Electric Dipole Moments – probes of fundamental symmetries

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Outline

Electric Dipole Moments (EDMs)

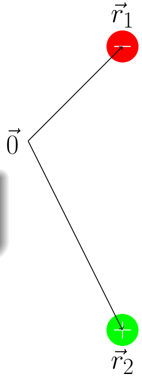
- What is it?
- Why is it interesting?
- What do we know about it?
- How to measure (**charged** particle) EDMs?
  Results of first test measurements

What is it?

Electric Dipoles

Classical definition:

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



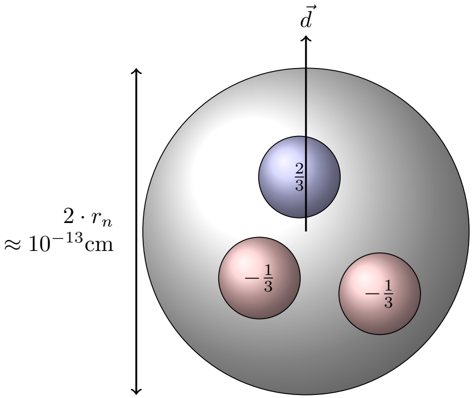
Order of magnitude

	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	

Order of magnitude

	atomic physics	**hadron physics**
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

Order of magnitude



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 ($\vec{r} \to -\vec{r}$):

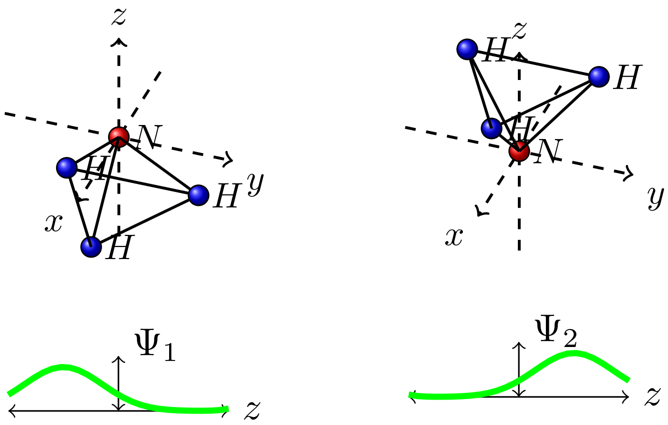
$$\mathcal{P}^{-1}\vec{d}\mathcal{P} = -\vec{d}$$

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

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

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

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

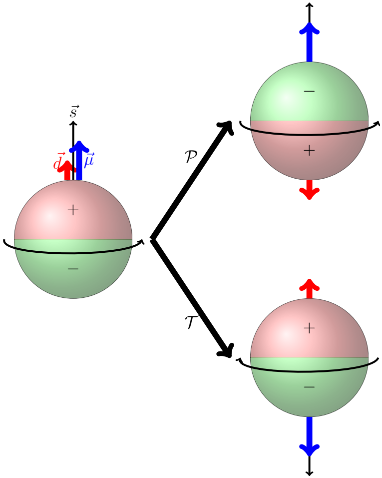
unless

$\mathcal{P}$ 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 $\mathcal{T}(\stackrel{\mathcal{CPT}}{=} \mathcal{CP})$

Symmetries 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)

Symmetries

- 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 $\ell^{\pm}$

	experiment	theory
electron	$1\,159\,652\,180.73\,(0.28) \cdot 10^{-12}$	$1\,159\,652\,181.13\,(0.86) \cdot 10^{-12}$
muon	$1\,165\,920.80(54)(33) \cdot 10^{-9}$	$1\,165\,918.28(49) \cdot 10^{-9}$
proton	1.792847356(23)	2^*

