Measurement of Electric Dipole Moments in Storage Rings

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on behalf of JEDI collaboration

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Outline

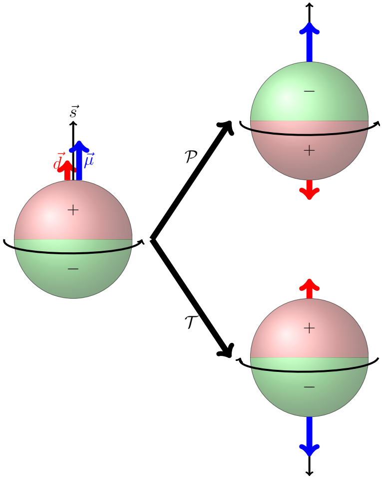
- Introduction:
  Motivation for charged particle Electric Dipole Momemt (EDM) measurements
- Method:
  EDM measurements in Storage Rings
- First test measurements:
  Spin Coherence time, spin tune

Introduction

$\mathcal{CP}$ violation and EDMs

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

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

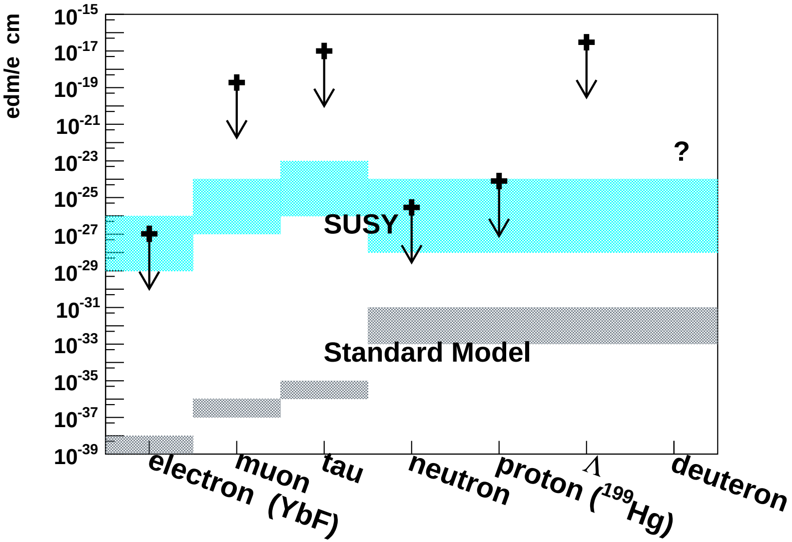


$\Rightarrow$ EDM measurement tests violation of fundamental symmetries $\mathcal{P}$ and $\mathcal{T}$ ($\overset{\mathcal{CPT}}{=}$ $\mathcal{CP}$)

Motivation: matter–anti-matter asymmetry, $\mathcal{CP}$ violation

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



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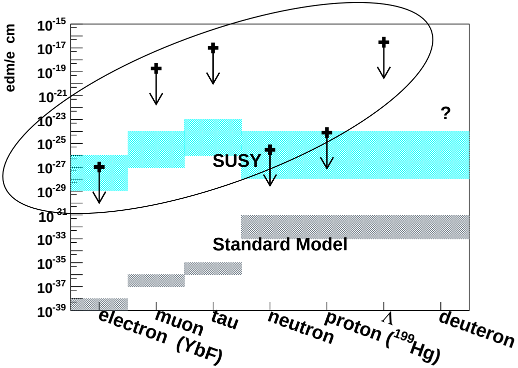

- no EDM observed yet, only limits

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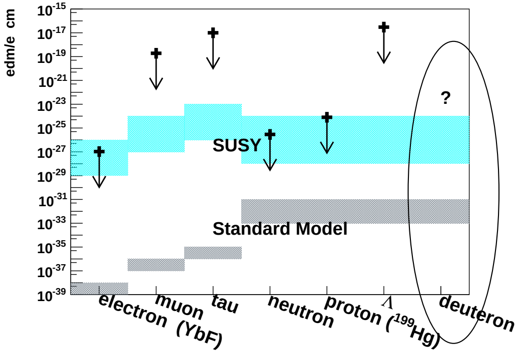

