Charged Particle Electric Dipole Moment Searches in Storage Rings

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for the JEDI collaboration

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Outline

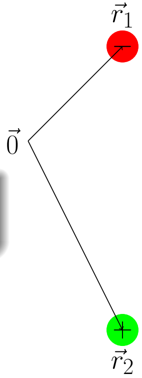
- **Introduction: Electric Dipole Moments (EDMs):**
  What is it?
  Why is it interesting?
  What do we know about EDMs?
- **Experimental Method:**
  How to measure charged particle EDMs?
- **Results of first test measurements:**
  Spin Coherence time and Spin tune

What is it?

Electric Dipoles

Classical definition:

$$\vec{d} = \sum_i q_i \vec{r}_i$$



Order of magnitude

	atomic physics	**hadron physics**
charges	e	
$\lvert\vec{r}_1 - \vec{r}_2\rvert$	1 Å= 10^{-8}cm	
EDM		
naive expectation	$10^{-8} e \cdot \mathrm{cm}$	
observed	water molecule	
	$2 \cdot 10^{-8} e\cdot$ cm	

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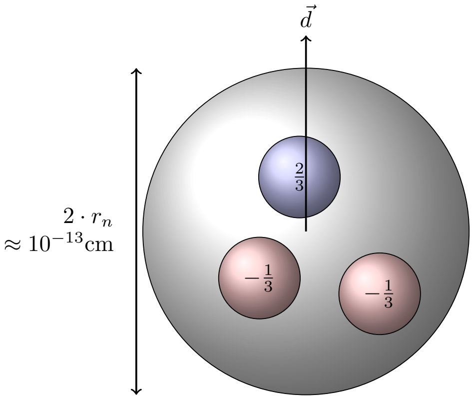
charges	e	e
$\lvert\vec{r}_1 - \vec{r}_2\rvert$	1 Å$= 10^{-8}$cm	$1\mathrm{fm} = 10^{-13}$cm
EDM		
naive expectation	$10^{-8} e \cdot \mathrm{cm}$	$10^{-13} e \cdot \mathrm{cm}$
observed	water molecule	neutron
	$2 \cdot 10^{-8} e\cdot$ cm	$< 3 \cdot 10^{-26} e\cdot$ cm

Neutron EDM



neutron EDM of $d_n = 3 \cdot 10^{-26} e{\cdot}$cm corresponds to separation of $u-$ from $d-$quarks of $\approx 5 \cdot 10^{-26}$cm

Operator $\vec{d} = q\vec{r}$

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

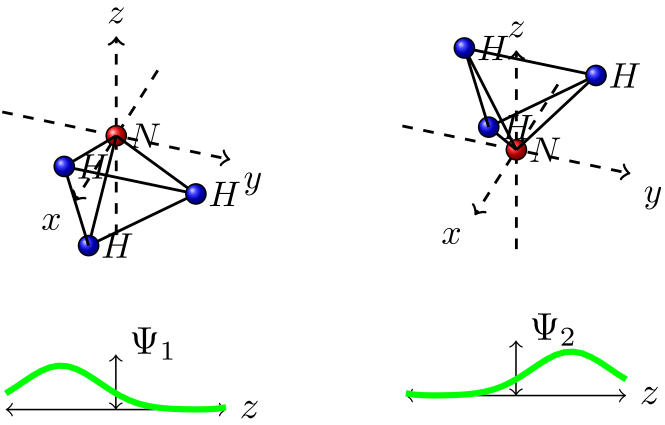
$$\mathcal{P}^{-1}\vec{d}\mathcal{P} = -\vec{d}$$

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

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

but if $|a\rangle = \alpha|P = +\rangle + \beta|P = -\rangle$
in general $\left\langle a|\vec{d}|a\right\rangle \neq 0 \Rightarrow$ i.e. molecules

EDM of molecules



ground state: mixture of

$$\Psi_s = \frac{1}{\sqrt{2}}(\Psi_1 + \Psi_2)\,, \quad P = +$$

$$\Psi_a = \frac{1}{\sqrt{2}}(\Psi_1 - \Psi_2)\,, \quad P = -$$

EDMs & symmetry breaking

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

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

EDMs & symmetry breaking

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

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

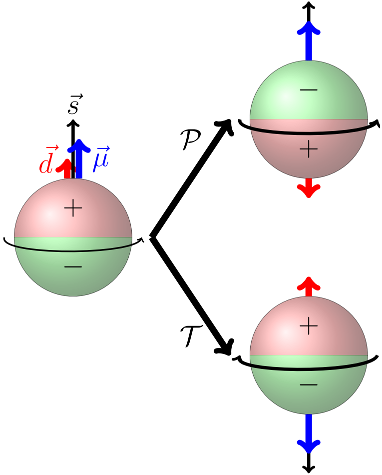
unless

$\mathcal{P}$ and time reversal $\mathcal{T}$ invariance are violated!