*): static quark model, SU(6) wave function

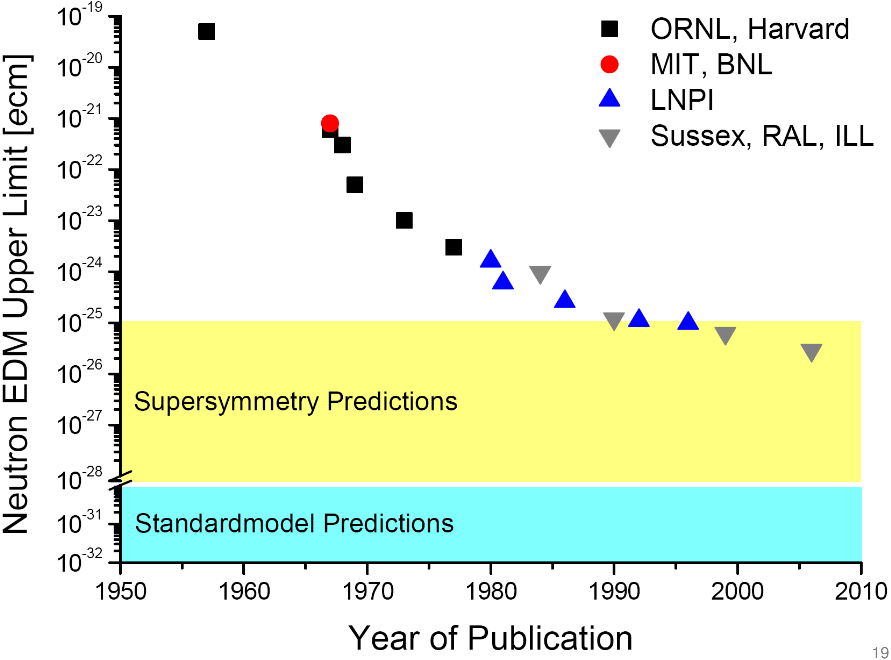
Why is it interesting?

$\mathcal{CP}$ violation

- We are surrounded by matter (and not anti–matter)
  $\eta = \frac{n_B - n_{\bar{B}}}{n_\gamma} = \mathbf{6} \times \mathbf{10}^{-\mathbf{10}}$
- Starting from equal amount of matter and anti-matter in the early universe, the $\mathcal{CP}$-violation in the Standard Model predicts only $\mathbf{10}^{-\mathbf{18}}$
- In 1967 Sakharov formulated three prerequisites for baryogenesis. One of these is the combined violation of the charge and parity, $\mathcal{CP}$, symmetry.
- New $\mathcal{CP}$ 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?

History of Neutron EDM



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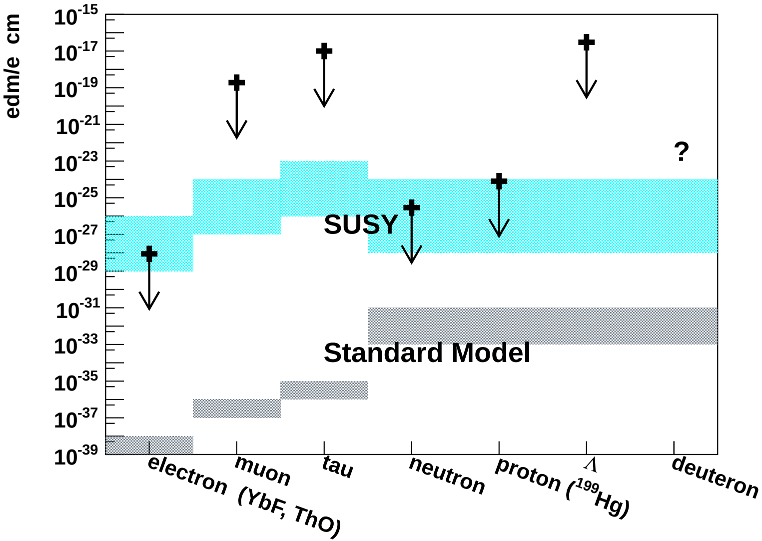

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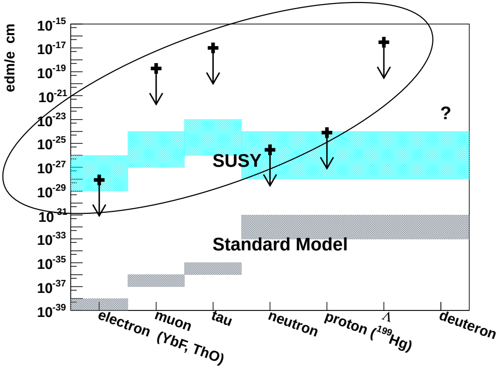

- no EDM observed yet, only limits

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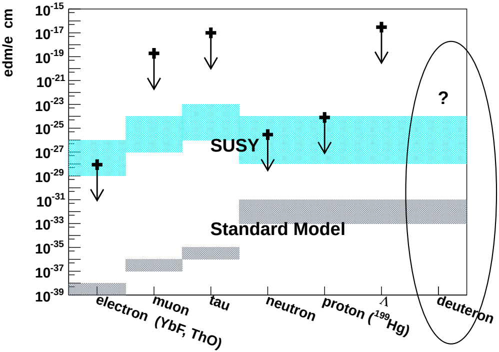

