Electric Dipole Moments – probes of fundamental symmetries

J. Pretz
RWTH Aachen/ FZ Jülich

Heidelberg, December 2013
Electric Dipole Moments (EDMs)

- What is it?
- Why is it interesting?
- What do we know about it?
- How to measure (charged particle) EDMs?
  Results of first test measurements
What is it?
Electric Dipoles

Classical definition:

\[ \vec{d} = \sum \limits_i q_i \vec{r}_i \]
## Order of magnitude

<table>
<thead>
<tr>
<th></th>
<th>atomic physics</th>
<th>hadron physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>charges</td>
<td>$e$</td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>\vec{r}_1 - \vec{r}_2</td>
<td>$</td>
</tr>
<tr>
<td>EDM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>naive expectation</td>
<td>$10^{-8} e \cdot \text{cm}$</td>
<td></td>
</tr>
<tr>
<td>observed</td>
<td>water molecule</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$2 \cdot 10^{-8} e \cdot \text{cm}$</td>
<td></td>
</tr>
</tbody>
</table>
### Order of magnitude

<table>
<thead>
<tr>
<th></th>
<th>atomic physics</th>
<th>hadron physics</th>
</tr>
</thead>
<tbody>
<tr>
<td>charges</td>
<td>$e$</td>
<td>$e$</td>
</tr>
<tr>
<td>$</td>
<td>\vec{r}_1 - \vec{r}_2</td>
<td>$</td>
</tr>
<tr>
<td>EDM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>naive expectation</td>
<td>$10^{-8} e \cdot \text{ cm}$</td>
<td>$10^{-13} e \cdot \text{ cm}$</td>
</tr>
<tr>
<td>observed</td>
<td>water molecule</td>
<td>neutron</td>
</tr>
<tr>
<td></td>
<td>$2 \cdot 10^{-8} e \cdot \text{ cm}$</td>
<td>$&lt; 3 \cdot 10^{-26} e \cdot \text{ cm}$</td>
</tr>
</tbody>
</table>
neutron EDM of \( d_n = 3 \cdot 10^{-26} \text{ e}\cdot\text{cm} \) corresponds to separation of \( u^- \) from \( d^- \) quarks of \( \approx 5 \cdot 10^{-26} \text{ cm} \)
Operator $\vec{d} = q\vec{r}$

is odd under parity transformation ($\vec{r} \rightarrow -\vec{r}$):

$$\mathcal{P}^{-1}\vec{d}\mathcal{P} = -\vec{d}$$

Consequences:
In a state $|a\rangle$ of given parity the expectation value is 0:

$$\langle a|\vec{d}|a\rangle = -\langle a|\vec{d}|a\rangle$$

If $|a\rangle = \alpha|P = +\rangle + \beta|P = -\rangle$

in general $\langle a|\vec{d}|a\rangle \neq 0 \Rightarrow$ i.e. molecules
EDM of molecules

ground state: mixture of

\[ \psi_s = \frac{1}{\sqrt{2}} (\psi_1 + \psi_2) \quad P = + \]
\[ \psi_a = \frac{1}{\sqrt{2}} (\psi_1 - \psi_2) \quad P = - \]

(Cohen-Tannoudji, B. Diu, F. Laloë, Mécanique quantique)
**Order of magnitude**

**Molecules** can have large EDM because of degenerated ground states with different parity.
**Order of magnitude**

**Molecules** can have large EDM because of degenerated ground states with different parity.

**Elementary particles** (including hadrons) have a definite parity and cannot possess an EDM.  
\[ P|\text{had} > = \pm 1|\text{had} > \]
Molecules can have large EDM because of degenerated ground states with different parity.

Elementary particles (including hadrons) have a definite parity and cannot possess an EDM unless \( P|\text{had} \rangle = \pm 1|\text{had} \rangle \)

unless \( P \) and time reversal \( T \) invariance are violated!
$\mathcal{T}$ and $\mathcal{P}$ violation of EDM

$\vec{d}$: EDM  
$\vec{\mu}$: magnetic moment
both $\parallel$ to spin

$$H = -\mu \vec{\sigma} \cdot \vec{B} - d \vec{\sigma} \cdot \vec{E}$$

$\mathcal{T}$:  
$$H = -\mu \vec{\sigma} \cdot \vec{B} + d \vec{\sigma} \cdot \vec{E}$$

$\mathcal{P}$:  
$$H = -\mu \vec{\sigma} \cdot \vec{B} + d \vec{\sigma} \cdot \vec{E}$$