$\mathcal{T}$ and $\mathcal{P}$ violation of EDM

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

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



⇒ EDM measurement tests violation of fundamental symmetries $\mathcal{P}$ and $\mathcal{T}(\stackrel{\mathcal{CPT}}{=} \mathcal{CP})$

Symmetry (Violations) in Standard Model

	electro-mag.	weak	strong
$\mathcal{C}$	✓	↯	✓
$\mathcal{P}$	✓	↯	(✓)
$\mathcal{T} \overset{CPT}{\rightarrow} \mathcal{CP}$	✓	(↯)	(✓)

- $\mathcal{C}$ and $\mathcal{P}$ are maximally violated in weak interactions (Lee, Yang, Wu)
- $\mathcal{CP}$ violation discovered in kaon decays (Cronin,Fitch) described by CKM-matrix in Standard Model
- $\mathcal{CP}$ violation allowed in strong interaction but corresponding parameter $\theta_{QCD} \lessapprox 10^{-10}$ (strong $\mathcal{CP}$-problem)

Sources of $\mathcal{CP}-$Violation

Standard Model	
Weak interaction	
CKM matrix	$\rightarrow$ unobservably small EDMs
Strong interaction	
θ_{QCD}	$\rightarrow$ best limit from neutron EDM
beyond Standard Model	
e.g. SUSY	$\rightarrow$ accessible by EDM measurements

Why is it interesting?

Matter-Antimatter Asymmetry

Excess of matter in the universe:

	observed	SM prediction
$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$	$\mathbf{6 \times 10^{-10}}$	$\mathbf{10^{-18}}$

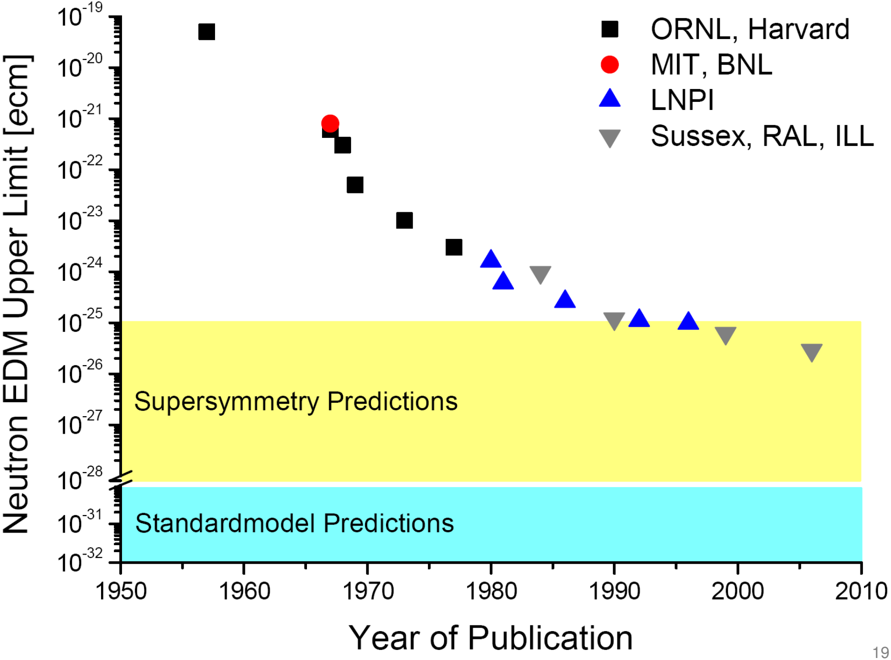
Sakharov (1967): $\mathcal{CP}$ violation needed for baryogenesis

$\Rightarrow$ New $\mathcal{CP}$ violating sources beyond SM needed to explain this discrepancy

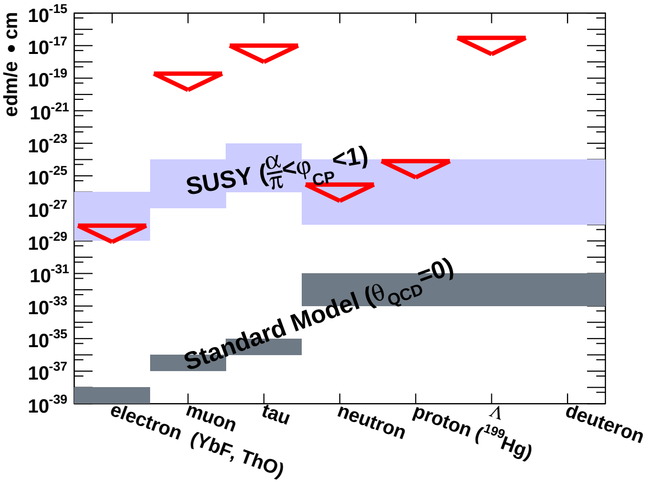
They could manifest in EDMs of elementary particles

What do we know about EDMs?

