Electric Dipole Moment Measurements at Storage Rings

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Outline

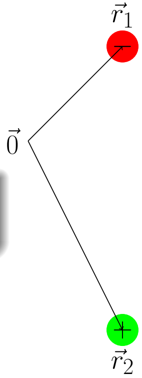
- **Introduction: Electric Dipole Moments (EDMs):**
  What is it?
  Why is it interesting?
  What do we know about EDMs?
- **Experimental Method:**
  How to measure charged particle EDMs?
- **Results of first test measurements:**
  Spin Coherence time and Spin tune

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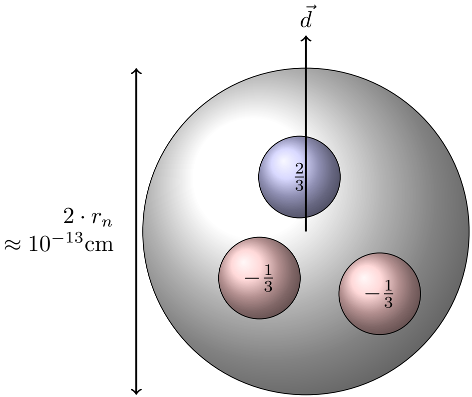
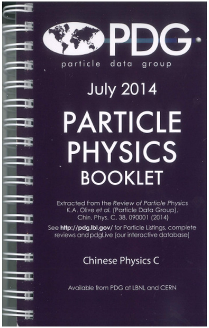
charges	e	e
$\|\vec{r}_1 - \vec{r}_2\|$	1 Å= 10^{-8}cm	$1\mathrm{fm} = 10^{-13}$cm
EDM		
naive expectation	$10^{-8} e \cdot \mathrm{cm}$	$10^{-13} e \cdot \mathrm{cm}$
observed	water molecule	neutron
	$2 \cdot 10^{-8} e\cdot$ cm	$< 3 \cdot 10^{-26} e\cdot$ cm

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



n

$$I(J^P) = \tfrac{1}{2}(\tfrac{1}{2}^+)$$

Mass $m = 1.0086649160 \pm 0.0000000004$ u
Mass $m = 939.565379 \pm 0.000021$ MeV [a]
$(m_n - m_{\overline{n}})/\ m_n = (9 \pm 6) \times 10^{-5}$
$m_n - m_p = 1.2933322 \pm 0.0000004$ MeV
$= 0.00138844919(45)$ u
Mean life $\tau = 880.3 \pm 1.1$ s $\quad$ (S = 1.9)
$c\tau = 2.6391 \times 10^8$ km
Magnetic moment $\mu = -1.9130427 \pm 0.0000005\ \mu_N$
Electric dipole moment $d < 0.29 \times 10^{-25}$ $e$cm, CL = 90%
Mean-square charge radius $\langle r_n^2 \rangle = -0.1161 \pm 0.0022$ fm^2 $\quad$ (S = 1.3)
Magnetic radius $\sqrt{\langle r_M^2 \rangle} = 0.862^{+0.009}_{-0.008}$ fm
Electric polarizability $\alpha = (11.6 \pm 1.5) \times 10^{-4}$ fm^3
Magnetic polarizability $\beta = (3.7 \pm 2.0) \times 10^{-4}$ fm^3
Charge $q = (-0.2 \pm 0.8) \times 10^{-21}$ e
Mean $n\overline{n}$-oscillation time $> 8.6 \times 10^7$ s, CL = 90% (free n)
Mean $n\overline{n}$-oscillation time $> 1.3 \times 10^8$ s, CL = 90% [f] (bound n)
Mean nn'-oscillation time > 414 s, CL = 90% [g]

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

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

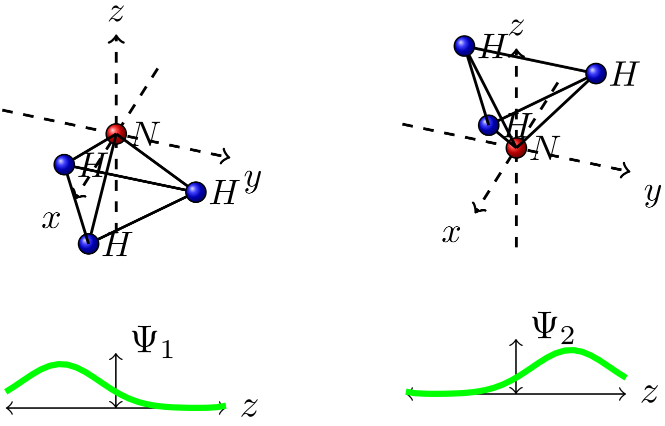
$$\mathcal{P}^{-1}\vec{d}\mathcal{P} = -\vec{d}$$

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

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

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

Order of magnitude

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
$P|\text{had}>= \pm 1|\text{had}>$

