Electric Dipole Moments – probes of fundamental symmetries

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Outline

Electric Dipole Moments (EDMs)

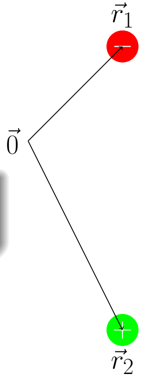
- What is it?
- Why is it interesting?
- What do we know about it?
- How to measure (charged particle) EDMs?

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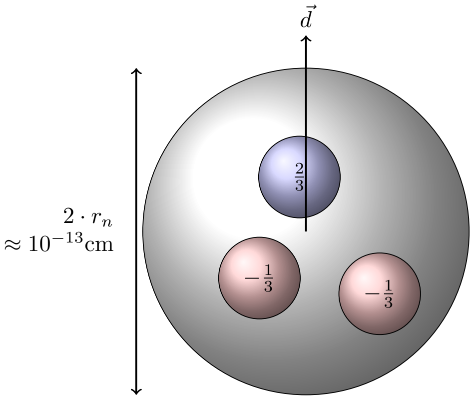
charges	e	e
$\lvert\vec{r}_1 - \vec{r}_2\rvert$	1 Å= 10^{-8}cm	$1\mathrm{fm} = 10^{-13}$cm
EDM		
naive expectation	$10^{-8} e \cdot \mathrm{cm}$	$10^{-13} e \cdot \mathrm{cm}$
observed	water molecule	neutron
	$2 \cdot 10^{-8} e\cdot$ cm	$< 3 \cdot 10^{-26} e\cdot$ cm

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

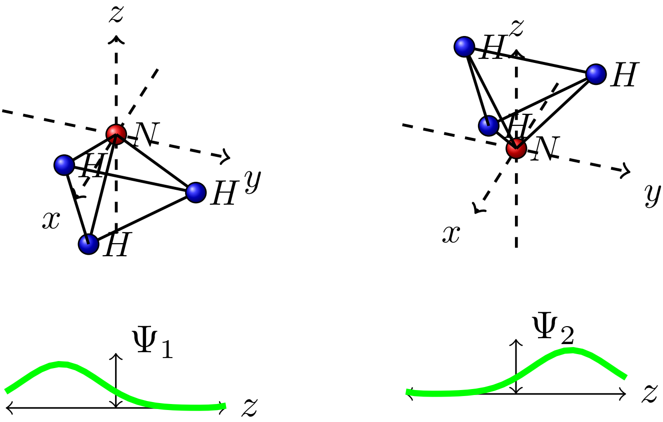
$$\mathcal{P}^{-1}\vec{d}\mathcal{P} = -\vec{d}$$

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)

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

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

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Elementary particles (including hadrons) have a definte parity and cannot posess an EDM
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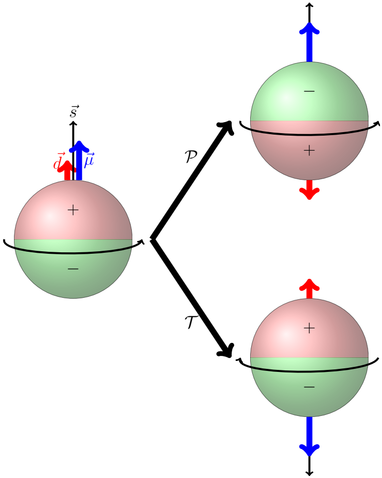
unless

$\mathcal{P}$ 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

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



$\Rightarrow$ 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
$\mathcal{C}$	✓	$\lightning$	✓
$\mathcal{P}$	✓	$\lightning$	✓
$\mathcal{T} \stackrel{CPT}{\to} \mathcal{CP}$	✓	($\lightning$)	(✓)

- $\mathcal{C}$ and $\mathcal{P}$ are maximally violated in weak interactions (Lee, Yang, Wu)
- $\mathcal{CP}$ violation discoverd 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

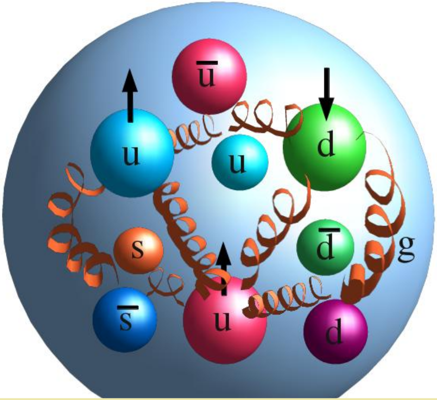
- EDM requires violation of symmetries
- but particles may have large **magnetic** dipole moment (MDM),
- for **structureless** particles theory even predicts that $\mu = g \frac{e\hbar}{2m} \frac{|\vec{S}|}{\hbar}$ with $g = 2$ in leading order