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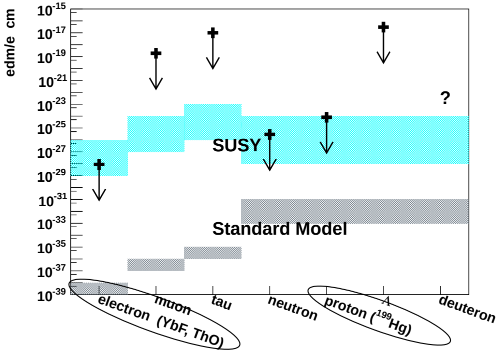

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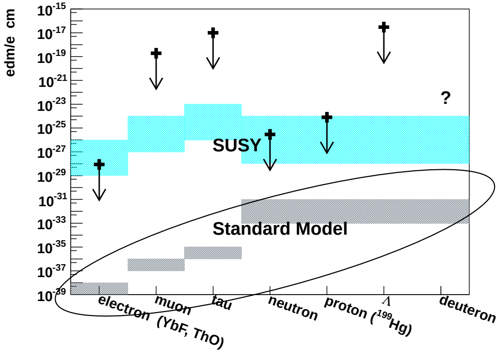

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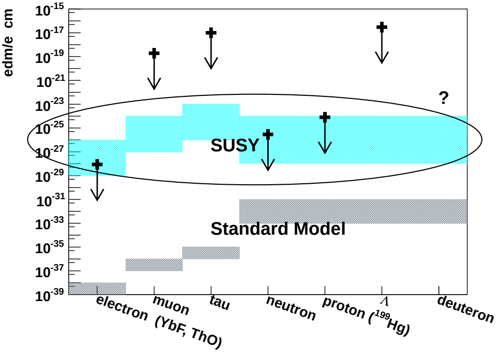

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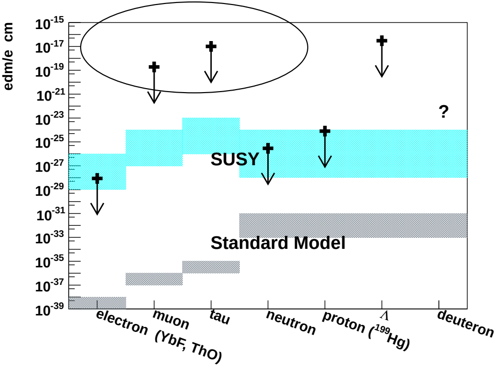
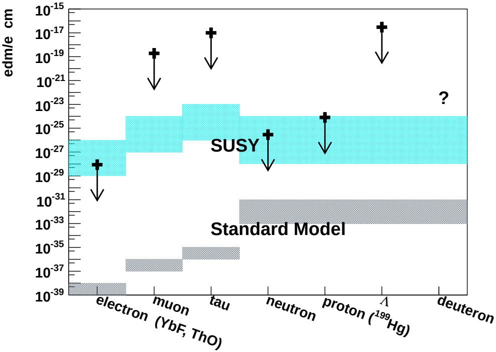
- Standard Model value essentially 0
- Beyond SM values accessible by experiments

What do we know about EDMs?



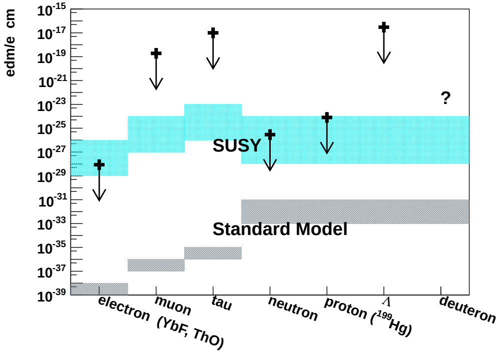
- direct charged particle EDM measurements less precise

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?



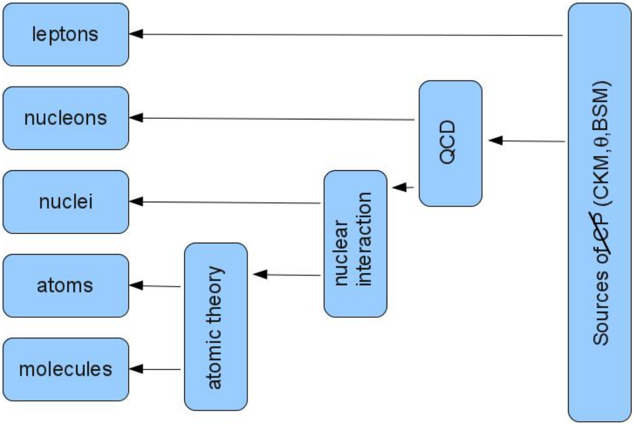
GOAL of JEDI (**J**ülich **E**lectric **D**ipole **I**nvestigations)collaboration:

Charged Hadron EDM measurements

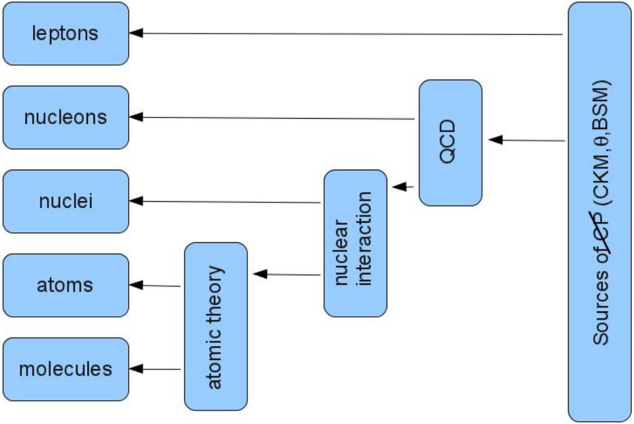
- First measurement of deuteron, ^{3}He EDM,
- first direct measurement of proton EDM

ultimately with a precision of $10^{-29}\,e\,\mathrm{cm}$

Sources of $\mathcal{CP}$ violation



Sources of $\mathcal{CP}$ violation



$\Rightarrow$ It is mandatory to measure EDM of many different particles to disentangle various sources of $\mathcal{CP}$ violation.

Difficulty of charged particle EDM measurement

- EDM of neutral particles can be measured in small volumes (trap)
- applying an electric field on a charged particle accelerates the particles
  $\Rightarrow$ particle cannot be kept in small volume
  $\Rightarrow$ storage rings have to be operated to measure EDM of charged particles
- already done for muon (parallel to $g-2$ measurement)
  μ: $0.1 \pm 0.9 \cdot 10^{-19} e \cdot \mathrm{cm}$

How to measure charged particle EDMs?

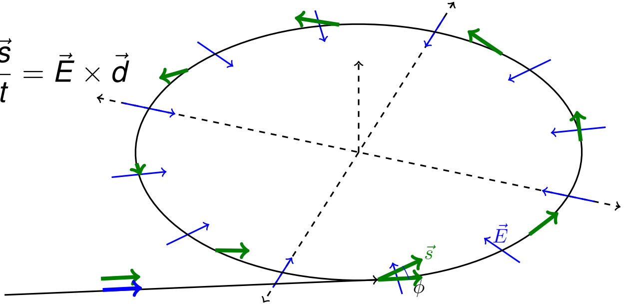
Measurement of charged particle EDMs

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: $$\frac{d\vec{s}}{dt} = \vec{\Omega} \times \vec{s}$$

Thomas-BMT equation

Spin Motion is governed by Thomas-BMT equation (Bargmann, Michel, Telegdi)

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

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

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

$\vec{d}$: electric dipole moment

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

γ: Lorentz factor

V. Bargmann, L. Michel and V. L. Telegdi, Phys. Rev. Lett. **2** (1959) 435.

Thomas-BMT equation

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

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

Thomas-BMT equation

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   $G\vec{B} + \left(G - \frac{1}{\gamma^2 - 1}\right)\vec{v}\times\vec{E} = 0$
3. **Pure magnetic ring**

JEDI

Required field strength

	$G = \frac{g-2}{2}$	p/GeV/c	E_R/MV/m	B_V/T
proton	1.79	0.701	10	0
deuteron	-0.14	1.0	-4	0.16
^{3}He	-4.18	1.285	17	-0.05

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

$$E = \frac{GBc\beta\gamma^2}{1 + G\beta^2\gamma^2}$$

1. Pure Electric Ring

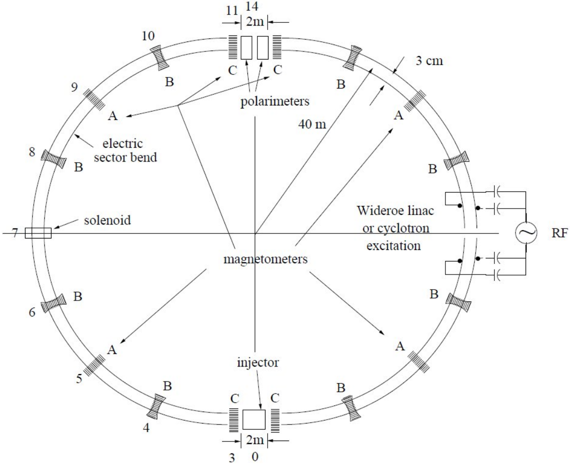


Figure 3: An all-electric storage ring lattice for measuring the electric dipole moment of the proton. Except for having longer straight sections and separated beam channels, the all-in-one lattice of Fig. 1 is patterned after this lattice. Quadrupole and sextupole families, and tunes and lattice functions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