$\Rightarrow$ EDM measurement tests violation of fundamental symmetries $\mathcal{P}$ and $\mathcal{T}$ ($\mathcal{CPT} \equiv \mathcal{CP}$)
### Symmetries in Standard Model

<table>
<thead>
<tr>
<th></th>
<th>electro-mag.</th>
<th>weak</th>
<th>strong</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C$</td>
<td>✓</td>
<td>⬠</td>
<td>✓</td>
</tr>
<tr>
<td>$\mathcal{P}$</td>
<td>✓</td>
<td>⬠</td>
<td>✓</td>
</tr>
<tr>
<td>$\mathcal{T}$ $\to$ $\mathcal{C\mathcal{P}}$</td>
<td>✓</td>
<td>(✓)</td>
<td>(✓)</td>
</tr>
</tbody>
</table>

- $C$ and $\mathcal{P}$ are maximally violated in weak interactions (Lee, Yang, Wu)
- $\mathcal{C\mathcal{P}}$ violation discovered in kaon decays (Cronin, Fitch) described by CKM-matrix in Standard Model
- $\mathcal{C\mathcal{P}}$ violation allowed in strong interaction but corresponding parameter $\theta_{QCD} \lesssim 10^{-10}$ (strong $\mathcal{C\mathcal{P}}$-problem)
EDM requires violation of symmetries
but particles may have large magnetic dipole moment (MDM),
for structureless particles theory even predicts that
\[ \mu = g \frac{e \hbar}{2m} \frac{|\vec{S}|}{\hbar} \]
with \( g = 2 \) in leading order
\[ G = \frac{g - 2}{2} \]
for various particles:
\[ \approx \frac{\alpha}{2\pi} \approx 0.00116 \] for \( \ell^\pm \)

<table>
<thead>
<tr>
<th>experiment</th>
<th>theory</th>
</tr>
</thead>
<tbody>
<tr>
<td>electron</td>
<td>1 159 652 180.73 (0.28) ( \cdot 10^{-12} )</td>
</tr>
<tr>
<td>muon</td>
<td>1 165 920.80(54)(33) ( \cdot 10^{-9} )</td>
</tr>
<tr>
<td>proton</td>
<td>1.792847356(23)</td>
</tr>
</tbody>
</table>

*: static quark model, SU(6) wave function
Why is it interesting?
**CP violation**

- We are surrounded by matter (and not anti–matter)
  \[ \eta = \frac{n_B - n_B}{n_\gamma} = 6 \times 10^{-10} \]

- Starting from equal amount of matter and anti-matter in the early universe, the $CP$-violation in the Standard Model predicts only $10^{-18}$

- In 1967 Sakharov formulated three prerequisites for baryogenesis. One of these is the combined violation of the charge and parity, $CP$, symmetry.

- New $CP$ violating sources outside the realm of the SM are clearly needed to explain this discrepancy of eight orders of magnitude.

- They could manifest in EDMs of elementary particles
What do we know about EDMs?
What do we know about EDMs?

To measure EDMs one needs large electric fields. Charged particles are accelerated by electric fields.

![Graph showing EDM measurements for different particles and models](image-url)
What do we know about EDMs?

- no EDM observed yet, only limits
What do we know about EDMs?

- no EDM observed yet, only limits
- no measurement for deuteron (or heavier nuclei),
What do we know about EDMs?

- no EDM observed yet, only limits
- no measurement for deuteron (or heavier nuclei),
- no direct measurement for proton or electron
What do we know about EDMs?

- no EDM observed yet, only limits
- no measurement for deuteron (or heavier nuclei),
- no direct measurement for proton or electron
- Standard Model value essentially 0
What do we know about EDMs?

- no EDM observed yet, only limits
- no measurement for deuteron (or heavier nuclei),
- no direct measurement for proton or electron
- Standard Model value essentially 0
- Beyond SM values accessible by experiments
What do we know about EDMs?

- direct charged particle EDM measurements less precise
What do we know about EDMs?

- direct charged particle EDM measurements less precise
- To measure EDMs one needs large electric fields. Charged particles are accelerated by electric fields.
What do we know about EDMs?