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- no measurement for deuteron (or heavier nuclei),

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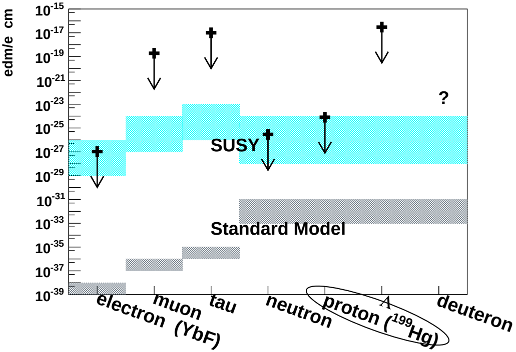

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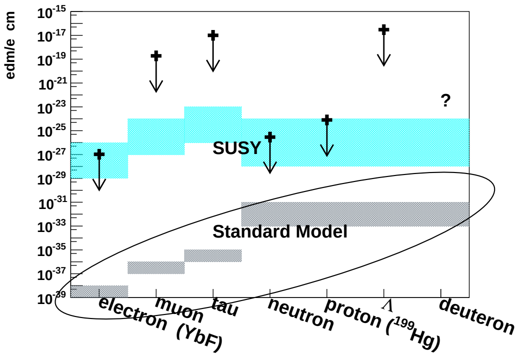

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- Standard Model value essentially 0

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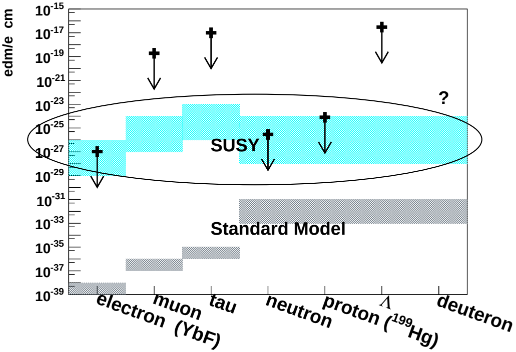

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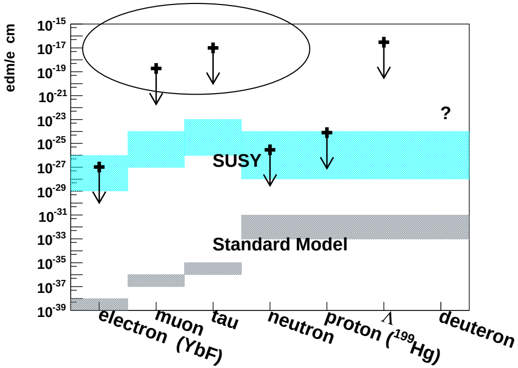
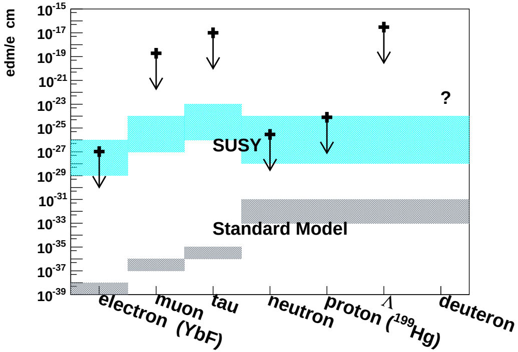
- no measurement for deuteron (or heavier nuclei),
- no direct measurement for proton
- Standard Model value essentially 0
- Beyond SM values accessible by experiments

What do we know about EDMs?



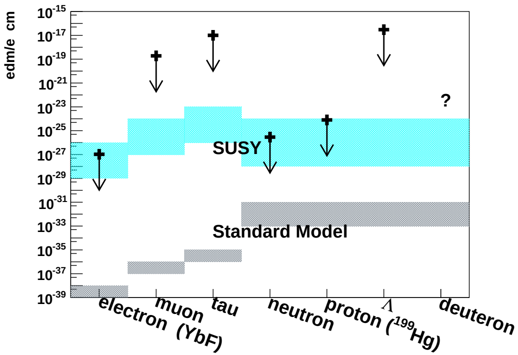
- charged particle EDM measurements less precise

What do we know about EDMs?



