Electric Dipole Moment Measurements at Storage Rings

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Outline

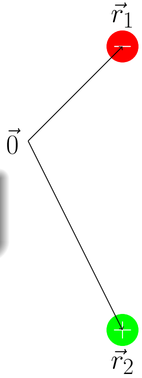
- Introduction: Electric Dipole Moments (EDMs):
  What is it?
- Motivation:
  Why is it interesting?
- Experimental Method:
  How to measure charged particle EDMs?
- Results of first test measurements:
  Spin tune and Spin Coherence time

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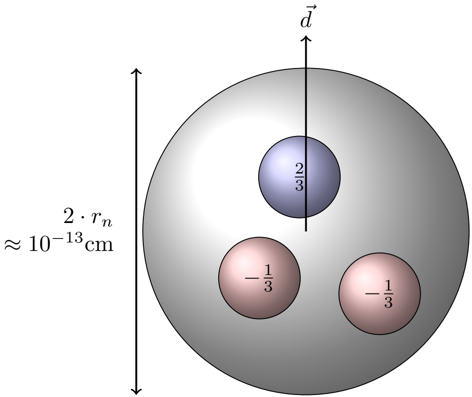
$\lvert\vec{r}_1 - \vec{r}_2\rvert$	1 Å= 10^{-8}cm	1$\mathrm{fm} = 10^{-13}$cm
EDM		
naive expectation	$10^{-8}e \cdot \mathrm{cm}$	$10^{-13}e \cdot \mathrm{cm}$
observed	water molecule	neutron
	$2 \cdot 10^{-8}e\cdot$ cm	$< 3 \cdot 10^{-26}e\cdot$ cm

Order of magnitude



neutron EDM of $d_n = 3 \cdot 10^{-26} e{\cdot}\mathrm{cm}$ 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 ($\vec{r} \rightarrow -\vec{r}$):

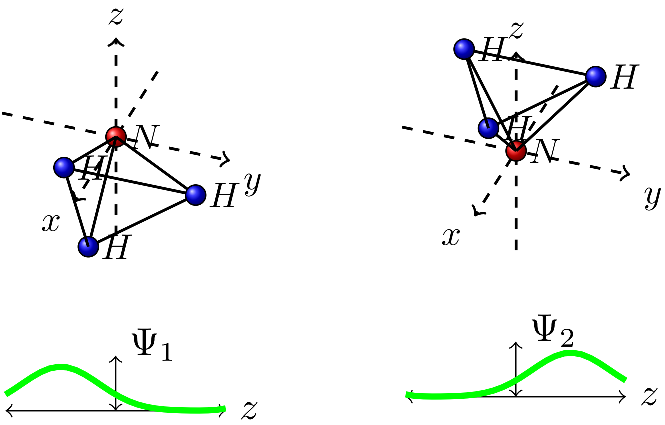
$$\mathcal{P}^{-1}\vec{d}\mathcal{P} = -\vec{d}$$

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

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

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

(Cohen-Tannoudji, B. Diu, F. Laloë, Mécanique quantique)

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

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

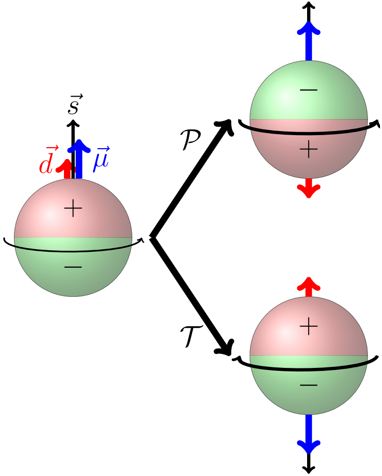
unless

$\mathcal{P}$ 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

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



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

Symmetries in Standard Model

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

- $\mathcal{C}$ 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)

Why is it interesting?

Motivation: 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

$\mathcal{CP}$ violation

Excess of matter in the universe:

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

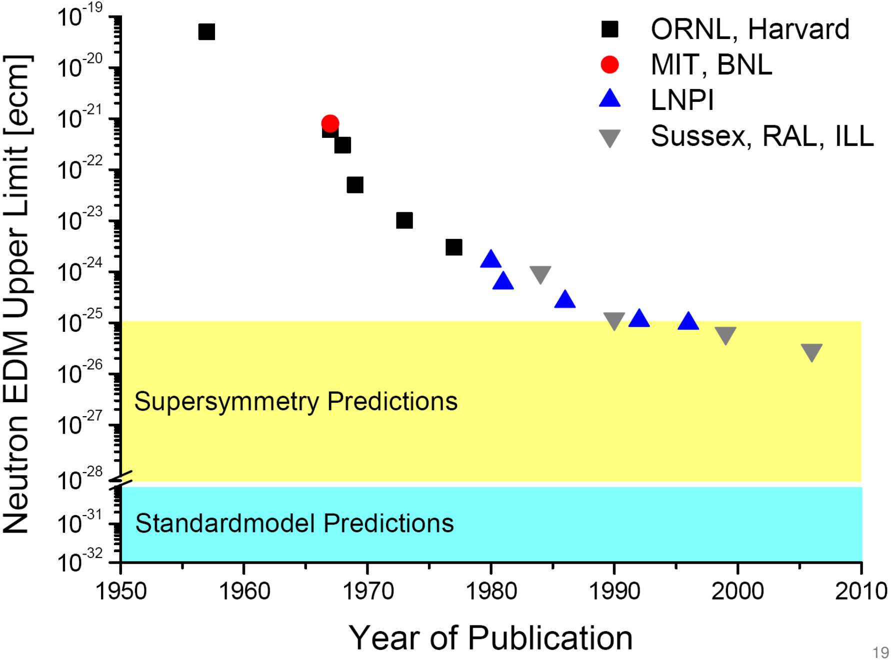
Sakharov (1967): $\mathcal{CP}$ violation needed for baryogenesis

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

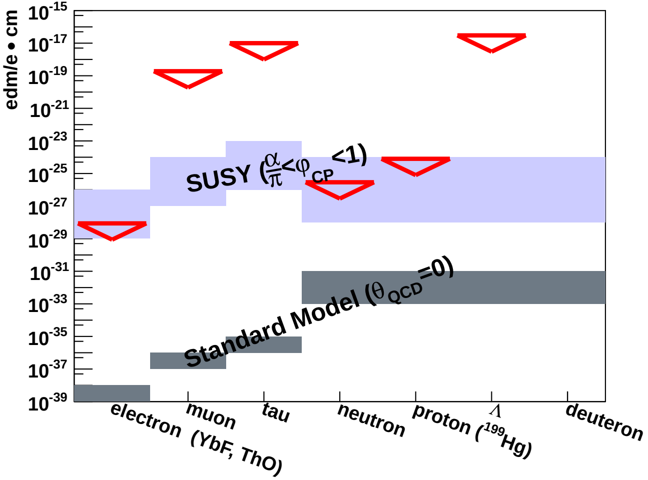
They could manifest in EDMs of elementary particles

What do we know about EDMs?

History of Neutron EDM



EDM: Current Upper Limits



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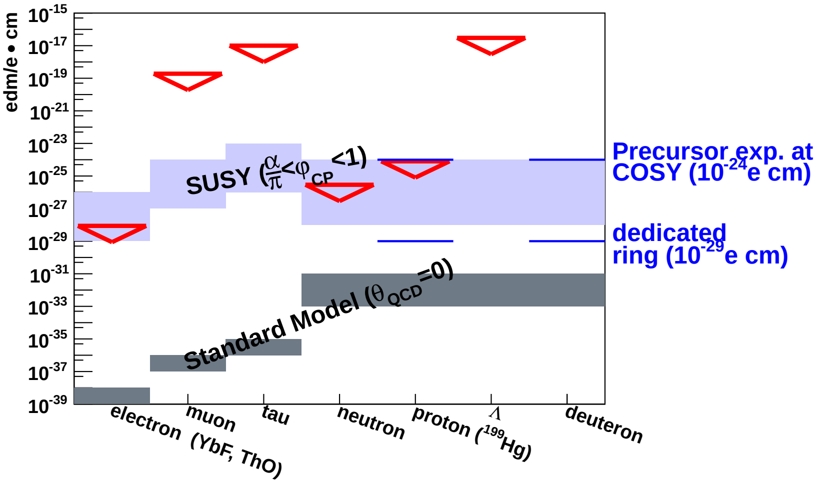
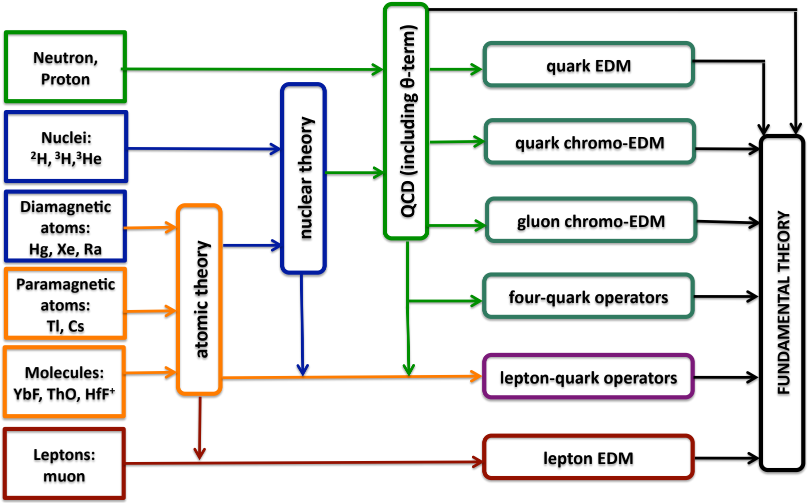