**GOAL of JEDI (Jülich Electric Dipole Investigations) collaboration:**

** Charged Hadron EDM measurements**
- First measurement of deuteron, $^3$He EDM,
- first direct measurement of proton EDM
ultimately with a precision of $10^{-29}$ e cm
It is mandatory to measure EDM of many different particles to disentangle various sources of CP violation.
Sources of $CP$ violation

⇒ It is mandatory to measure EDM of many different particles to disentangle various sources of $CP$ violation.
EDM of neutral particles can be measured in small volumes (trap)

- applying an electric field on a charged particle accelerates the particles
  - ⇒ particle cannot be kept in small volume
  - ⇒ storage rings have to be operated to measure EDM of charged particles

- already done for muon (parallel to $g - 2$ measurement)
  \[ \mu : 0.1 \pm 0.9 \cdot 10^{-19} \text{e}\cdot\text{cm} \]
How to measure charged particle EDMs?
Measurement of charged particle EDMs

Generic Idea:

For all edm experiments (neutron, proton, atom, ...):

Interaction of $\vec{d}$ with electric field $\vec{E}$

For charged particles: apply electric field in a storage ring:

$$\frac{d\vec{s}}{dt} = \vec{E} \times \vec{d}$$

Wait for build-up of vertical polarization $s_\perp \propto |d|$, then determine $s_\perp$ using polarimeter

In general:

$$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s}$$
Spin Motion is governed by Thomas-BMT equation (Bargmann, Michel, Telegdi)

\[
\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s}
\]

\[
\vec{\Omega} = \frac{e\hbar}{mc} [G\vec{B} + \left( G - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E} + \frac{1}{2} \eta (\vec{E} + \vec{v} \times \vec{B})]
\]

\[
\vec{d} = \eta \frac{e\hbar}{2mc} \vec{S}, \quad \vec{\mu} = 2(G + 1) \frac{e\hbar}{2m} \vec{S}, \quad G = \frac{g - 2}{2},
\]

\( \vec{d} \): electric dipole moment

\( \vec{\mu} \): magnetic moment, \( g \):\(-\)factor , \( G \): anomalous magnetic moment

\( \gamma \): Lorentz factor

Thomas-BMT equation

\[ \tilde{\Omega} = \frac{e\hbar}{mc}[G\tilde{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\tilde{v} \times \tilde{E} + \frac{1}{2} \eta(\tilde{E} + \tilde{v} \times \tilde{B})] \]

Several Options (try to get rid terms \( \propto G \)):
Thomas-BMT equation

\[ \vec{\Omega} = \frac{e\hbar}{mc} [G\vec{B} + \left( G - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E} + \frac{1}{2} \eta (\vec{E} + \vec{v} \times \vec{B})] \]

Several Options (try to get rid terms \( \propto G \)):

1. Pure electric ring
   
   with \( \left( G - \frac{1}{\gamma^2 - 1} \right) = 0 \), works only for \( G > 0 \)
Thomas-BMT equation

\[ \vec{\Omega} = \frac{e\hbar}{mc} [G\vec{B} + \left( G - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E} + \frac{1}{2} \eta (\vec{E} + \vec{v} \times \vec{B})] \]

Several Options (try to get rid terms \( \propto G \)):

1. **Pure electric ring**
   
   with \( \left( G - \frac{1}{\gamma^2 - 1} \right) = 0 \), works only for \( G > 0 \)

2. **Combined \( \vec{E}/\vec{B} \) ring**
   
   \( G\vec{B} + \left( G - \frac{1}{\gamma^2 - 1} \right) \vec{v} \times \vec{E} = 0 \)
Thomas-BMT equation

\[ \tilde{\Omega} = \frac{e\hbar}{mc} [G\tilde{B} + \left( G - \frac{1}{\gamma^2 - 1} \right) \tilde{v} \times \tilde{E} + \frac{1}{2} \eta ( \tilde{E} + \tilde{v} \times \tilde{B})] \]

Several Options (try to get rid terms \( \propto G \)):

1. **Pure electric ring**
   
   with \( \left( G - \frac{1}{\gamma^2 - 1} \right) = 0 \), works only for \( G > 0 \)

2. **Combined \( \tilde{E}/\tilde{B} \) ring**
   
   \[ G\tilde{B} + \left( G - \frac{1}{\gamma^2 - 1} \right) \tilde{v} \times \tilde{E} = 0 \]

3. **Pure magnetic ring**
Required field strength

\[ G = \frac{g-2}{2} \quad p/\text{GeV}/c \quad E_R/\text{MV}/m \quad B_V/T \]

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>proton</td>
<td>1.79</td>
<td>0.701</td>
<td>10</td>
<td>0</td>
</tr>
<tr>
<td>deuteron</td>
<td>−0.14</td>
<td>1.0</td>
<td>−4</td>
<td>0.16</td>
</tr>
<tr>
<td>(^3\text{He})</td>
<td>−4.18</td>
<td>1.285</td>
<td>17</td>
<td>−0.05</td>
</tr>
</tbody>
</table>