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

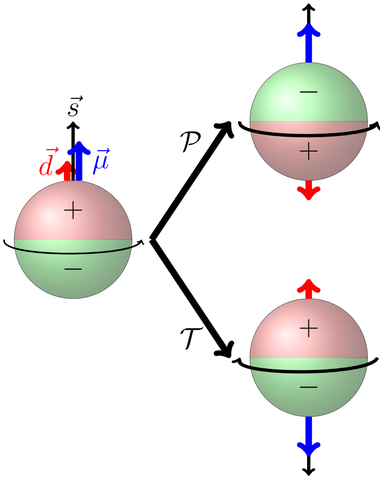
unless

$\mathcal{P}$ 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

$$
\begin{array}{rrcl}
 & H & = & -\mu\vec{\sigma}\cdot\vec{B} - d\vec{\sigma}\cdot\vec{E} \\
\mathcal{T}: & H & = & -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E} \\
\mathcal{P}: & H & = & -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}
\end{array}
$$



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

Symmetry (Violations) in Standard Model

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

- $\mathcal{C}$ 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
$\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma}$	$\mathbf{6 \times 10^{-10}}$	$\mathbf{10^{-18}}$

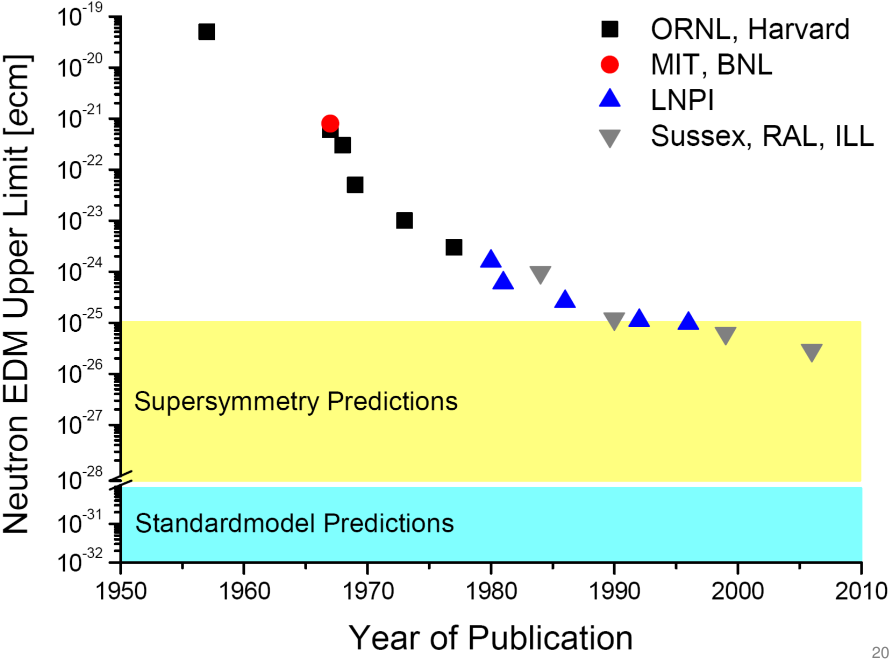
Sakharov (1967): $\mathcal{CP}$ violation needed for baryogenesis

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

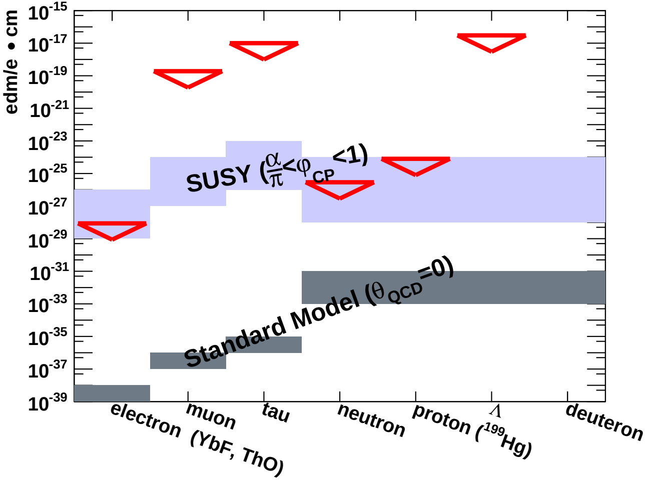
They could manifest in EDMs of elementary particles

What do we know about EDMs?