History of Neutron EDM



EDM: Current Upper Limits



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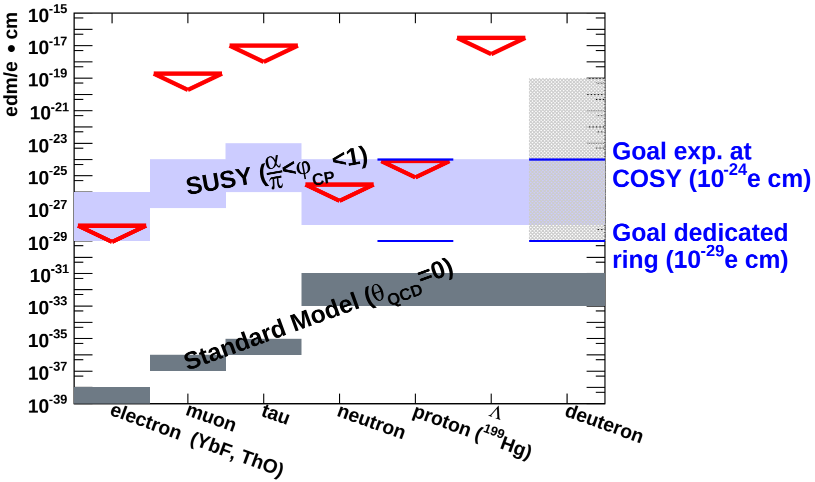
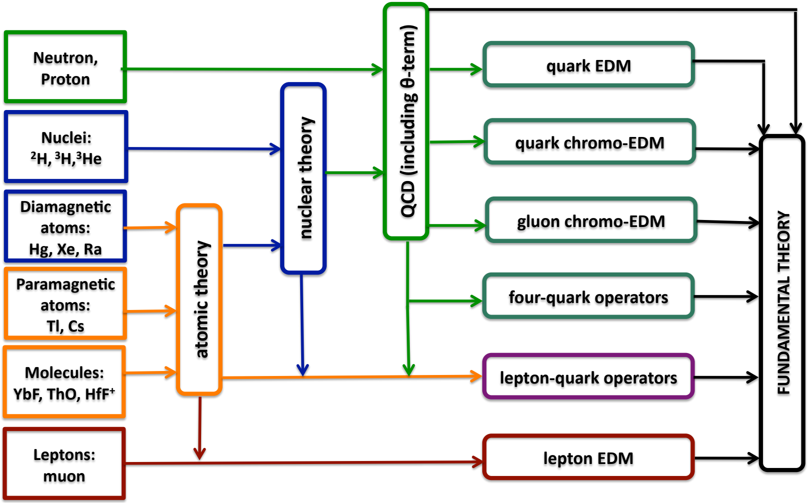


FZ Jülich: EDMs of **charged** hadrons: *p*, *d*, ^{3}He

Why Charged Particle EDMs?

- no direct measurements for charged hadrons exist
- potentially higher sensitivity (compared to neutrons):
  - longer life time,
  - more stored protons/deuterons
- complementary to neutron EDM:
  $d_d \stackrel{?}{=} d_p + d_n \Rightarrow$ access to θ_{QCD}
- EDM of one particle alone not sufficient to identify $\mathcal{CP}-$violating source

Sources of $\mathcal{CP}$ Violation

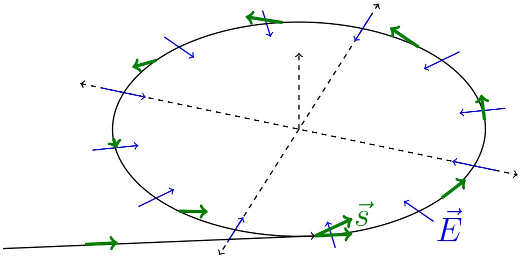


J. de Vries

How to measure charged particle EDMs?

Experimental Method: Generic Idea

For **all** EDM experiments (neutron, proton, atoms, . . .):
  Interaction of $\vec{d}$ with electric field $\vec{E}$
For charged particles: apply electric field in a storage ring:



$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} \propto d\vec{E} \times \vec{s}$$

In general:

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\Omega} \times \vec{s}$$

build-up of vertical polarization $s_\perp \propto |d|$

Experimental Requirements

- high precision storage ring
  (alignment, stability, field homogeneity)
- high intensity beams ($N = 4 \cdot 10^{10}$ per fill)
- polarized hadron beams ($P = 0.8$)
- large electric fields ($E = 10\,\text{MV/m}$)
- long spin coherence time ($\tau = 1000\,\text{s}$),
- polarimetry (analyzing power $A = 0.6$, acc. $f = 0.005$)

$$\sigma_{\text{stat}} \approx \frac{1}{\sqrt{Nf\tau}PAE} \quad \Rightarrow \sigma_{\text{stat}}(1\text{year}) = 10^{-29}\, e\cdot\text{cm}$$

challenge: get σ_{sys} to the same level

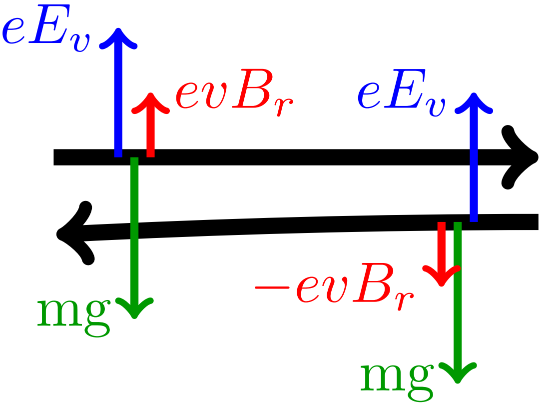
Systematics

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 $d = 10^{-29} e{\cdot}\text{cm}$ in a field of $E_r = 10\text{MV/m}$
- This corresponds to a magnetic field:
  $$B_r = \frac{dE_r}{\mu_N} = \frac{10^{-22} e\mathrm{V}}{3.1 \cdot 10^{-8} e\mathrm{V}/\mathrm{T}} \approx 3 \cdot 10^{-17}\mathrm{T}$$