$G = \frac{g-2}{2}$ for various particles:

	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

Nucleon Spin Puzzle



$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Spin		orbital angular momentum	
quarks	gluons	quarks	gluons

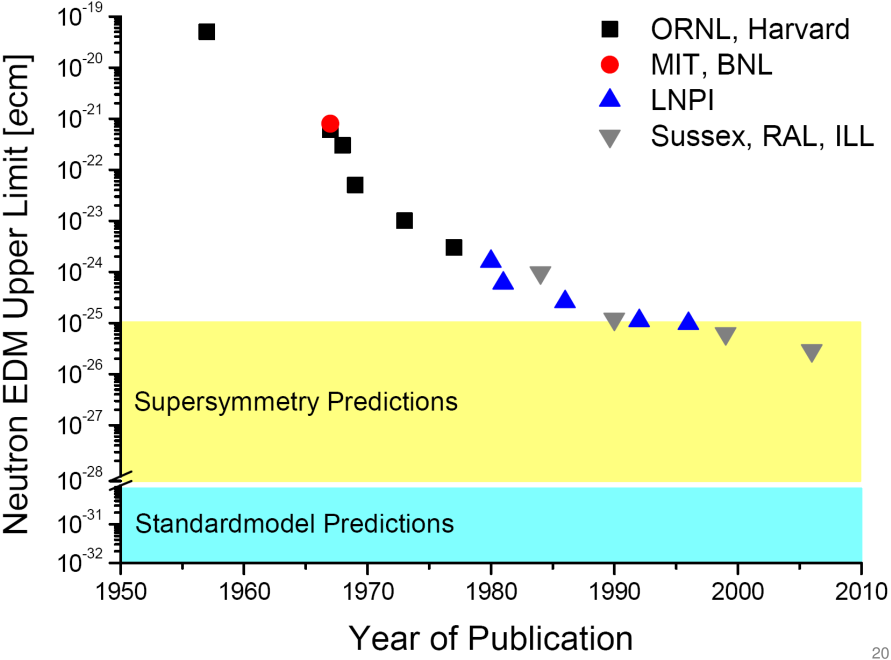
Why is it interesting?

$\mathcal{CP}$ violation

- We are suronded 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?

History of Neutron EDM



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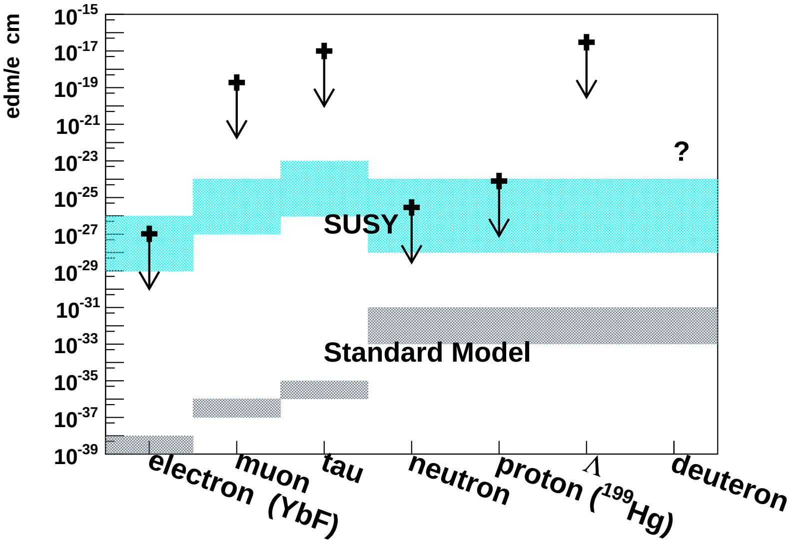

