cm} (3) \]

and \( n \) the field focusing index, a positive number less than 1. The non-linear term comes in from the application of Maxwell’s equations in cylindrical coordinates [7] (without this term the vertical betatron oscillations are not linear).

The time averaged, relative B-field change is then

\[ \left\langle \frac{B_y}{B_0} - 1 \right\rangle = -\frac{n}{R_0} \left\langle x \right\rangle + n \frac{y_0^2}{4R_0^2} = \frac{n}{1-n} \frac{\mathcal{Q}^2}{2} + \frac{\mathcal{Q}^2}{4}, \]  \hspace{1cm} (4) \]
Radial oscillations

\[ \frac{\langle x \rangle}{R_0} = -\alpha_p \frac{\varphi_0^2}{2} = -\frac{1}{1-n} \frac{\varphi_0^2}{2}, \]

Figure 2. The particle deviation [m] from the ideal radial position vs. time [s]. Eq. (5) predicts a maximum of $-1.8 \times 10^{-6}$ m, consistent with the tracking results shown here. The maximum angle is 0.5mrad and $n=0.01$. 
B-field vs. vertical position

\[
\frac{\langle B_y \rangle - 1}{B_0} = -\frac{n}{R_0} \langle x \rangle + n \frac{y_0^2}{4R_0^2} = \frac{n}{1 - n} \frac{\mathcal{G}_0^2}{2} + \frac{\mathcal{G}_0^2}{4},
\]

Figure 7. The relative B-field change as a function of the radial position [m] for two \( n \)-values: 0.01 (red) and 0.137 (green).
Figure 7. The relative B-field change as a function of the radial position [m] for two $n$-values: 0.01 (red) and 0.137 (green).