Solution: Use two beams running clockwise and counter clockwise, separation of the two beams is sensitive to B_r

Systematics



Sensitivity needed: 1.25 fT/$\sqrt{\text{Hz}}$ for $d = 10^{-29}$ e cm
(possible with SQUID technology)

Spin Precession: Thomas-BMT Equation

$$\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\Omega} \times \vec{s} = \frac{e}{m}\left[G\vec{B} + \left(G - \frac{1}{\gamma^2-1}\right)\vec{v} \times \vec{E} + \frac{m}{e\,s} d(\vec{E} + \vec{v} \times \vec{B})\right] \times \vec{s}$$

Ω: angular precession frequency

G: anomalous magnetic moment

d: electric dipole moment

γ: Lorentz factor

BMT: Bargmann, Michel, Telegdi

Spin Precession: Thomas-BMT Equation

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dedicated ring: pure electric field,

freeze horizontal spin motion $\left(G - \frac{1}{\gamma^2 - 1}\right) = 0$

Spin Precession: Thomas-BMT Equation

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COSY: pure magnetic ring
access to EDM via motional electric field $\vec{v} \times \vec{B}$,
requires additional radio-frequency E and B fields
to suppress $G\vec{B}$ contribution

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COSY: pure magnetic ring
access to EDM via motional electric field $\vec{v} \times \vec{B}$,
requires additional radio-frequency E and B fields
to suppress $G\vec{B}$ contribution

neglecting EDM term

spin tune: $\nu_s \approx \frac{|\vec{\Omega}|}{|\omega_{\mathrm{cyc}}|} = \gamma G$, $\quad (\vec{\omega}_{cyc} = \frac{e}{\gamma m}\vec{B})$

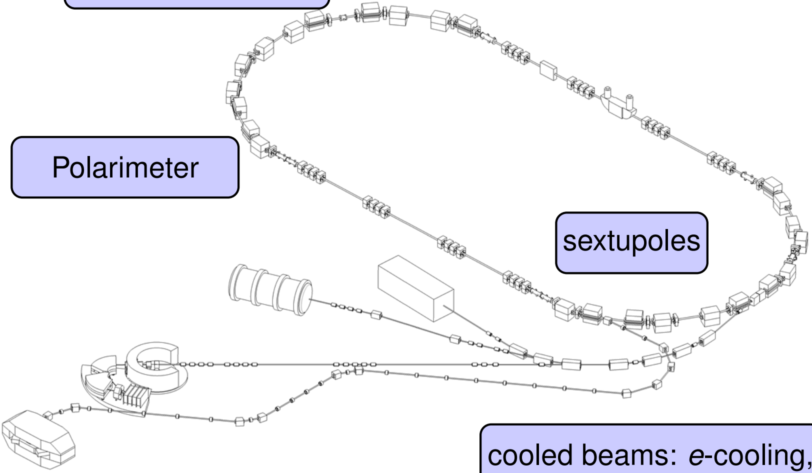
Results of first test measurements

Cooler Synchrotron COSY

COSY provides (polarized) protons and deuterons with
$p = 0.3 - 3.7\text{GeV}/c$

$\Rightarrow$ **Ideal starting point for charged particle EDM searches**

COSY



RF $E \times B$ dipole

RF solenoid

Polarimeter

sextupoles

cooled beams: e-cooling, stochastic cooling

Polarized proton & deuterons

R & D at COSY

- maximize spin coherence time (SCT)
- precise measurement of spin precession (spin tune)
- rf- Wien filter design and construction
- tests of electro static deflectors (goal: field strength > 10 MV/m)
- development of high precision beam position monitors
- polarimeter development
- spin tracking simulation tools

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E. Stephenson:	Deuteron polarimeter developments for a storage ring EDM search
I. Keshelashvili:	Towards EDM Polarimetry
N. Hempelman:	FPGA-Based Upgrade of the Read-Out Electronics for the Low Energy Polarimeter at COSY/Jülich

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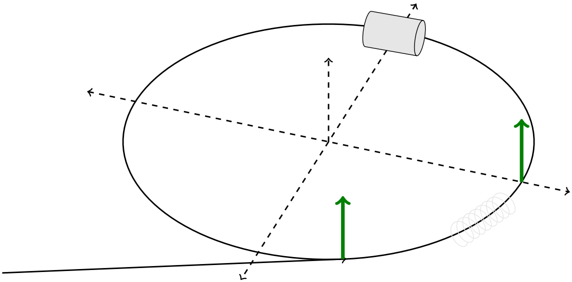
S. Mey:	Spin Manipulation with an RF Wien-Filter at COSY
J. Slim:	Towards a High-Accuracy RF Wien Filter for Spin Manipulation at COSY Jülich