Ring radius \(\approx 40\)m
Smaller ring size possible if \(B_V \neq 0\) for proton

\[ E = \frac{GBc\beta\gamma^2}{1 + G\beta^2\gamma^2} \]
Figure 3: An all-electric storage ring lattice for measuring the electric dipole moment of the proton. Except for having longer straight sections and separated beam channels, the all-in-one lattice of Fig. 1 is patterned after this lattice. Quadrupole and sextupole families, and tunes and lattice functions of the all-in-one lattice of Fig. 1 will be quite close to those given for this lattice in reference[3]. The match will be even closer with magnetic field set to zero for proton operation.
2. Combined $\vec{E}/\vec{B}$ ring

Figure 1: “All-In-One” lattice for measuring EDM’s of protons, deuterons, and helions.

Under discussion at Forschungszentrum Jülich (design: R. Talman)
3. Pure Magnetic Ring

Main advantage:
Experiment can be performed at the existing (upgraded) COSY (COoler SYnchrotron) in Jülich on a shorter time scale!

COSY provides (polarized) protons and deuterons with $p = 0.3 - 3.7\text{GeV/c}$ ⇒ Ideal starting point
3. Pure Magnetic Ring

\[ \tilde{\Omega} = \frac{e\hbar}{mc} \left( G\tilde{B} + \frac{1}{2} \eta \tilde{v} \times \tilde{B} \right) \]

Problem:
Due to precession caused by magnetic moment, 50% of time longitudinal polarization component is || to momentum, 50% of the time it is anti-||.

\[ \vec{E}^* = \vec{v} \times \vec{B} \]

\[ 50\% \, \dot{s}_d = \bigotimes \]

\[ 50\% \, \dot{s}_d = \bigotimes \]

\( E^* \) field in the particle rest frame tilts spin due to EDM up and down ⇒ no net EDM effect
3. Pure Magnetic Ring

\[ \tilde{\Omega} = \frac{e \hbar}{mc} \left( GB + \frac{1}{2} \eta \vec{v} \times \vec{B} \right) \]

Problem:
Due to precession caused by magnetic moment, 50% of time longitudinal polarization component is \( \parallel \) to momentum, 50% of the time it is anti-\( \parallel \).

\[ \vec{E}^* = \vec{v} \times \vec{B} \]

\( \vec{s} \rightarrow \vec{p} \)

\( > 50\% \ \dot{s}_d = \otimes \)

\( < 50\% \ \dot{s}_d = \circ \)

\( \Rightarrow \) no net EDM effect

\( E^* \) field in the particle rest frame tilts spin due to EDM up and down

Use resonant “magic Wien-Filter” in ring (\( \vec{E} + \vec{v} \times \vec{B} = 0 \)):

\( E^* = 0 \rightarrow \) part. trajectory is not affected but

\( B^* \neq 0 \rightarrow \) mag. mom. is influenced

\( \Rightarrow \) net EDM effect can be observed!
Horizontal spin motion $\propto G$ \hspace{1cm} vertical spin motion $s_\perp \propto d$
## Summary of different options

<table>
<thead>
<tr>
<th>Option</th>
<th>Description</th>
<th>Preference</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.) pure electric ring</td>
<td>no $\vec{B}$ field needed</td>
<td>works only for $p$</td>
</tr>
<tr>
<td>(BNL)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.) combined ring</td>
<td>works for $p$, $d$, $^3$He, ...</td>
<td>both $\vec{E}$ and $\vec{B}$ required</td>
</tr>
<tr>
<td>(Jülich)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.) pure magnetic ring</td>
<td>existing (upgraded) COSY ring can be used, shorter time scale</td>
<td>lower sensitivity</td>
</tr>
<tr>
<td>(Jülich)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Statistical Sensitivity (pure electric or combined ring)

\[ \sigma \approx \frac{\hbar}{\sqrt{N f T \tau_p PEA}} \]