History of Neutron EDM



EDM: Current Upper Limits



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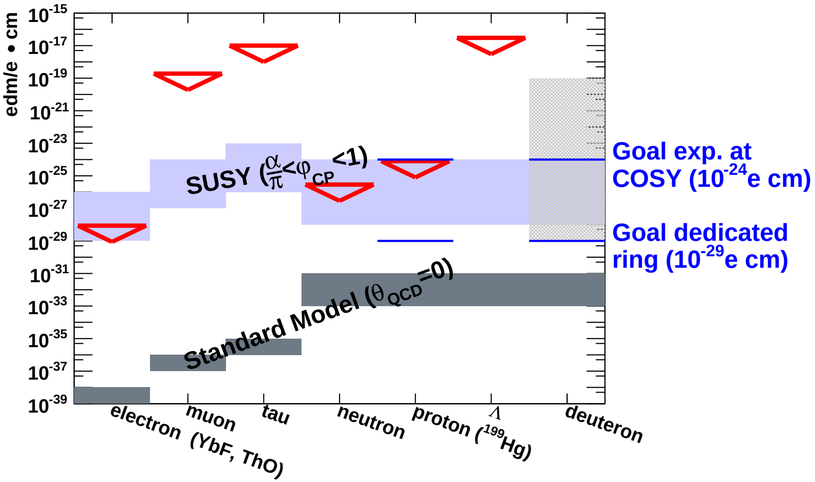
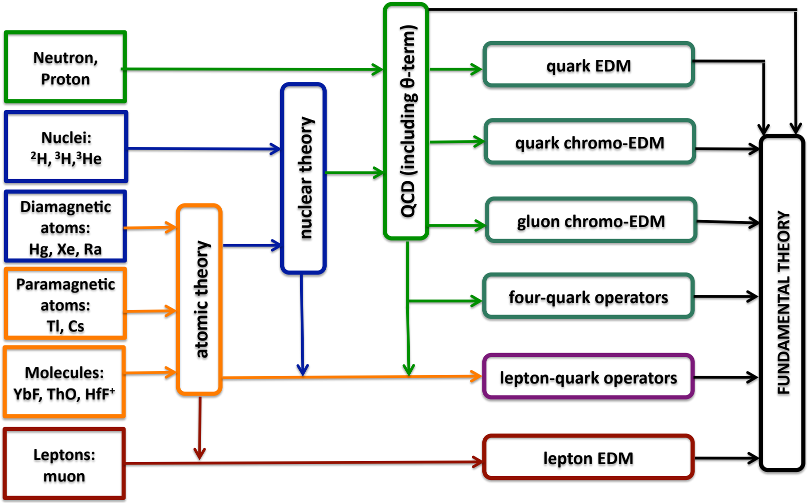


FZ Jülich: EDMs of **charged** hadrons: p, d, ^{3}He

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

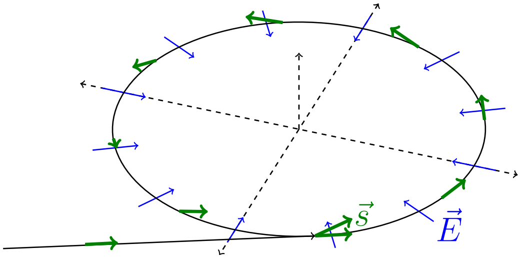
How to measure charged particle EDMs?

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:

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

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 ($E = 10\,\mathrm{MV/m}$)
- long spin coherence time ($\tau = 1000\,\mathrm{s}$),
- polarimetry (analyzing power $A = 0.6$, acc. $f = 0.005$)

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

challenge: get σ_{sys} to the same level

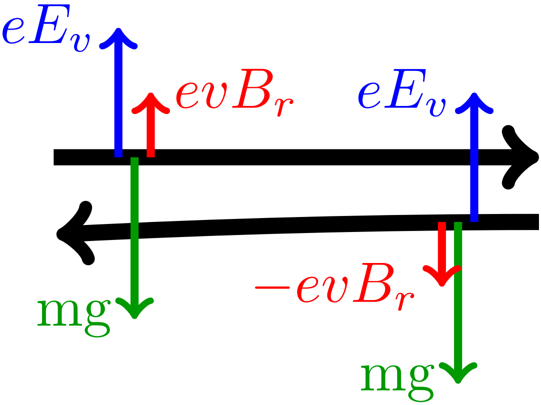
Systematics

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 $d = 10^{-29} e{\cdot}$cm in a field of $E_r = 10$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: $1.25\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$ for $d = 10^{-29}\,e\,\mathrm{cm}$
(possible with SQUID technology)

Spin Precession: Thomas-BMT Equation

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

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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Ω: angular precession frequency

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dedicated ring: pure electric field,

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

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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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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