- charged particle EDM measurements less precise
- To measure EDMs one needs large **electric** fields. Charged particles are accelerated in **electric** fields

What do we know about EDMs?



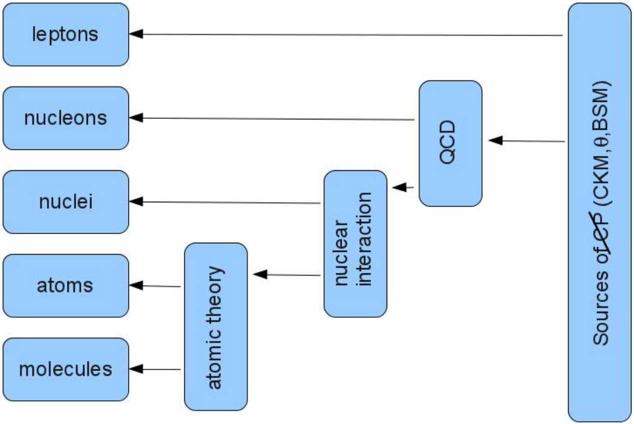
GOAL of JEDI (**J**ülich **E**lectric **D**ipole **I**nvestigations)collaboration:

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



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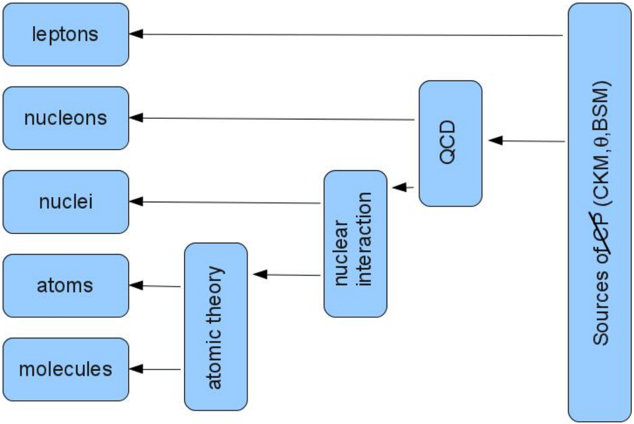


$\Rightarrow$ It is mandatory to measure EDM of many different particles to disentangle various sources of $\mathcal{CP}$ violation.

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·cm

Method:
How to measure charged particle EDMs?

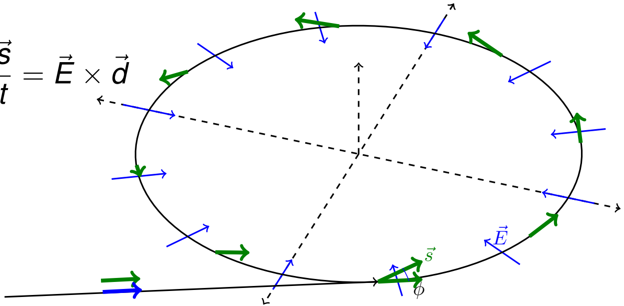
Generic Idea:

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:

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



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

In general: $$\boxed{\frac{\mathrm{d}\vec{s}}{\mathrm{d}t} = \vec{\Omega} \times \vec{s}, \quad \vec{s}||\vec{d}}$$

Thomas-BMT equation

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

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

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

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

$\vec{d}$: electric dipole moment

$\vec{\mu}$: magnetic moment, g:$g-$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 $\Rightarrow$ **frozen spin**

$\eta \approx 10^{-14}$ for $d = 10^{-29} e{\cdot}$cm:

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

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

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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**