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

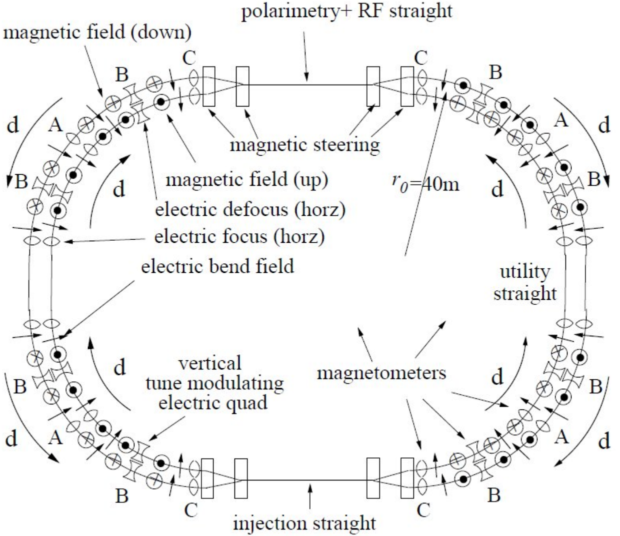


Figure 1: "All-In-One" lattice for measuring EDM's of protons, deuterons, and helions.

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!

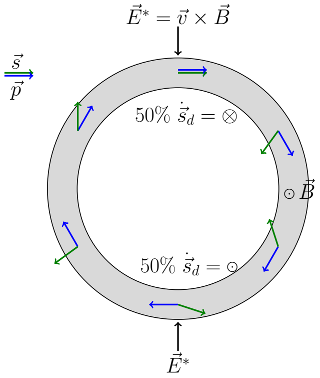
COSY provides (polarized) protons and deuterons with
$p = 0.3 - 3.7\text{GeV}/c \Rightarrow$ **Ideal starting point**

JEDI

3. 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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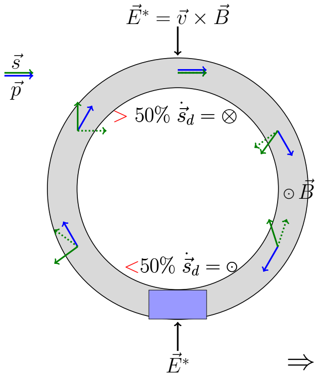

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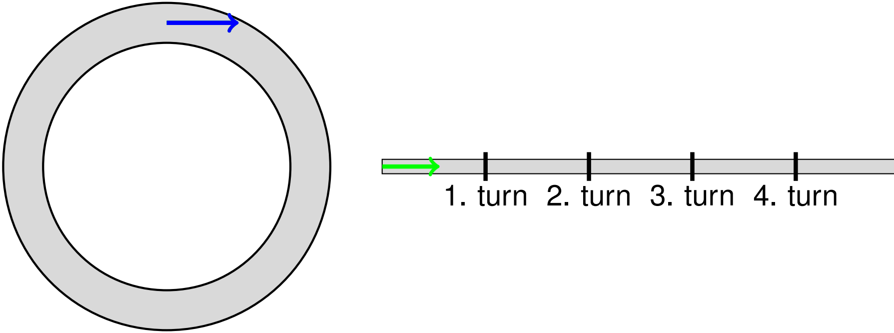
Use resonant "magic Wien-Filter" in ring ($\vec{E} + \vec{v}\times\vec{B} = 0$):
$E^* = 0 \rightarrow$ part. trajectory is not affected but
$B^* \neq 0 \rightarrow$ mag. mom. is influenced

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

Horizontal spin motion $\propto$ G vertical spin motion $s_{\perp} \propto d$



Summary of different options

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

Statistical Sensitivity (pure electric or combined ring)

$$\sigma \approx \frac{\hbar}{\sqrt{NfT\tau_p}PEA}$$

E	electric field	10 MV/m
P	beam polarization	0.8
A	analyzing power	0.6
N	nb. of stored particles/cycle	4×10^{10}
f	detection efficiency	0.005
τ_p	spin coherence time	1000 s
T	running time per year	10^7s

$\Rightarrow \sigma \approx 10^{-29} e\cdot$cm/year
Expected signal $\approx$ 3nrad/s (for $d = 10^{-29} e\cdot$cm)
(BNL proposal)