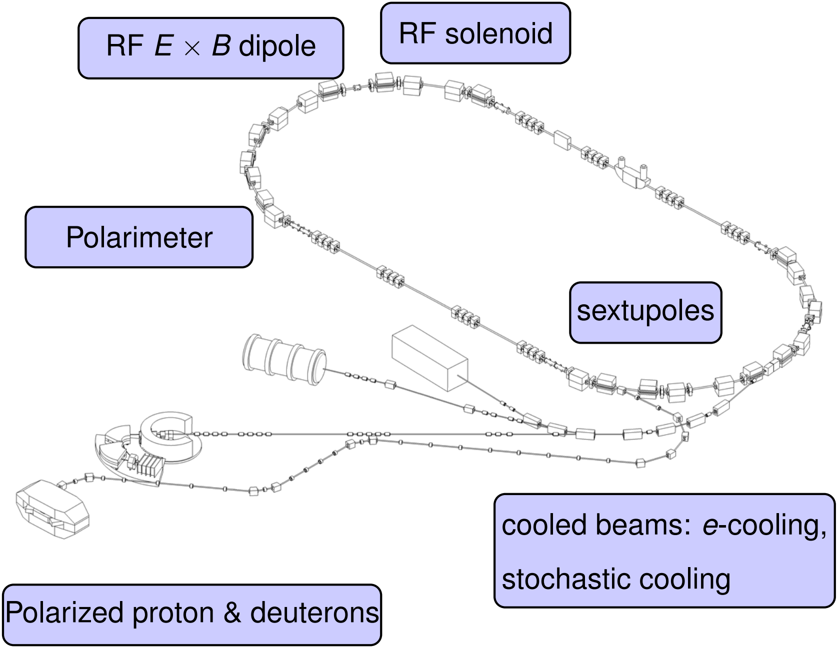
spin tune: $\nu_s \approx \frac{|\vec{\Omega}|}{|\omega_{\mathrm{cyc}}|} = \gamma G, \qquad (\vec{\omega}_{cyc} = \frac{e}{\gamma m}\vec{B})$

Results of first test measurements

Cooler Synchrotron COSY

COSY provides (polarized) protons and deuterons with
$p = 0.3 - 3.7\mathrm{GeV}/c$
$\Rightarrow$ **Ideal starting point for charged particle EDM searches**

COSY



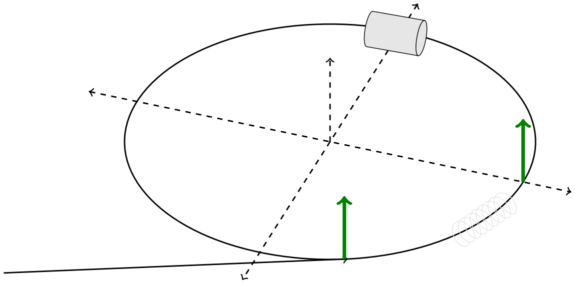
RF $E \times B$ dipole
RF solenoid
Polarimeter
sextupoles
cooled beams: e-cooling, stochastic cooling
Polarized proton & deuterons