FZ Jülich: EDMs of **charged** hadrons: p, d, ^{3}He

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

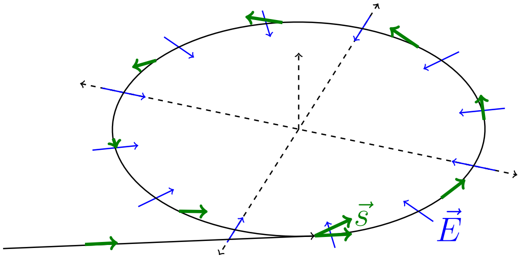


J. de Vries

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. $f = 0.005$)

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

challenge: get σ_{sys} to the same level

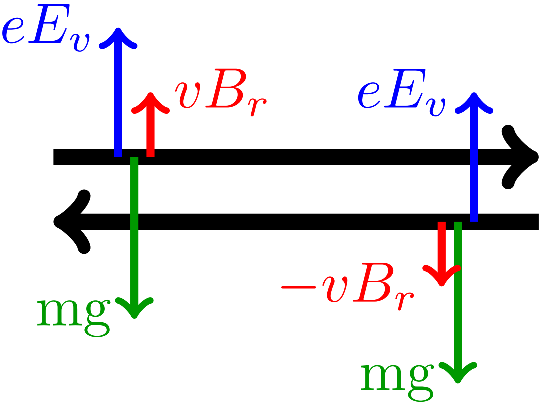
Systematics

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

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

Systematics



Sensitivity needed: $1.25\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$
(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

d: electric dipole moment

G: anomalous magnetic moment

γ: Lorentz factor

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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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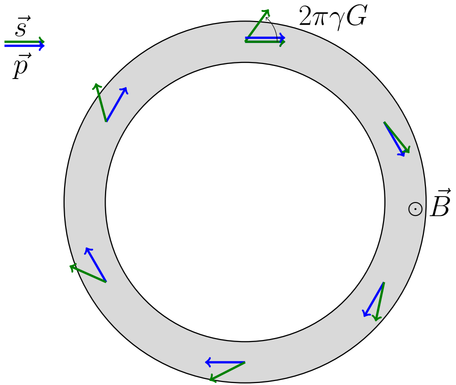
to suppress $G\vec{B}$ contribution

neglecting EDM term
spin tune: $\nu_s \approx \frac{|\vec{\Omega}|}{\omega_{\mathrm{rev}}} = \gamma G$

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 ($\gamma = 1.13$), $G = -0.14256177(72)$

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

Results of first test measurements

Cooler Synchrotron COSY

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

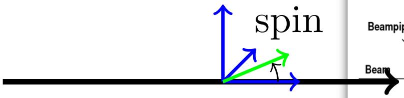
$\Rightarrow$ **Ideal starting point for charged particle EDM searches**

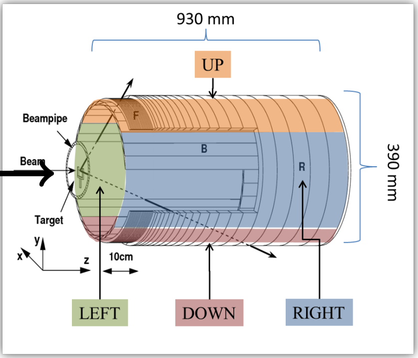
Experimental Setup

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

Polarimeter

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





$$N_{up,dn} \propto 1 \pm PA \sin(\nu_s f_{rev} t), \quad f_{rev} \approx 781\,\mathrm{kHz}$$

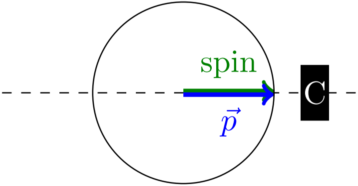
Asymmetry Measurements

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

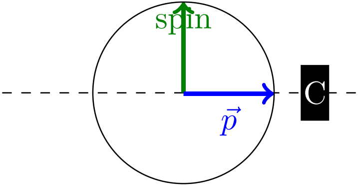
$$A_{up,dn} = \frac{N^{up} - N^{dn}}{N^{up} + N^{dn}} = P\,A\,\sin(\gamma G f_{rev} t)$$