Experimental Setup

- Inject and accelerate vertically polarized deuterons to $p \approx 1$ GeV/c



Experimental Setup

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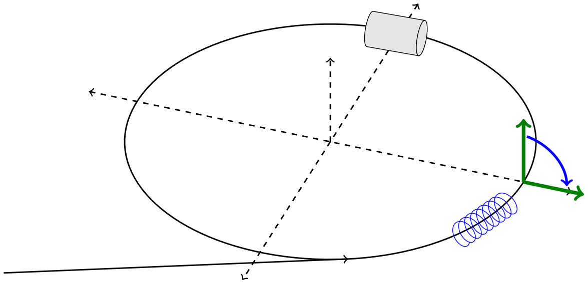
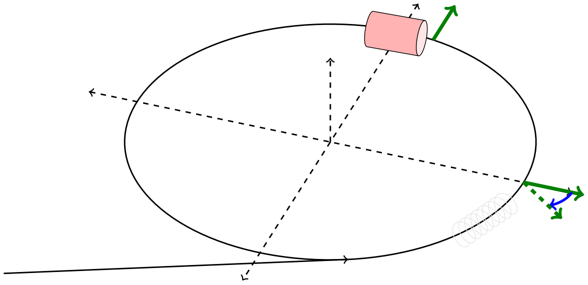
- flip spin with help of solenoid into horizontal plane



Experimental Setup

- Inject and accelerate vertically polarized deuterons to $p \approx 1$ GeV/c
- flip spin with help of solenoid into horizontal plane
- Extract beam slowly (in 100 s) on target
- Measure asymmetry and determine spin precession



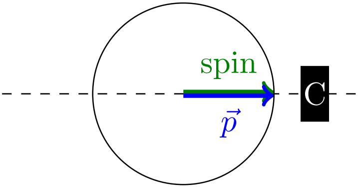
Asymmetry Measurements

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

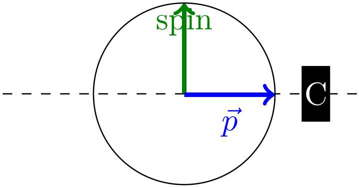
  $$A_{up,dn} = \frac{N^{up} - N^{dn}}{N^{up} + N^{dn}} = P\,A\,\sin(\gamma G \omega_{rev} t)$$

  A: analyzing power, P : polarization

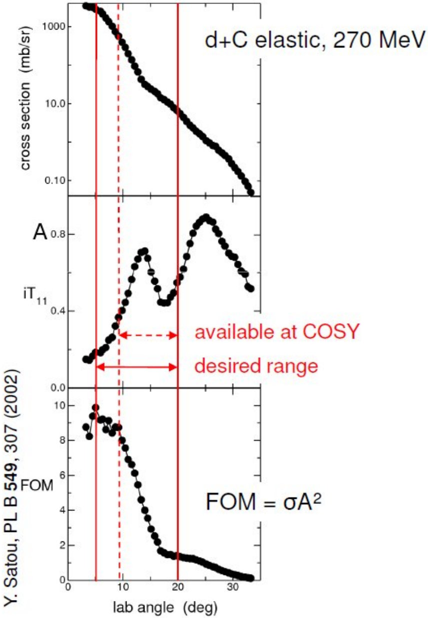
$A_{up,dn} = 0$



$A_{up,dn} = PA$



Polarimetry



Cross Section &
Analyzing Power
for deuterons

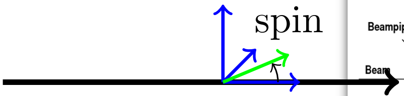
$N_{up,dn} \propto$
$(1 \pm P\,A\,\sin(\nu_s \omega_{rev} t))$

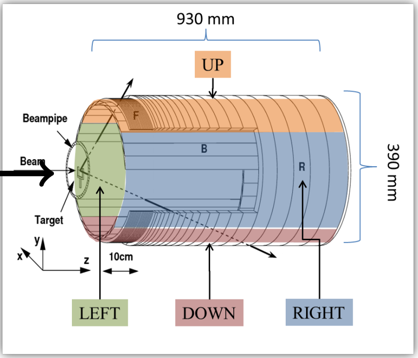
$$A_{up,dn} = \frac{N^{up} - N^{dn}}{N^{up} + N^{dn}}$$
$$= P\,A\,\sin(\nu_s \omega_{rev} t)$$

A : analyzing power
P : beam polarization

Polarimeter

elastic deuteron-carbon scattering
Up/Down asymmetry $\propto$ horizontal polarization $\rightarrow \nu_s = \gamma G$
Left/Right asymmetry $\propto$ vertical polarization $\rightarrow d$





$$N_{up,dn} \propto 1 \pm PA\sin(\nu_s \omega_{rev} t), \quad f_{rev} \approx 750\,\text{kHz}$$