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

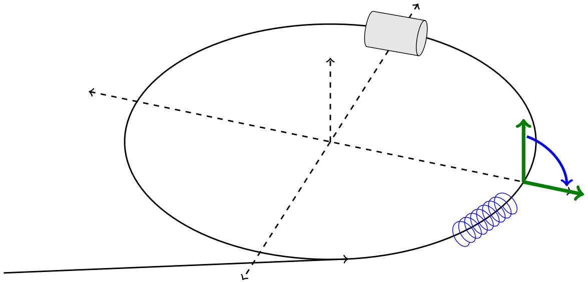
Experimental Setup

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



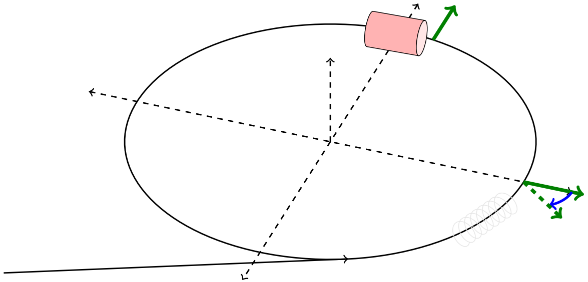
Experimental Setup

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



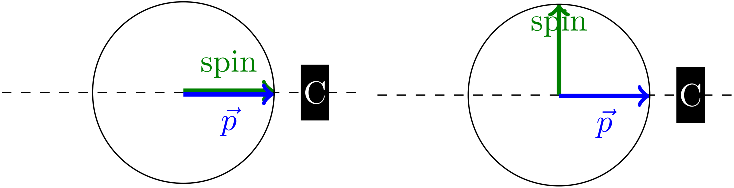
Asymmetry Measurements

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

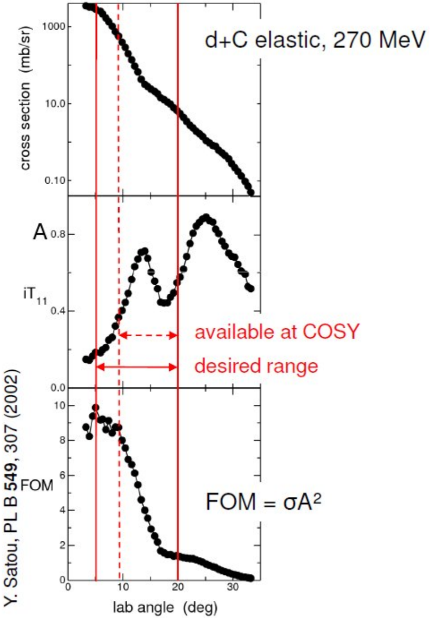
$$A_{up,dn} = \frac{N^{up} - N^{dn}}{N^{up} + N^{dn}} = P\,A\,\sin(\gamma G \omega_{rev} t)$$

A: analyzing power, P : polarization

$A_{up,dn} = 0$ $\qquad$ $A_{up,dn} = PA$



Polarimetry



Cross Section &
Analyzing Power
for deuterons

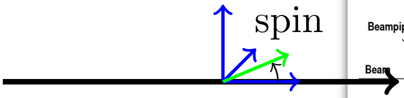
$$N_{up,dn} \propto (1 \pm P\,A\,\sin(\nu_s \omega_{rev} t))$$

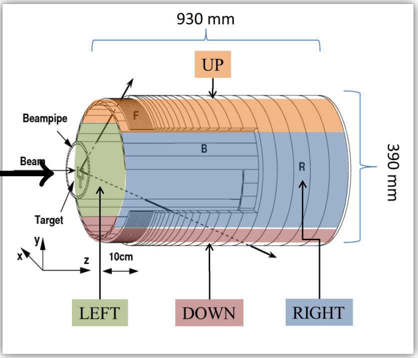
$$A_{up,dn} = \frac{N^{up} - N^{dn}}{N^{up} + N^{dn}} = P\,A\,\sin(\nu_s \omega_{rev} t) = P\,A\,\sin(2\pi \nu_s n_{turn})$$

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 $\rightarrow d$





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

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

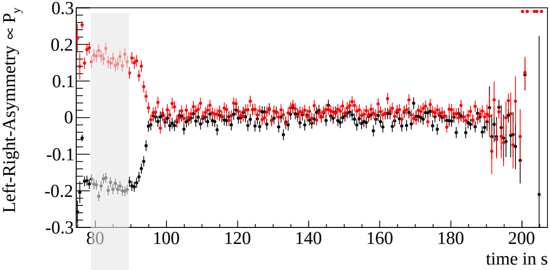
$$A_{up,dn}(t) \quad = \quad AP_0 e^{-t/\tau} \sin(\nu_s \omega_{rev} t + \varphi)$$

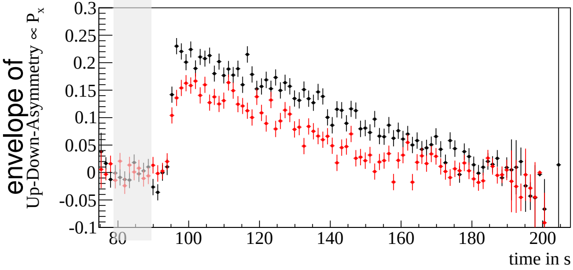
- $\tau \rightarrow$ spin decoherence
- $\nu_s \rightarrow$ spin tune

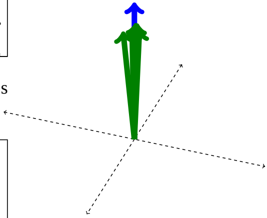
time scales: $\nu_s f_{rev} \approx 120$ kHz

τ in the range 1-1000 s

Polarization Flip







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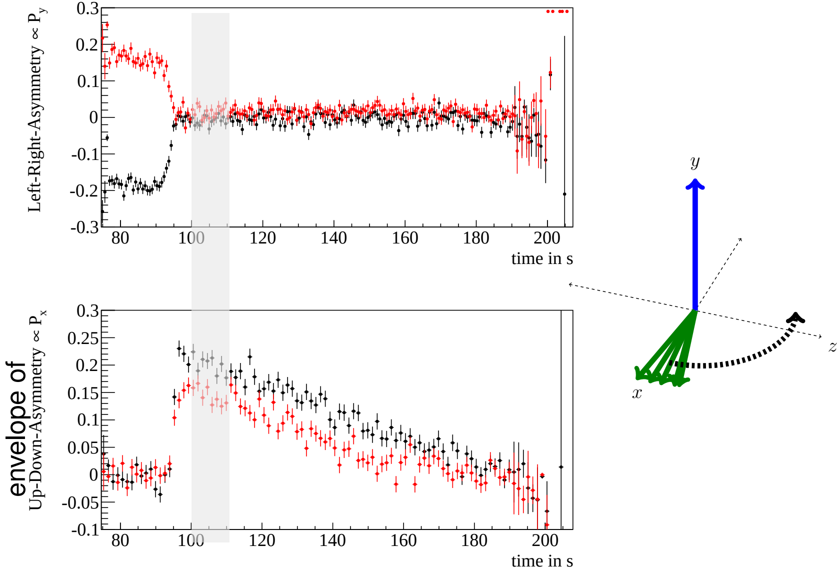