A: analyzing power, P : polarization

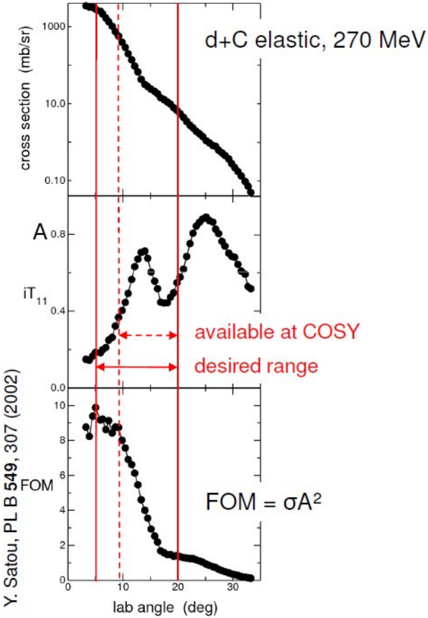
$A_{up,dn} = 0$



$A_{up,dn} = PA$



Polarimetry



Cross Section & Analyzing Power for deuterons

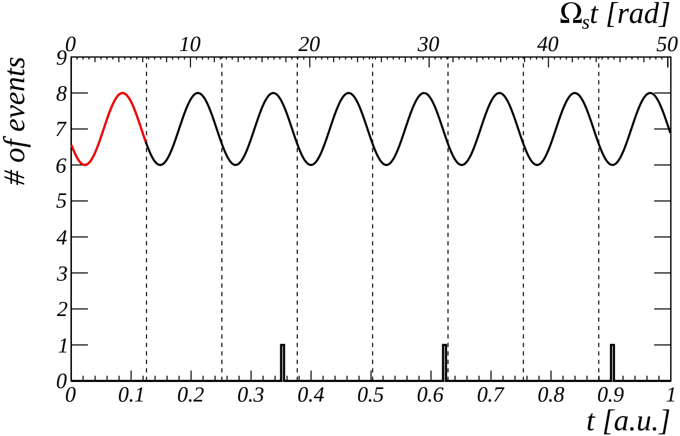
$N_{up,dn} \propto$
$(1 \pm P\,A \sin(\nu_s f_{rev} t))$

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

A : analyzing power
P : beam polarization

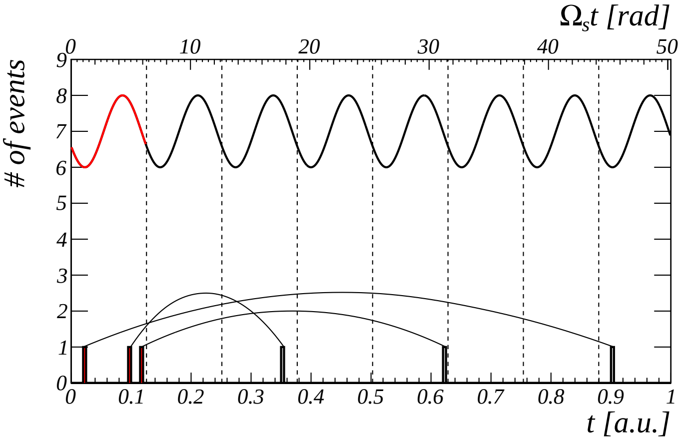
Spin Tune ν_s measurement

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

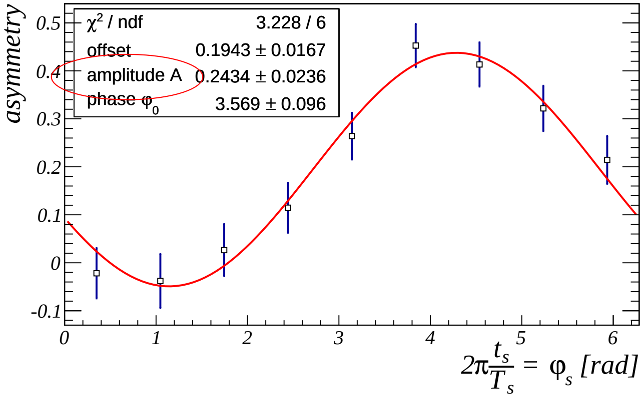


Spin Tune ν_s measurement

- map all events into first period ($T = 1/(\nu_s f_{rev}) \approx 8\mu$s) and perform χ^2-fit
  (requires knowledge of $\nu_s f_{rev}$)
- Analysis is done in macroscopic time bins of $\approx$ 2s