Statistical Sensitivity pure magnetic ring (COSY)

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

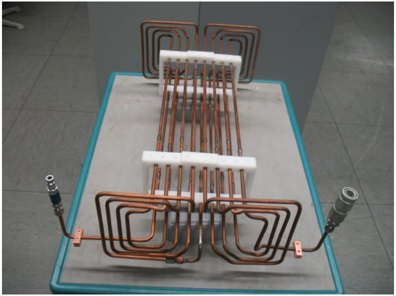
G	anomalous magnetic moment	
γ	relativistic factor $p =$1GeV/c	1.13
U	circumference of COSY	180 m
$E \cdot L$	integrated electric field	$0.1 \cdot 10^6$ V
N	nb. of stored particles/cycle	$2 \cdot 10^9$

$\Rightarrow \sigma \approx 10^{-25} e\cdot$cm/year

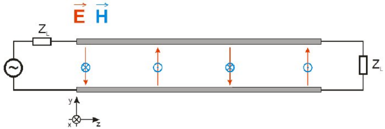
Electrostatic Deflectors

- 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
(IHF RWTH Aachen)

Systematics

One major source:
Radial B field mimics an EDM effect:

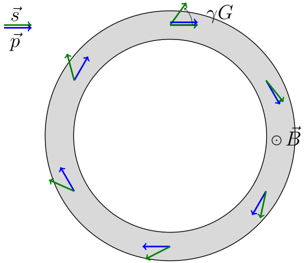
- Difficulty: even small radial magnetic field, B_r can mimic EDM effect if :$\mu B_r \approx dE_r$
- Suppose $d = 10^{-29} e{\cdot}\text{cm}$ in a field of $E = 10\text{MV/m}$
- This corresponds to a magnetic field:
  $$B_r = \frac{dE_r}{\mu_N} = \frac{10^{-22} e\mathrm{V}}{3.1 \cdot 10^{-8} e\mathrm{V/T}}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



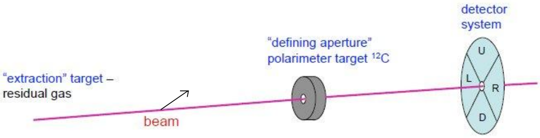
For $p_d = 1$ GeV/c ($\gamma = 1.13$), $G = -0.14256177(72)$)

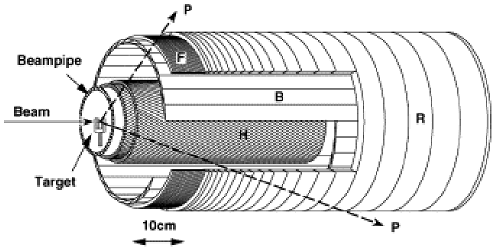
$$\Rightarrow \nu = \gamma G = -0.161$$

ν 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





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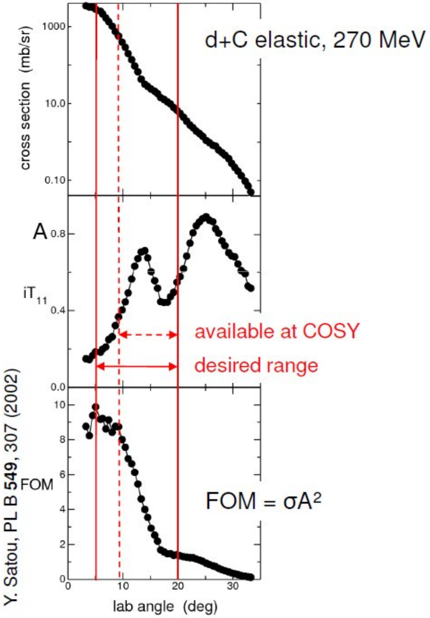


Cross Section & Analyzing Power for deuterons

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

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

A : analyzing power
P : beam polarization

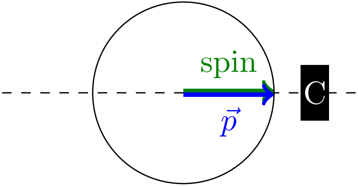
Asymmetry Measurements

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

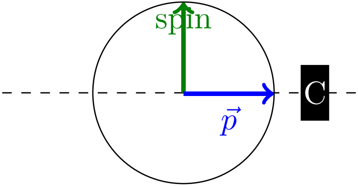
$$A_{up,dn} = \frac{N^{up} - N^{dn}}{N^{up} + N^{dn}} = P\,A \sin(\gamma G f_{rev} t)$$