Up - dn asymmetry $A_{up,dn}$

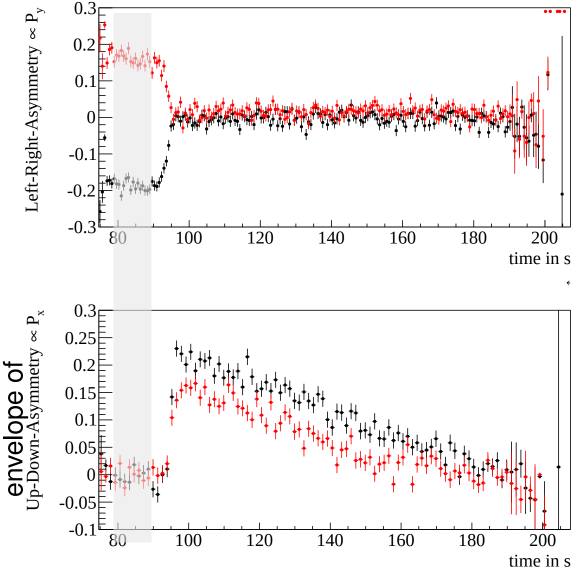
$$A_{up,dn}(t) \quad = \quad AP_0 e^{-t/\tau} \sin(\nu_s \omega_{rev} t + \varphi)$$

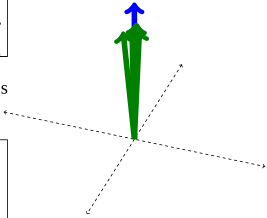
- $\tau \rightarrow$ spin decoherence
- $\nu_s \rightarrow$ spin tune

time scales: $\nu_s f_{rev} \approx$ 120 kHz

τ in the range 1-1000 s

Polarization Flip





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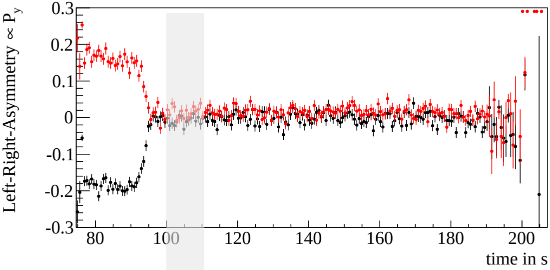

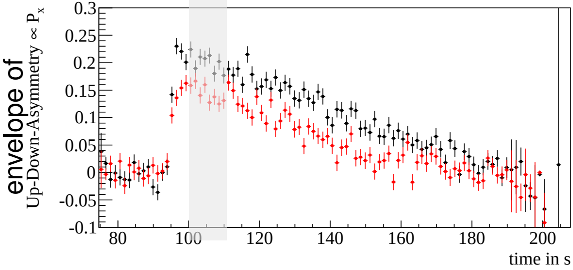

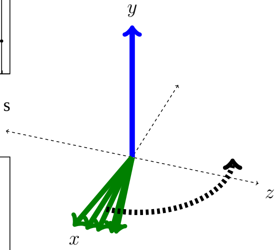

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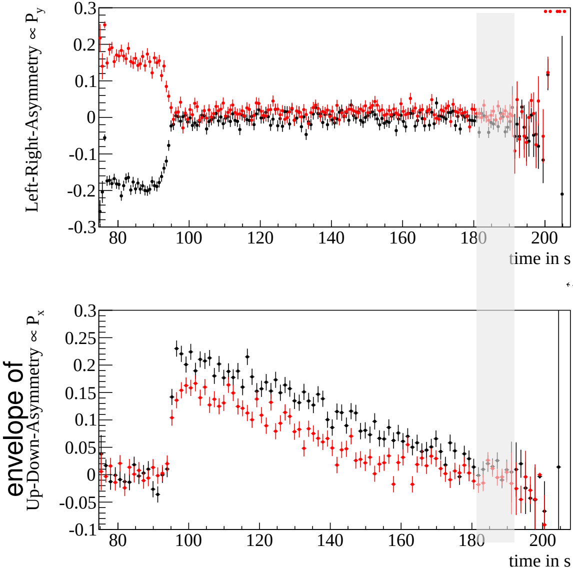
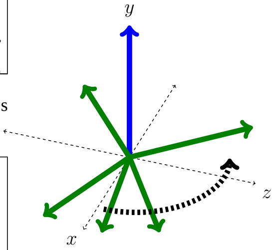
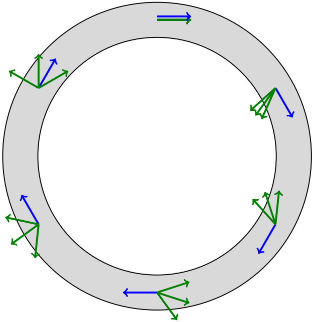
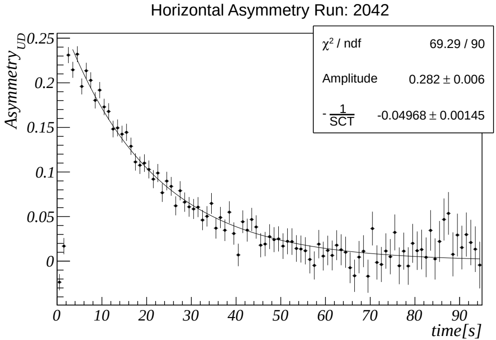




Results: Spin Coherence Time (SCT)

Short Spin Coherence Time





unbunched beam

$\Delta p/p = 10^{-5} \Rightarrow \Delta\gamma/\gamma = 2 \cdot 10^{-6}$, $T_{rev} \approx 10^{-6}$ s