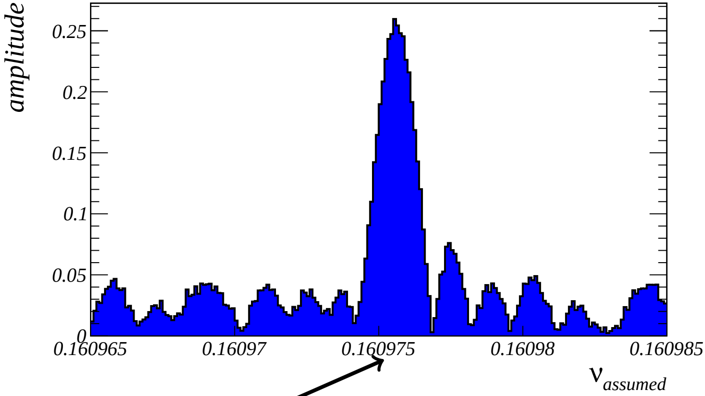


Asymmetry in 1st period



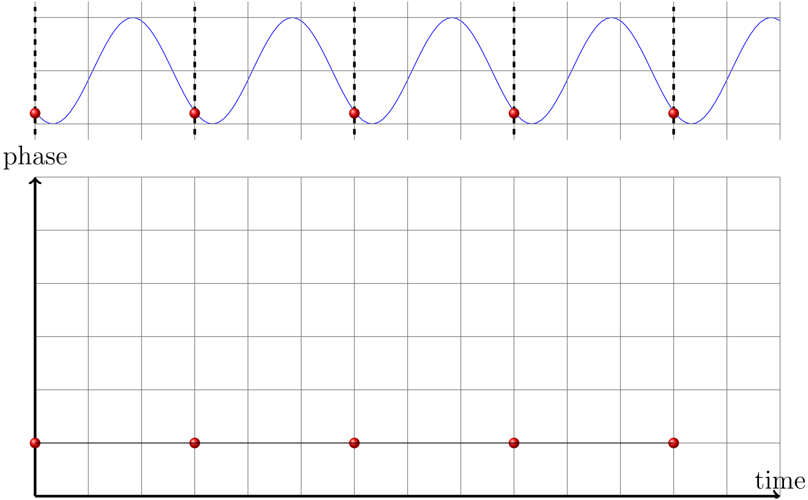
- only works if $T_s = \dfrac{1}{\nu_s f_{rev}}$ is correct.

Scan of ν_s

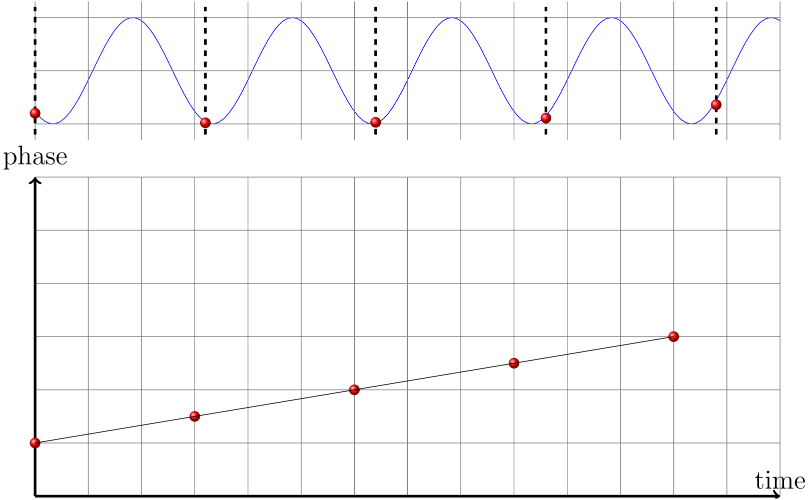


- set $\nu_s = \nu_{max}$ and determine phase in macroscopic time bins of $\approx$ 2s
- allows for $\sigma_{\nu_s} \approx 10^{-6}$