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

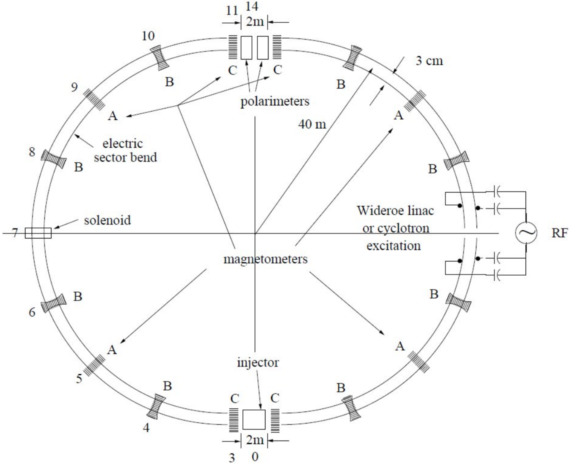


Figure 3: An all-electric storage ring lattice for measuring the electric dipole moment of the proton. Except for having longer straight sections and separated beam channels, the all-in-one lattice of Fig. 1 is patterned after this lattice. Quadrupole and sextupole families, and tunes and lattice functions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

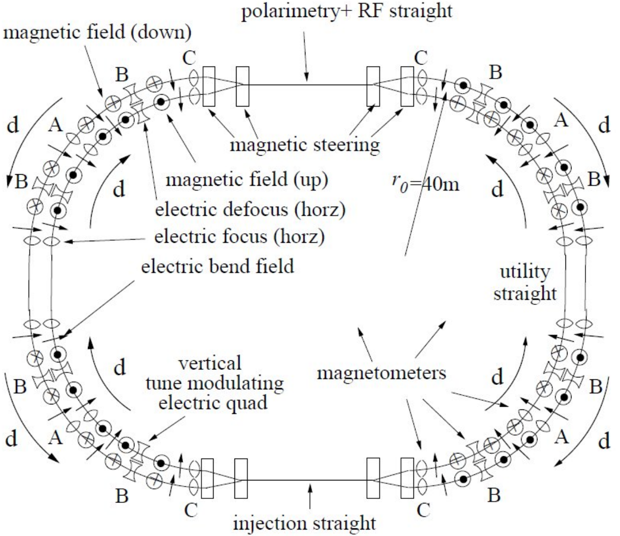


Figure 1: “All-In-One” lattice for measuring EDM’s of protons, deuterons, and helions.

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

3. Pure Magnetic Ring

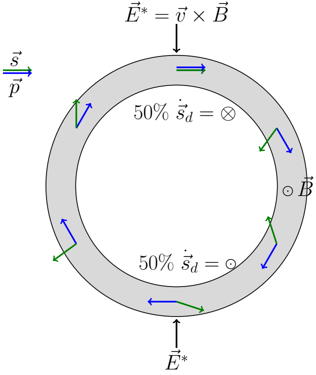
Main advantage:
Experiment can be performed at the existing (upgraded) COSY (COoler SYnchrotron) in Jülich on a shorter time scale!

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

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-$||$.



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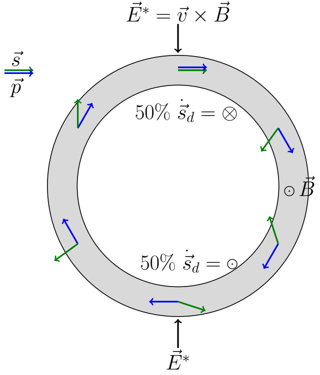

E^* field in the particle rest frame tilts spin due to EDM up and down
$\Rightarrow$ **no net EDM effect**

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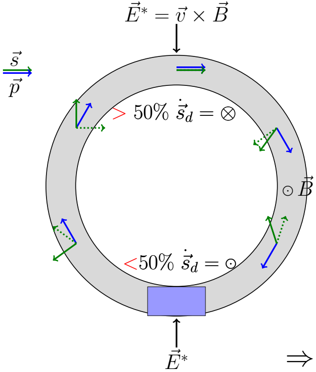