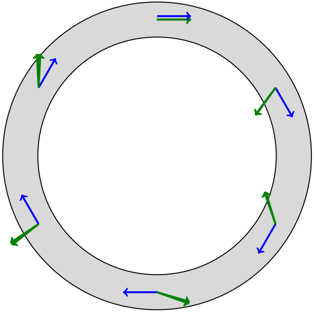
$\Rightarrow$ decoherence after < 1 s

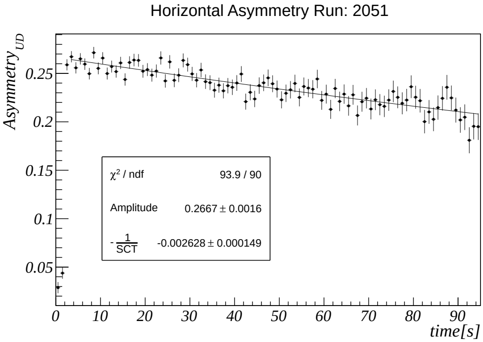
bunched beam eliminates 1st order effects in $\Delta p/p$

$\Rightarrow$ SCT τ = 20 s

Results: Spin Coherence Time (SCT)

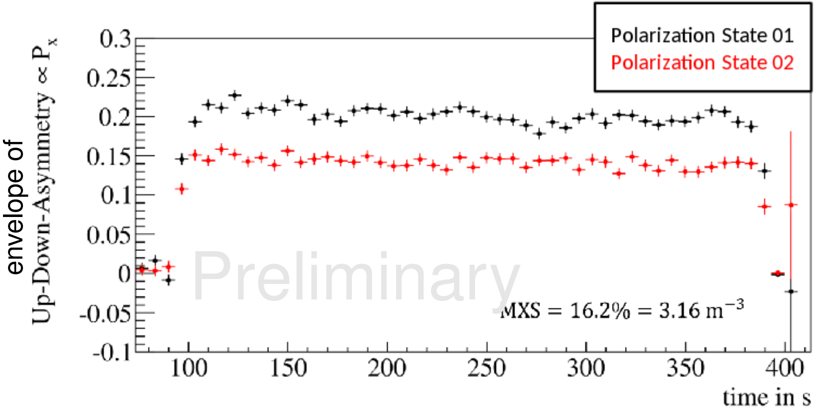
Long Spin Coherence Time





SCT of τ =400 s, after correction with sextupoles (chromaticities $\xi \approx 0$)

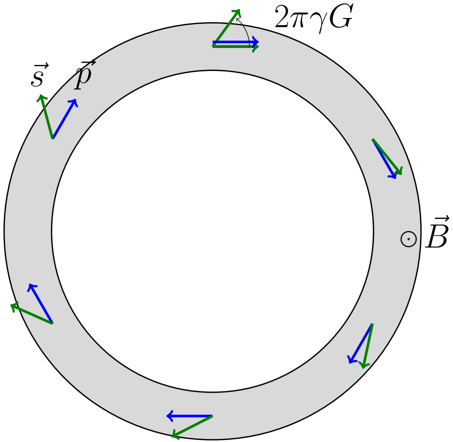
Longer cycle



(data taken a few weeks ago)

Spin Tune ν_s

Spin tune: $\nu_s = \gamma G = \dfrac{\text{nb. of spin rotations}}{\text{nb. of particle revolutions}}$



deuterons: $p_d = 1$ GeV/c ($\gamma = 1.13$), $G = -0.14256177(72)$

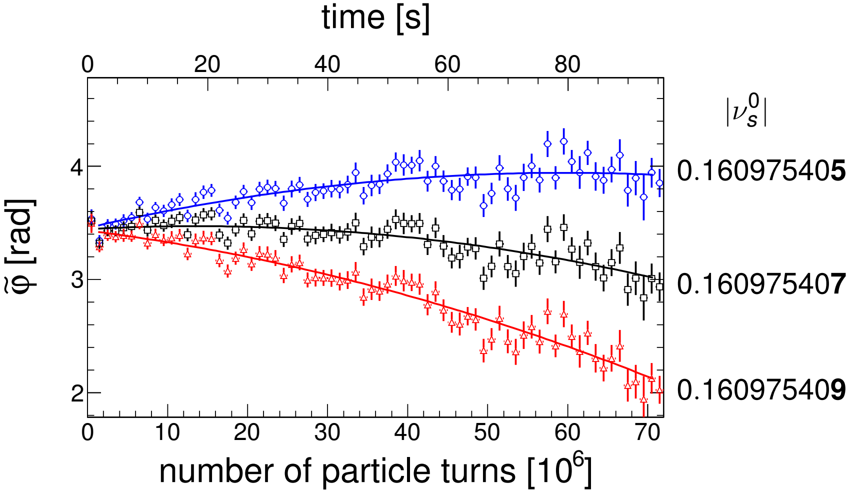
$\Rightarrow \nu_s = \gamma G \approx -0.161$

Up - dn asymmetry $A_{up,dn}$

Long SCT τ allows now to observe $\nu_s(t) \approx \gamma G$, respectively $\varphi(t)$

$$
\begin{aligned}
A_{up,dn}(t) &= AP_0 e^{-t/\tau} \sin(\nu_s(t)\omega_{rev} t + \varphi) \\
&= AP_0 e^{-t/\tau} \sin(\nu_s^0 \omega_{rev} t + \varphi(t))
\end{aligned}
$$