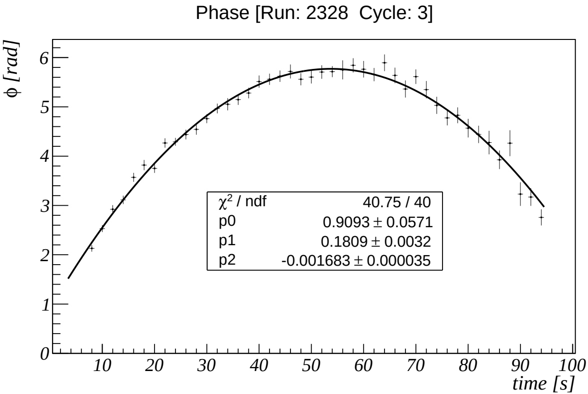
Phase Measurements



Phase Measurements

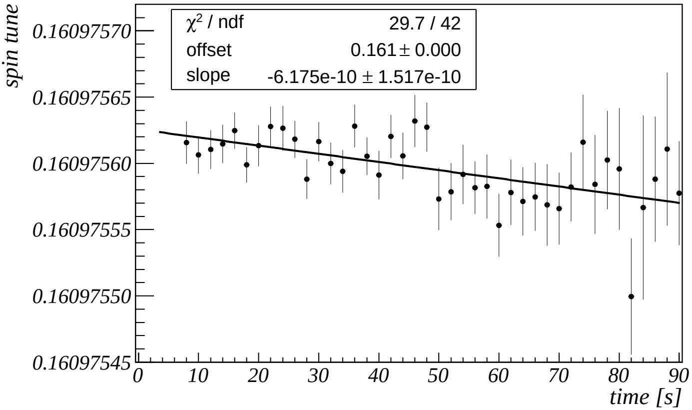


Phase Measurements



- 1st derivative gives deviation from assumed spin tune

Results: Spin Tune ν_s



- Spin tune ν_s can be determined to $\approx 10^{-8}$ in 2 s
- Average $\overline{\nu_s}$ in cycle ($\approx$ 100 s) determined to 10^{-10}
  (for $G = 0$, $d = 10^{-24}\,e{\cdot}\mathrm{cm} \Rightarrow$ spin tune = $5 \cdot 10^{-11}$)

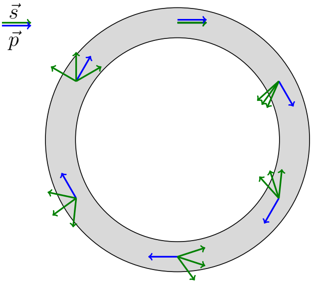
Spin Tune ν_s

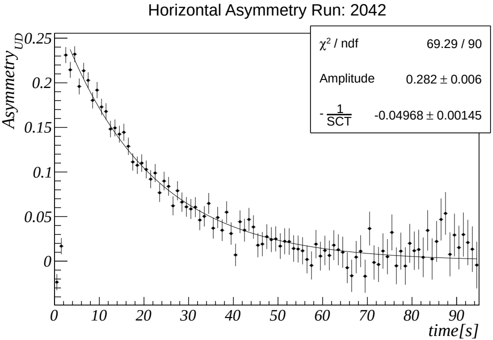
Experiment	Gedankenexperiment
$G \approx -0.14$, $d \approx 0$	$G = 0$, $d = 10^{-24}\,e\,\mathrm{cm}$
$\nu_s = \gamma G = -0.16$	$\nu_s = \frac{vm\gamma d}{es} = 5 \cdot 10^{-11}$

compare to $\sigma(\nu_s) = 10^{-10}$ in 100 s measurement

Results: Spin Coherence Time (SCT)

Short Spin Coherence Time

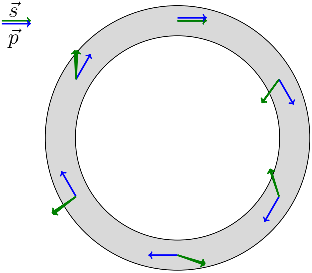


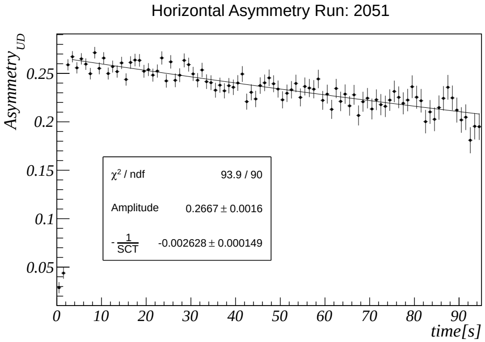


cooled bunched beam $\Rightarrow$ SCT τ = 20 s

Results: Spin Coherence Time (SCT)

Long Spin Coherence Time





using correction sextupole to correct for higher order effects leads to SCT of $\tau =$400 s

Results: Spin Coherence Time (SCT)

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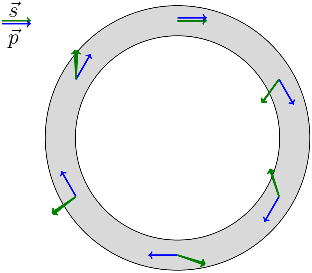
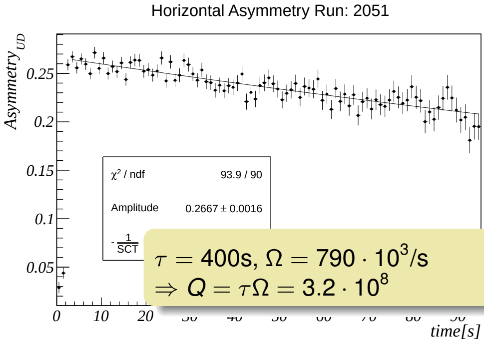




$\tau = 400\text{s}, \Omega = 790 \cdot 10^3/\text{s}$
$\Rightarrow Q = \tau\Omega = 3.2 \cdot 10^8$

using correction sextupole to correct for higher order effects leads to SCT of $\tau =$400 s