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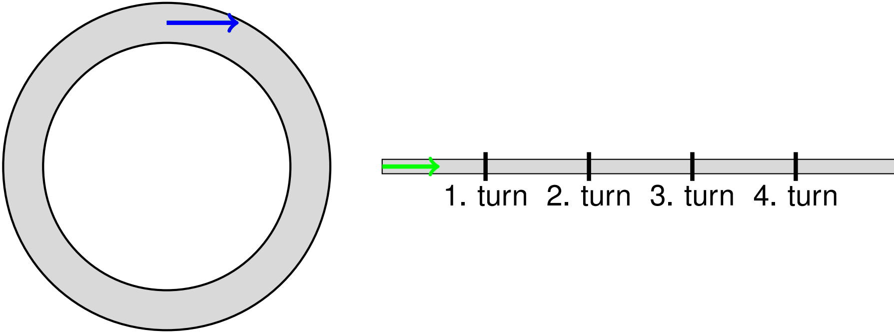
Use resonant "magic Wien-Filter" in ring ($\vec{E} + \vec{v}\times\vec{B} = 0$):
$E^* = 0 \rightarrow$ part. trajectory is not affected but
$B^* \neq 0 \rightarrow$ mag. mom. is influenced

$\Rightarrow$ **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

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

Statistical Sensitivity pure magnetic ring (COSY)

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

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

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

JEDI

Systematics

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

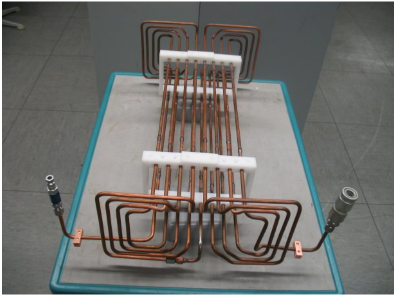
- Difficulty: even small radial magnetic field, B_r can mimic EDM effect if :$\mu B_r \approx dE_r$
- Suppose $d = 10^{-29} e{\cdot}\text{cm}$ in a field of $E = 10\text{MV/m}$
- This corresponds to a magnetic field:
  $$B_r = \frac{dE_r}{\mu_N} = \frac{10^{-22} e\mathrm{V}}{3.1 \cdot 10^{-8} e\mathrm{V/T}}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

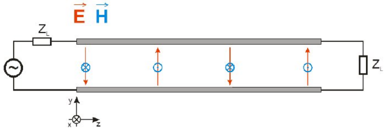
Electrostatic Deflectors

- 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



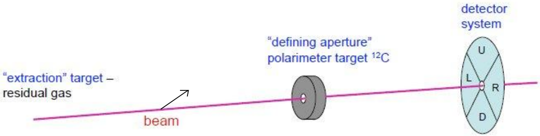
Conventional design
R. Gebel, S. Mey (FZ Jülich)

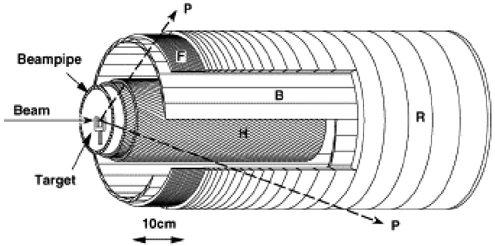


stripline design
D. Hölscher, J. Slim
(IHF RWTH Aachen)

Polarimeter

Principle: Particles hit a target:
Left/Right asymmetry gives information on EDM
Up/Down asymmetry gives information on MDM





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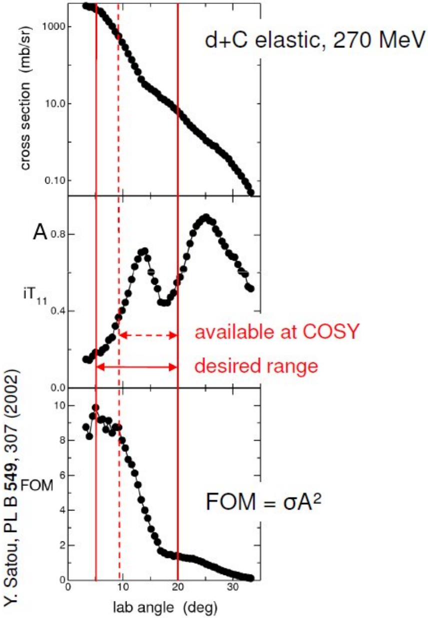
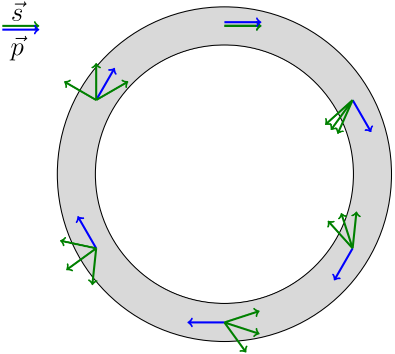