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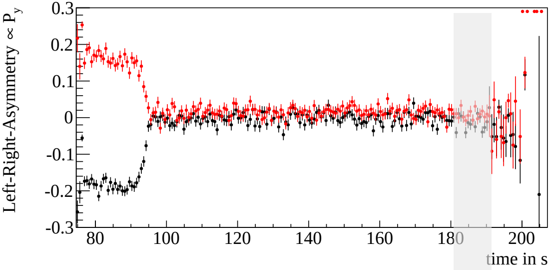
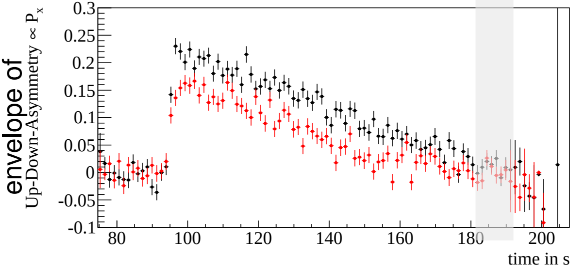
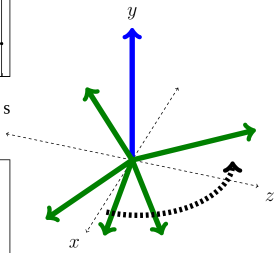
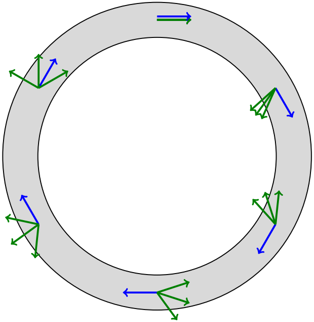


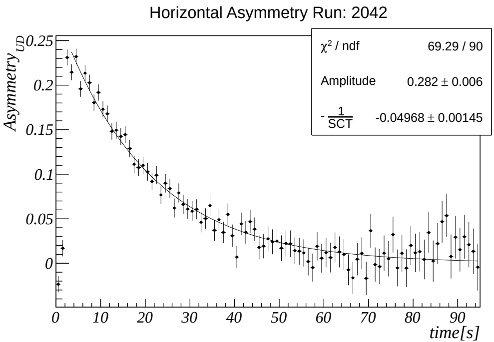




Results: Spin Coherence Time (SCT)

Short Spin Coherence Time

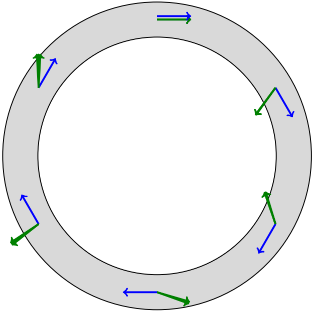


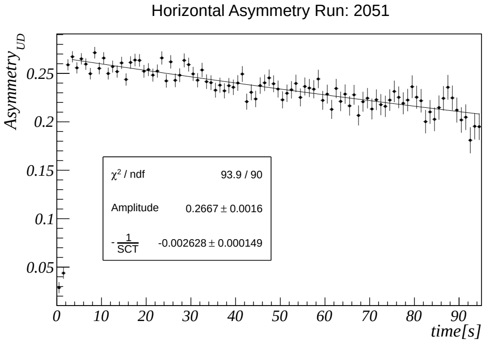


unbunched beam
$\Delta p/p = 10^{-5} \Rightarrow \Delta\gamma/\gamma = 2 \cdot 10^{-6}$, $T_{rev} \approx 10^{-6}$ s
$\Rightarrow$ decoherence after < 1 s
bunched beam eliminates 1st order effects in $\Delta p/p$
$\Rightarrow$ SCT τ = 20 s

Results: Spin Coherence Time (SCT)