JEDI Collaboration

- **JEDI** = **J**ülich **E**lectric **D**ipole Moment **I**nvestigations
- $\approx$ 100 members
  (Aachen, Dubna, Ferrara, Indiana, Ithaca, Jülich, Krakow, Michigan, Minsk, Novosibirsk, St. Petersburg, Stockholm, Tbilisi, . . .)
- $\approx$ 10 PhD students

Summary & Outlook

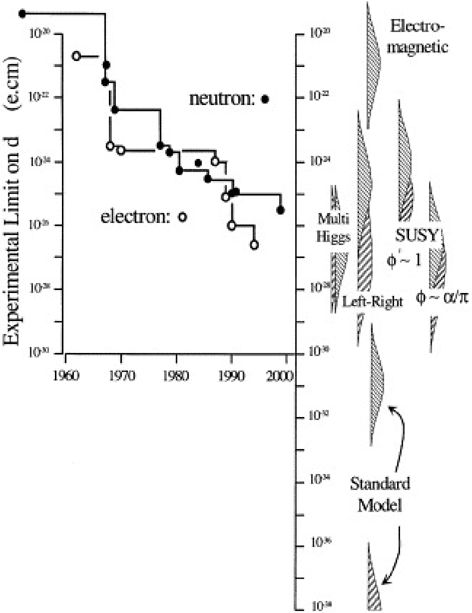
- EDMs of elementary particles are of high interest to disentangle various sources of $\mathcal{CP}$ violation searched for to explain matter - antimatter asymmetry in the Universe
- EDM of charged particles can be measured in storage rings

  Plans in Jülich: $10^{-24}\,e\,\mathrm{cm}$ at COSY

  $10^{-29}\,e\,\mathrm{cm}$ with dedicated ring
- Experimentally very challenging because effect is tiny
- First promising results from test measurements at COSY

Spare

Electron and Neutron EDM



J. M. Pendlebury &
E.A. Hinds,
NIMA 440(2000) 471

EDM: SUSY Limits

electron:

MSSM: $\varphi \approx 1 \Rightarrow d = 10^{-24} - 10^{-27} e{\cdot}\text{cm}$

$\varphi \approx \alpha/\pi \Rightarrow d = 10^{-26} - 10^{-30} e{\cdot}\text{cm}$

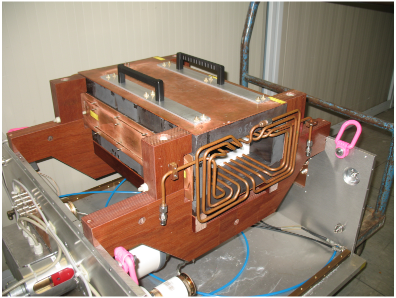
neutron:

MSSM: $d = 10^{-24} e{\cdot}\text{cm} \cdot \sin\phi_{CP} \frac{200\text{GeV}}{M_{SUSY}}$

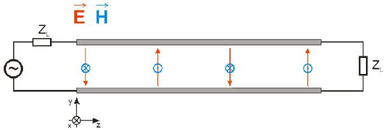
Electrostatic Deflectors

- Electrostatic deflectors from Fermilab ($\pm$125kV at 5 cm $\hat{=}$ 5MV/m)
- large-grain Nb at plate separation of a few cm yields $\approx$ 20MV/m

Wien Filter



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



stripline design
D. Hölscher, J. Slim
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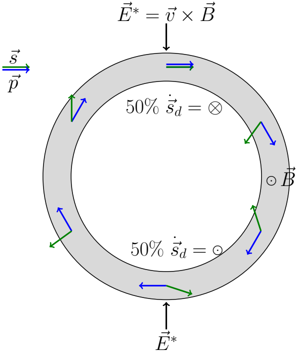
1. Pure Magnetic Ring

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

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



E^* field in the particle rest frame tilts spin due to EDM up and down
$\Rightarrow$ **no net EDM effect**

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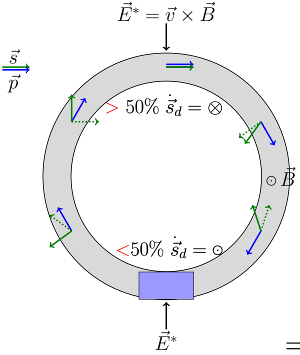

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Use resonant "magic Wien-Filter" in ring ($\vec{E} + \vec{v}\times\vec{B} = 0$):
$E^* = 0 \rightarrow$ part. trajectory is not affected but
$B^* \neq 0 \rightarrow$ mag. mom. is influenced