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E)</td>
<td>electric field</td>
<td>10 MV/m</td>
</tr>
<tr>
<td>(P)</td>
<td>beam polarization</td>
<td>0.8</td>
</tr>
<tr>
<td>(A)</td>
<td>analyzing power</td>
<td>0.6</td>
</tr>
<tr>
<td>(N)</td>
<td>nb. of stored particles/cycle</td>
<td>(4 \times 10^{10})</td>
</tr>
<tr>
<td>(f)</td>
<td>detection efficiency</td>
<td>0.005</td>
</tr>
<tr>
<td>(\tau_p)</td>
<td>spin coherence time</td>
<td>1000 s</td>
</tr>
<tr>
<td>(T)</td>
<td>running time per year</td>
<td>(10^7) s</td>
</tr>
</tbody>
</table>

\[ \Rightarrow \sigma \approx 10^{-29} \text{e}\cdot\text{cm/year} \]

Expected signal \(\approx 3\text{nrad/s (for } d = 10^{-29} \text{e}\cdot\text{cm)}\)

(BNL proposal)
Statistical Sensitivity pure magnetic ring (COSY)

\[ \sigma \approx \frac{\hbar}{2} \frac{G \gamma^2}{G + 1} \frac{U}{E \cdot L} \frac{1}{\sqrt{NfT \tau_p PA}} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( G )</td>
<td>anomalous magnetic moment</td>
<td></td>
</tr>
<tr>
<td>( \gamma )</td>
<td>relativistic factor</td>
<td>1.13</td>
</tr>
<tr>
<td>( p )</td>
<td>=1GeV/c</td>
<td></td>
</tr>
<tr>
<td>( U )</td>
<td>circumference of COSY</td>
<td>180 m</td>
</tr>
<tr>
<td>( E \cdot L )</td>
<td>integrated electric field</td>
<td>0.1 ( \cdot 10^6 ) V</td>
</tr>
<tr>
<td>( N )</td>
<td>nb. of stored particles/cycle</td>
<td>2 ( \cdot 10^9 )</td>
</tr>
</tbody>
</table>

\[ \Rightarrow \sigma \approx 10^{-25} \text{e}\cdot\text{cm/year} \]
Electrostatic Deflectors

- Electrostatic deflectors from Fermilab (±125kV at 5 cm ≈ 5MV/m)
- large-grain Nb at plate separation of a few cm yields ≈ 20MV/m
Wien filter

Conventional design
R. Gebel, S. Mey (FZ Jülich)

stripline design
D. Hölscher, J. Slim
(IHF RWTH Aachen)
One major source:
Radial $B$ field mimics an EDM effect:

- Difficulty: even small radial magnetic field, $B_r$ can mimic EDM effect if $\mu B_r \approx dE_r$
- Suppose $d = 10^{-29} \text{e}\cdot\text{cm}$ in a field of $E = 10 \text{MV/m}$
- This corresponds to a magnetic field:
  \[
  B_r = \frac{dE_r}{\mu N} = \frac{10^{-22} \text{eV}}{3.1 \cdot 10^{-8} \text{eV/T}} \approx 3 \cdot 10^{-17} \text{T}
  \]
  (Earth Magnetic field $\approx 5 \cdot 10^{-5} \text{T}$)

Solution: Use two beams running clockwise and counter clockwise, separation of the two beams is sensitive to $B_r$
First test measurements: Spin Coherence Time (SCT), spin tune
Spin tune & Spin Coherence Time

Spin tune: $\nu = \gamma G$, number of spin revolution with respect to the momentum vector per particle turn

For $p_d = 1 \text{ GeV}/c$ ($\gamma = 1.13$), $G = -0.14256177(72)$

$\Rightarrow \nu = \gamma G = -0.161$

$\nu$ can be determined by measuring the horizontal polarization of beam. **If spins do not decohere.**

Problem: spin tune depends on $\gamma \Rightarrow$ momentum spread $\Delta p/p$ leads to decoherence.
Polarimeter

Principle: Particles hit a target:
Left/Right asymmetry gives information on vertical polarization
Up/Down asymmetry gives information on horizontal polarization
Polarimeter

Cross Section &
Analyzing Power
for deuterons

\[ N_{up,dn} \propto (1 \pm P A \sin(\gamma G_{frev} t)) \]

\[ A_{up,dn} = \frac{N_{up} - N_{dn}}{N_{up} + N_{dn}} = P A \sin(\gamma G_{frev} t) \]

\( A \) : analyzing power
\( P \) : beam polarization

Asymmetry Measurements

Detector signal $N^{up, dn} \propto (1 \pm P \ A \ \sin(\gamma G_{rev} t))$

$$A_{up, dn} = \frac{N^{up} - N^{dn}}{N^{up} + N^{dn}} = P \ A \ \sin(\gamma G_{rev} t)$$

$A$: analyzing power, $P$: polarization

$A_{up, dn} = 0$  

$A_{up, dn} = PA$
Spin Coherence Time (SCT)