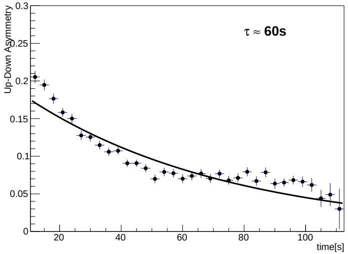
Cross Section &
Analyzing Power
for deuterons

First test measurements: Spin Coherence Time (SCT), spin tune

Spin Coherence Time (SCT)

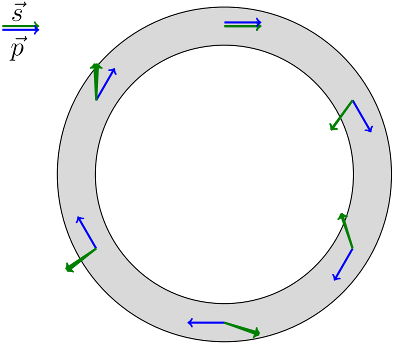
Short Spin Coherence Time

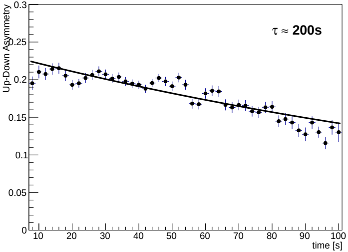




Spin Coherence Time (SCT)

Large Spin Coherence Time

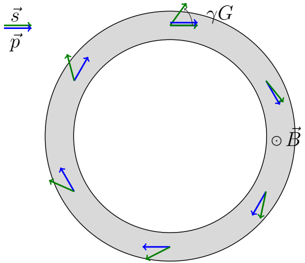




using correction sextupole
(Ed. Stephenson)

Spin tune measurements

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

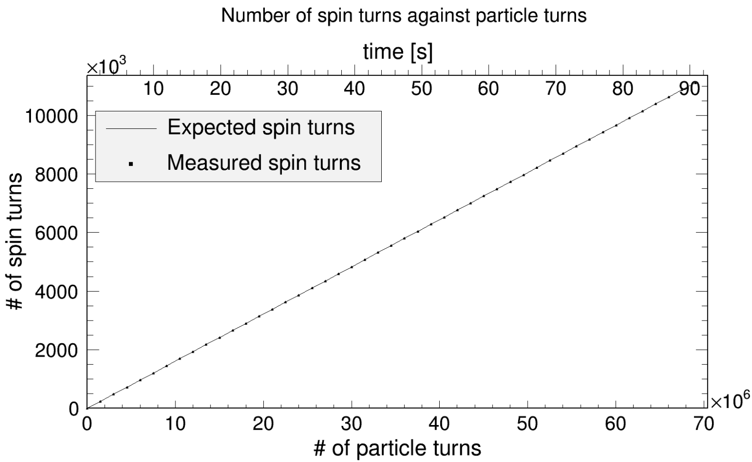


In our case ($p_d = 1$ GeV/c, $\gamma = 1.13$, $G = -0.14256177(72)$)

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

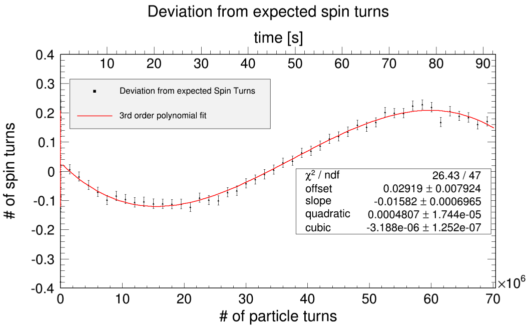
Can be determined by measuring the horizontal polarization of beam

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)

JEDI Collaboration

- **JEDI** = **J**ülich **E**lectric **D**ipole Moment **I**nvestigations
- $\approx$ 80 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

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 at Brookhaven and Jülich to perform such measurements