$\Rightarrow$ **net EDM effect can be observed!**

2. Pure Electric Ring

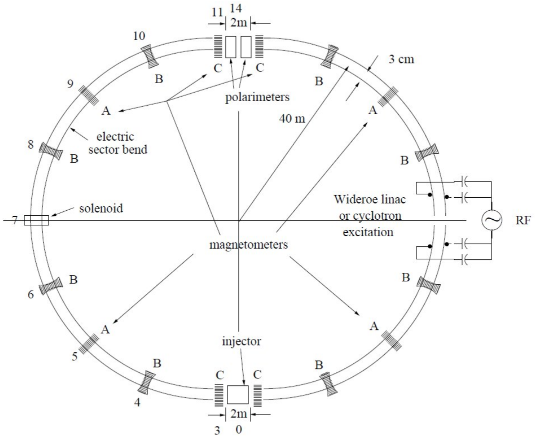


Figure 3: An all-electric storage ring lattice for measuring the electric dipole moment of the proton. Except for having longer straight sections and separated beam channels, the all-in-one lattice of Fig. 1 is patterned after this lattice. Quadrupole and sextupole families, and tunes and lattice functions 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.

Brookhaven National Laboratory (BNL) Proposal

3. Combined $\vec{E}/\vec{B}$ ring

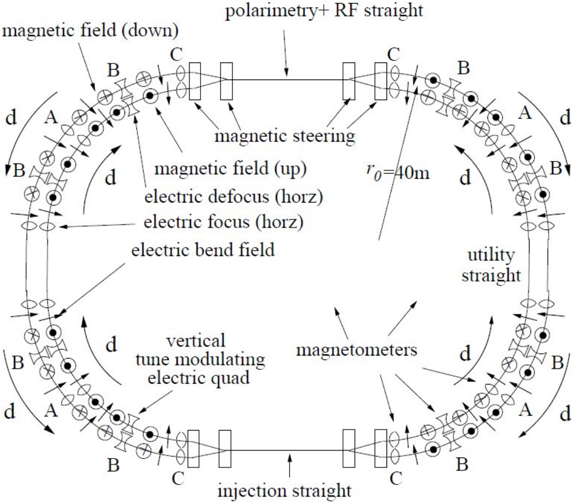


Figure 1: "All-In-One" lattice for measuring EDM's of protons, deuterons, and helions.

Under discussion at Forschungszentrum Jülich (design: R. Talman)

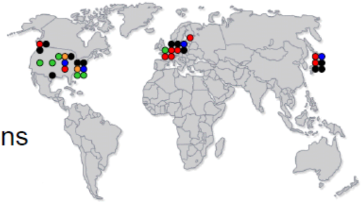
Summary of different options

	☺	☹
1.) pure magnetic ring (Jülich)	existing (upgraded) COSY ring can be used , shorter time scale	lower sensitivity
2.) pure electric ring (BNL)	no $\vec{B}$ field needed	works only for p
3.) combined ring (Jülich)	works for p, d, ^{3}He, ...	both $\vec{E}$ and $\vec{B}$ required

EDM Activities Around the World

Rough estimate of numbers of researchers, in total ~500 (with some overlap)

- **Neutrons** ~200
  - @ILL
  - @ILL,@PNPI
  - @PSI
  - @FRM-2
  - @RCNP,@TRIUMF
  - @SNS
  - @J-PARC
- **Molecules** ~50
  - YbF@Imperial
  - PbO@Yale
  - ThO@Harvard
  - HfF+@JILA
  - WC@UMich
  - PbF@Oklahoma
- **Atoms** ~100
  - Hg@UWash
  - Xe@Princeton
  - Xe@TokyoTech
  - Xe@TUM
  - Xe@Mainz
  - Cs@Penn
  - Cs@Texas
  - Fr@RCNP/CYRIC
  - Rn@TRIUMF
  - Ra@ANL
  - Ra@KVI
  - Yb@Kyoto



- **Ions-Muons** ~200
  - @BNL
  - @FZJ
  - @FNAL
  - @JPARC
- **Solids** ~10
  - GGG@Indiana
  - ferroelectrics@Yale

K. Kirch

Systematics

- Splitting of beams: $\delta y = \pm \frac{\beta c R_0 B_r}{E_r Q_y^2} = \pm 1 \cdot 10^{-12}\,\mathrm{m}$
- $Q_y \approx 0.1$: vertical tune
- Modulate $Q_y = Q_y^0\,(1 - m\cos(\omega_m t)),\ m \approx 0.1$
- Splitting causes B field of $\approx 0.4 \cdot 10^{-3}\,\mathrm{fT}$
- in one year: 10^4 fills of 1000 s $\Rightarrow \sigma_B = 0.4 \cdot 10^{-1}$fT per fill needed
- Need sensitivity $1.25\,\mathrm{fT}/\sqrt{\mathrm{Hz}}$

Systematics