A: analyzing power, *P* : polarization

$A_{up,dn} = 0$

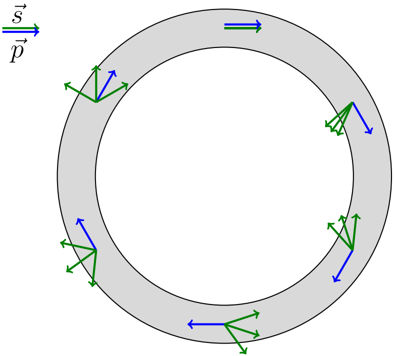


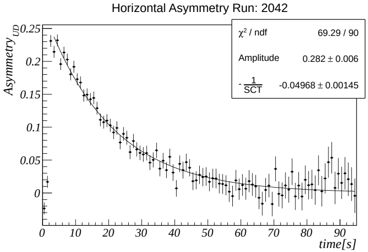
$A_{up,dn} = PA$



Spin Coherence Time (SCT)

Short Spin Coherence Time

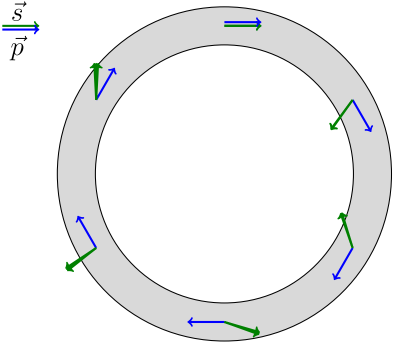


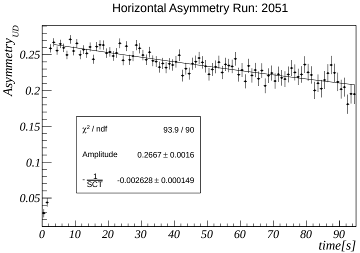


cooled bunched beam ⇒ SCT= 20s

Spin Coherence Time (SCT)

Large Spin Coherence Time

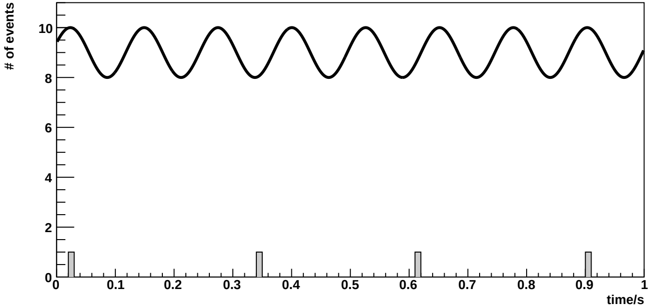




using correction sextupole to correct for higher order effects leads to SCT of 400s

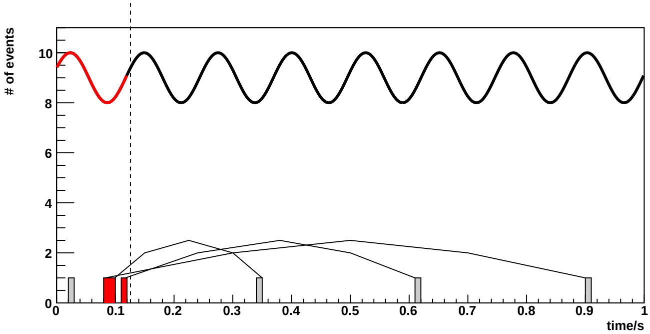
Spin Tune ν

- 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)