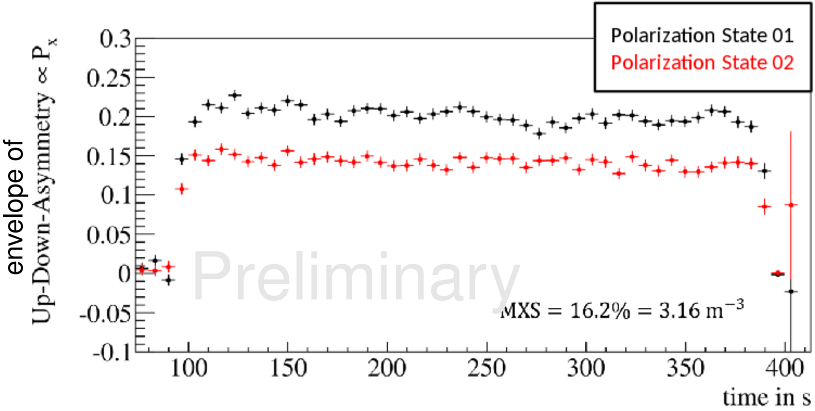
Long Spin Coherence Time





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

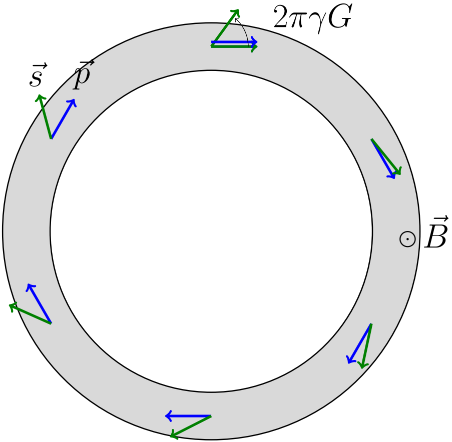
Longer cycle



(data taken a few days 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 ($\gamma = 1.13$), $G = -0.14256177(72)$

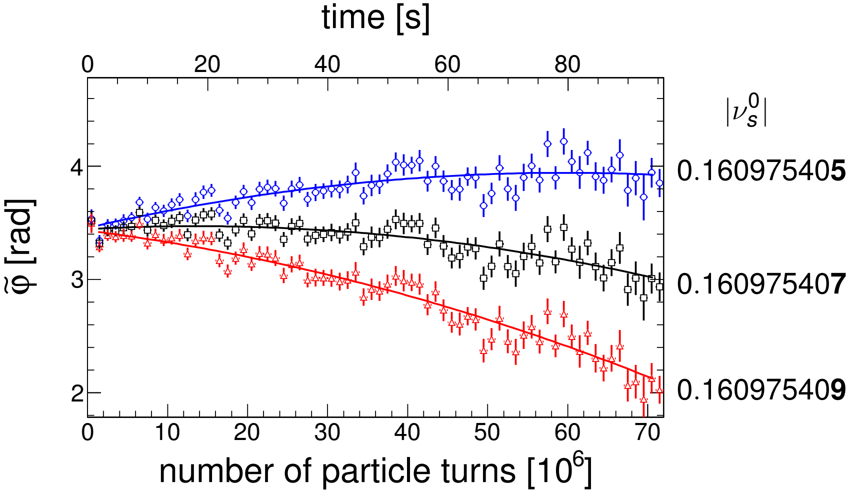
$\Rightarrow \nu_s = \gamma G \approx -0.161$

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

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

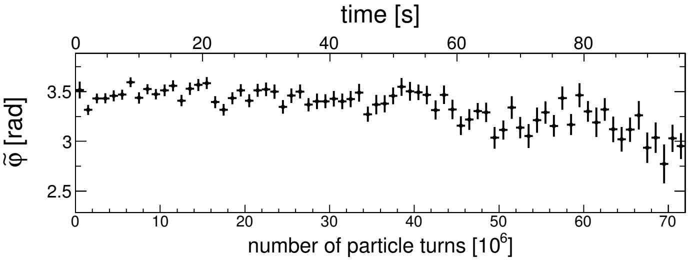
$$
\begin{aligned}
A_{up,dn}(t) &= AP_0 e^{-t/\tau} \sin(\nu_s(t)\omega_{rev} t + \varphi) \\
&= AP_0 e^{-t/\tau} \sin(\nu_s^0 \omega_{rev} t + \varphi(t))
\end{aligned}
$$

Phase vs. turn number

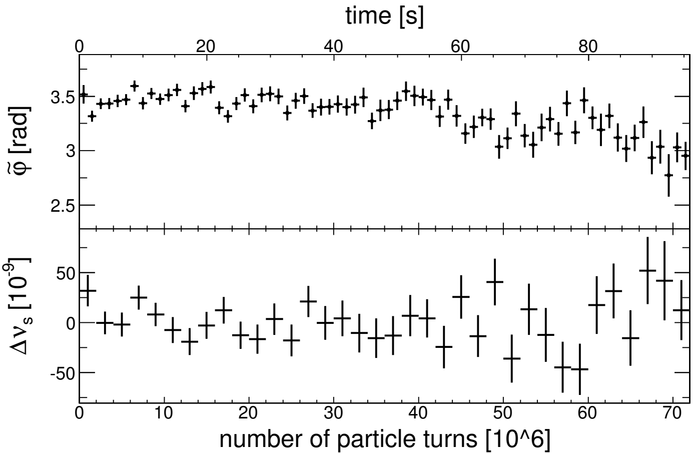


$$|\nu_s(t)| = |\nu_s^0| + \frac{1}{\omega_{rev}} \frac{\mathrm{d}\tilde{\varphi}}{\mathrm{d}t}$$