Phase vs. turn number



$$|\nu_s(t)| = |\nu_s^0| + \frac{1}{\omega_{rev}} \frac{\mathrm{d}\tilde{\varphi}}{\mathrm{d}t}$$

$$\Rightarrow |\nu_s(38\,\mathrm{s})| = (16\,097\,540\,628.3 \pm 9.7) \times 10^{-11}$$

Editors' Suggestion

New Method for a Continuous Determination of the Spin Tune in Storage Rings and Implications for Precision Experiments

D. Eversmann *et al.* (JEDI collaboration)

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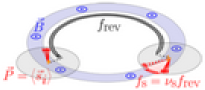


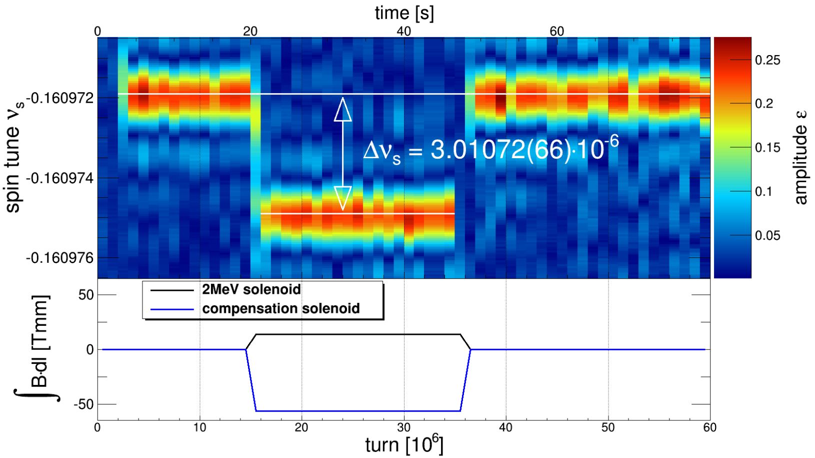
The spin precession frequency of a charged particle in a stora
ring is determined with substantially increased precision. This
allows for improved measurements of the electric dipole
moments of charged particles.

Show Abstract +

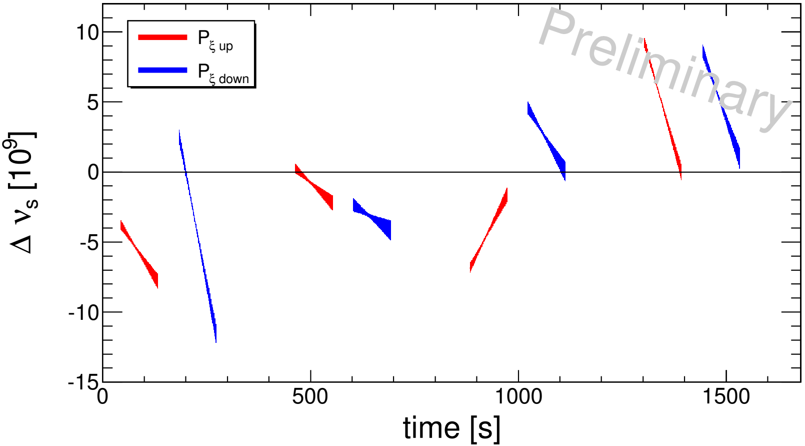
Spin Tune Measurement

- precision of spin tune measurement 10^{-10} in one cycle (most precise spin tune measurement)
- Compare to muon $g-2$: $\sigma_{\nu_s} \approx 3 \cdot 10^{-8}$ per year
  main difference: measurement duration 600μs compared to 100 s
- spin rotation due to electric dipole moment:
  $\nu_s = \frac{vm\gamma d}{es} = 5 \cdot 10^{-11}$ for $d = 10^{-24} e\,\mathrm{cm}$
  (in addition rotations due to G and imperfections)
- spin tune measurement can now be used as tool to investigate systematic errors

Spin Tune jumps



Spin Tune for different cycles



$\Delta\nu_s = 10^{-8} \rightarrow \Delta p/p \approx 10^{-7}$

JEDI Collaboration

- **JEDI** = **J**ülich **E**lectric **D**ipole Moment **I**nvestigations
- $\approx$ 100 members
  (Aachen, Bonn, Daejeon, Dubna, Ferrara, Grenoble, Indiana, Ithaca, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St. Petersburg, Stockholm, Tbilisi, . . .)
- $\approx$ 10 PhD students
- close collaboration with srEDM collaboration in US/Korea

http://collaborations.fz-juelich.de/ikp/jedi/index.shtml

Summary & Outlook

- **EDMs** of elementary particles are of high interest to disentangle various sources of $\mathcal{CP}$ **violation** searched for to explain **matter - antimatter asymmetry** in the Universe
- EDM of **charged** particles can be measured in **storage rings**
- Experimentally very challenging because effect is tiny
- First promising results from test measurements at COSY:

spin coherence time:	few hundred seconds
spin tune:	10^{-10} in 100 s