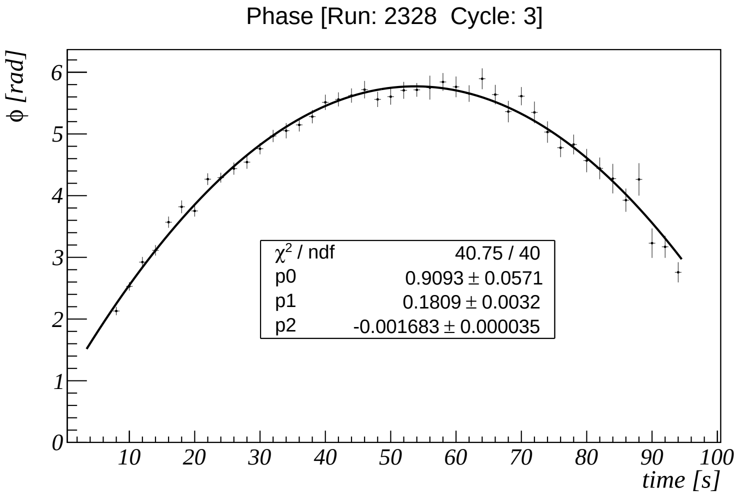


Spin Tune ν

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

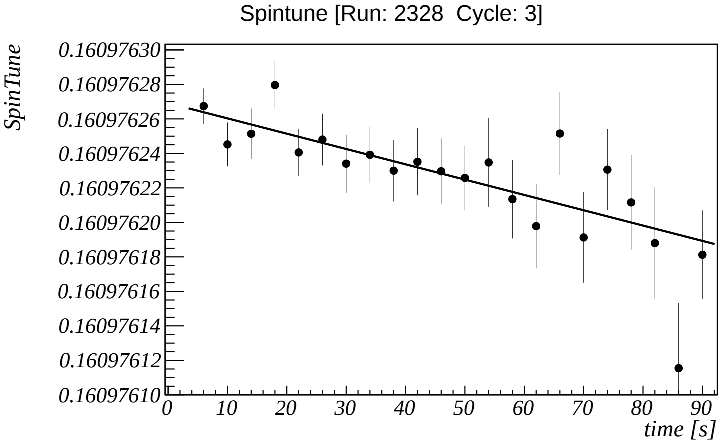


Phase Measurements



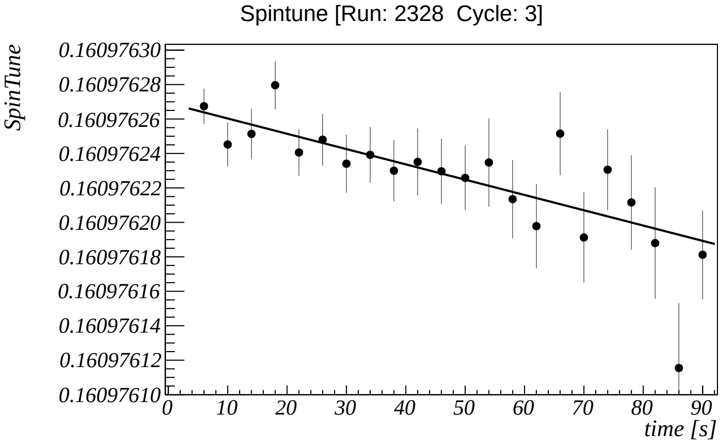
1st derivative gives deviation from assumed spin tune

Spin tune measurements



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

Spin tune measurements



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

We started to do precision physics!

Summary & Outlook

JEDI Collaboration

- **JEDI** = Jülich Electric Dipole Moment Investigations
- $\approx$ 100 members
  (Aachen, Dubna,, Ferrara, Ithaca, Jülich, Krakow, Michigan, St. Petersburg, Minsk, Novosibirsk, Stockholm, Tbilisi, . . .)
- $\approx$ 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

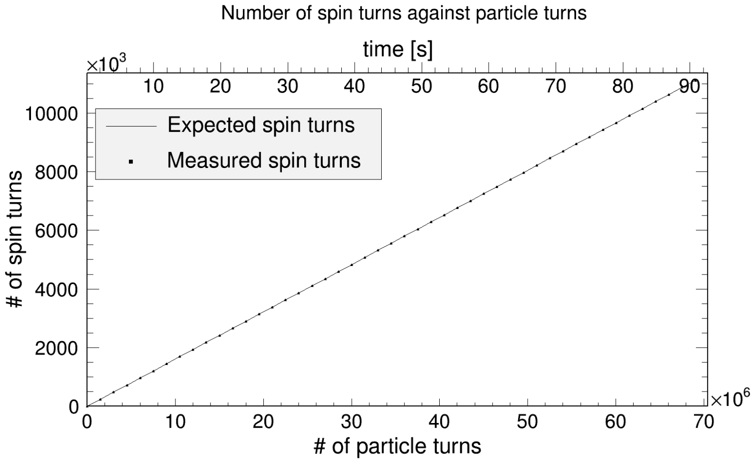
- first direct measurement with upgraded COSY
- all-in-one ring (p,d,^{3}He)

Summary

- EDM of charged particles can be measured in storage rings
- 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
- 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

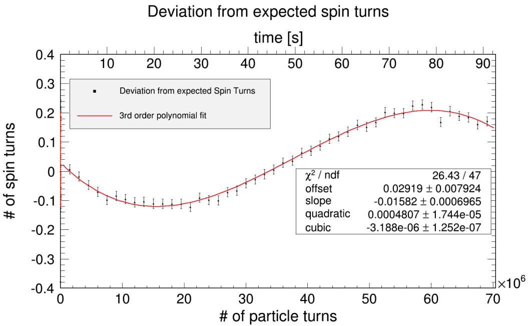
Spare

Spin tune measurements



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)