Results: Spin Tune ν_s

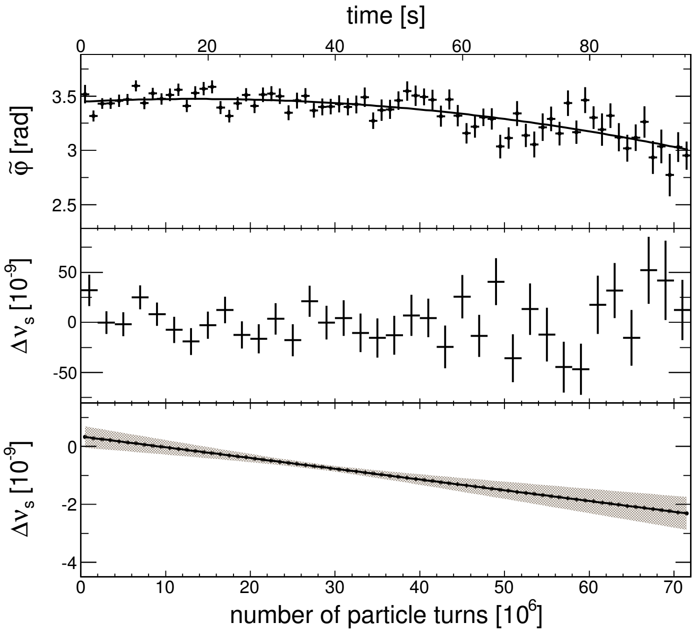


Results: Spin Tune ν_s



$\sigma_{\nu_s} \approx 10^{-8}$

Results: Spin Tune ν_s



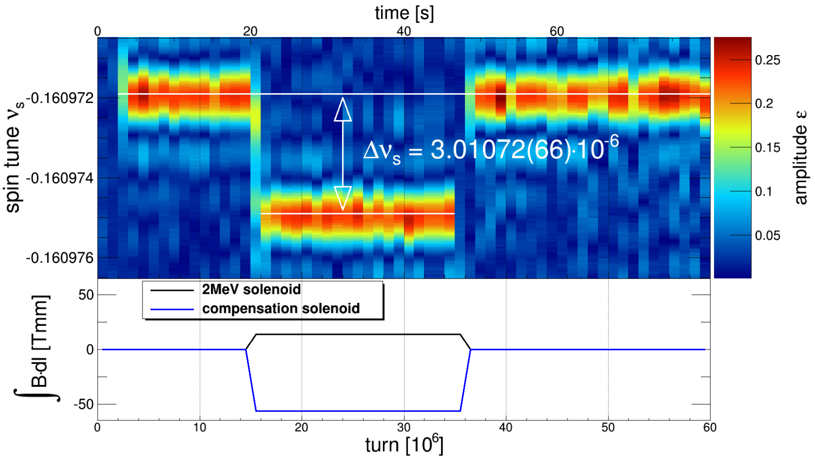
$\sigma_{\nu_s} \approx 10^{-8}$

$\sigma_{\nu_s} \approx 10^{-10}$

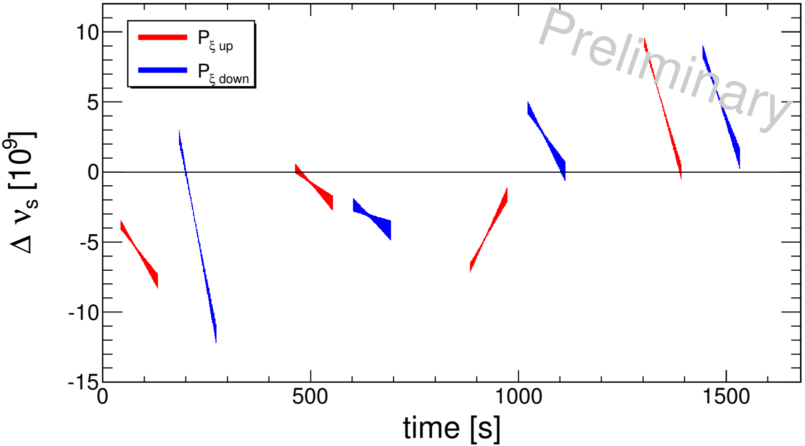
Spin Tune Measurement

- 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 600μ s compared to 100 s
- spin rotation due to electric dipole moment:
  $\nu_s = \dfrac{vm\gamma d}{es} = 5 \cdot 10^{-11}$ 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