**Short Spin Coherence Time**

Cooled bunched beam $\Rightarrow$ SCT = 20s
Spin Coherence Time (SCT)

**Large Spin Coherence Time**

\[ \vec{s} = \vec{p} \]

Horizontal Asymmetry Run: 2051

\[ \chi^2 / \text{ndf} = 93.9 / 90 \]

Amplitude: \[ 0.2667 \pm 0.0016 \]

\[ \frac{1}{\text{SCT}} = 0.002628 \pm 0.000149 \]

using correction sextupole to correct for higher order effects leads to SCT of 400s
Spin Tune $\nu$

- Problem: detector rate $\approx 5$ kHz, $f_{rev} = 781$ kHz
  $\Rightarrow$ only 1 hit every 25th period
- not possible to use usual $\chi^2$-fit
- use unbinned Maximum Likelihood (under investigation)
Spin Tune $\nu$

- Map all events in the first period ($T = 1/(\nu f_{rev}) \approx 8\mu s$) and perform $\chi^2$-fit
  (requires knowledge of $\nu f_{rev}$)
- Do fit for fixed frequency $\nu f_{rev}$ and retain phase
- Analysis is done in macroscopic time bins of $\approx 2s$

![Graph showing event distribution over time with peaks at 0.1 and 0.2 seconds]
Phase Measurements

Phase [Run: 2328  Cycle: 3]

1st derivative gives deviation from assumed spin tune

\[ \begin{align*}
\chi^2 / \text{ndf} & : 40.75 / 40 \\
p0 & : 0.9093 \pm 0.0571 \\
p1 & : 0.1809 \pm 0.0032 \\
p2 & : -0.001683 \pm 0.000035
\end{align*} \]
Spin tune measurements

<table>
<thead>
<tr>
<th>time [s]</th>
<th>SpinTune</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.16097610</td>
</tr>
<tr>
<td>10</td>
<td>0.16097612</td>
</tr>
<tr>
<td>20</td>
<td>0.16097614</td>
</tr>
<tr>
<td>30</td>
<td>0.16097616</td>
</tr>
<tr>
<td>40</td>
<td>0.16097618</td>
</tr>
<tr>
<td>50</td>
<td>0.16097620</td>
</tr>
<tr>
<td>60</td>
<td>0.16097622</td>
</tr>
<tr>
<td>70</td>
<td>0.16097624</td>
</tr>
<tr>
<td>80</td>
<td>0.16097626</td>
</tr>
<tr>
<td>90</td>
<td>0.16097628</td>
</tr>
</tbody>
</table>

Spintune [Run: 2328  Cycle: 3]

Spin tune $\gamma G$ can be determined to $\approx 10^{-8}$ in a 2 second measurement.

Average Spin tune in cycle ($\approx 100$ s) known to $10^{-10}$
Spin tune measurements
Spintune [Run: 2328  Cycle: 3]

- Spin tune $\gamma G$ can be determined to $\approx 10^{-8}$ in a 2 second measurement
- Average Spin tune in cycle ($\approx 100$ s) known to $10^{-10}$

We started to do precision physics!
Summary & Outlook
JEDI Collaboration

- **JEDI** = Jülich Electric Dipole Moment Investigations
- ≈ 100 members
  (Aachen, Dubna, Ferrara, Ithaca, Jülich, Krakow, Michigan, St. Petersburg, Minsk, Novosibirsk, Stockholm, Tbilisi, ...)
- ≈ 10 PhD students
Storage Ring EDM Efforts

Common R&D work
- Spin Coherence Time
- Beam position monitors (BPMs)
- Spin Tracking
- Polarimetry
- ...

BNL
- all electric ring (p)

Jülich
- first direct measurement with upgraded COSY
- all-in-one ring (p,d,³He)
Summary

- EDM of charged particles can be measured in storage rings.
- EDMs of elementary particles are of high interest to disentangle various sources of $CP$ violation searched for to explain matter - antimatter asymmetry in the Universe.
- Experimentally very challenging because effect is tiny.
- Efforts in Jülich and in the US to perform such measurements.
- First measurements on spin coherence time in spin tune.
Spare
Spin tune measurements

Number of spin turns against particle turns

Slope equals $\nu = \gamma G$
Spin tune measurements

- We are sensitive to spin tune changes of the order of $10^{-9}$ in a single cycle ($\approx 100s$)
- reason for varying spin tune is still under investigation
- powerful to keep spin aligned with momentum vector (vital for frozen spin method)