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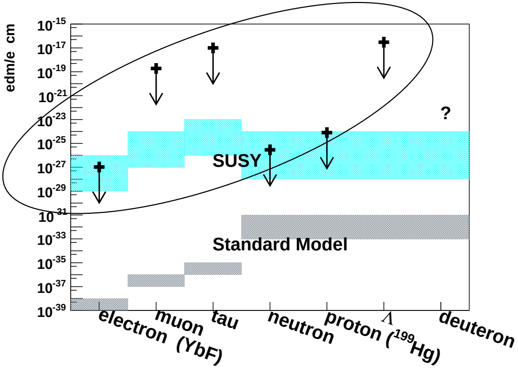
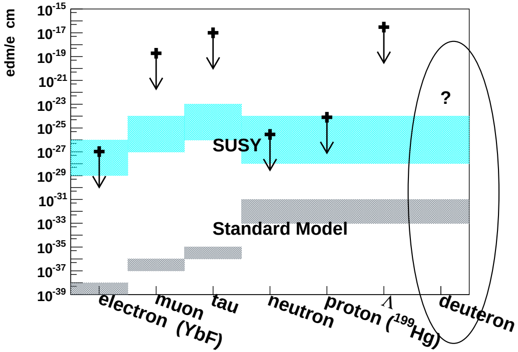


- no EDM observed yet, only limits

What do we know about EDMs?



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- no measurement for deuteron (or heavier nuclei),

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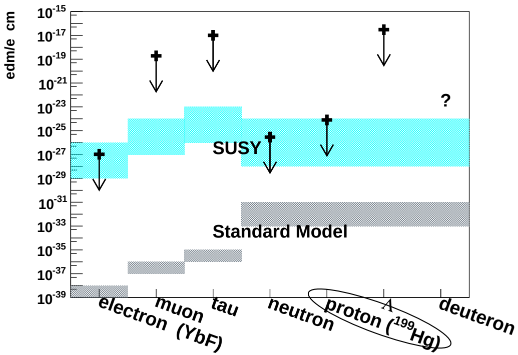

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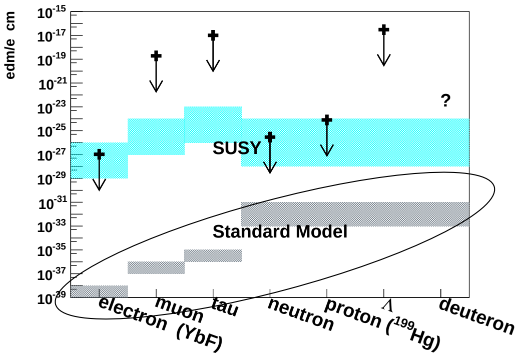

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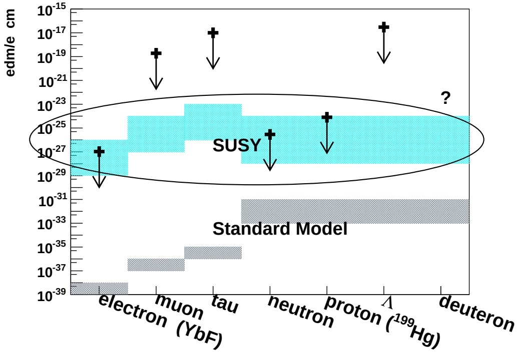

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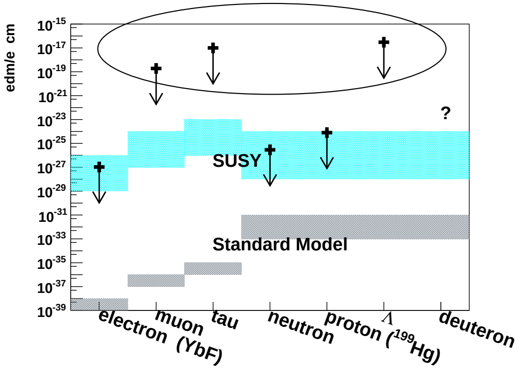
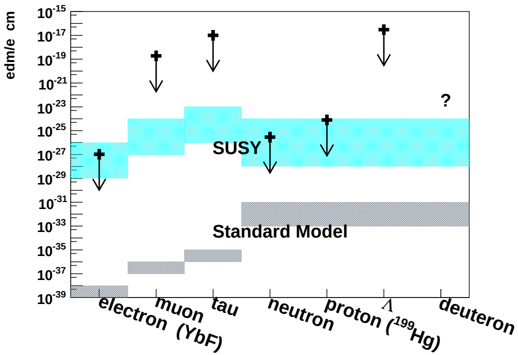
- Standard Model value essentially 0
- Beyond SM values accessible by experiments

What do we know about EDMs?



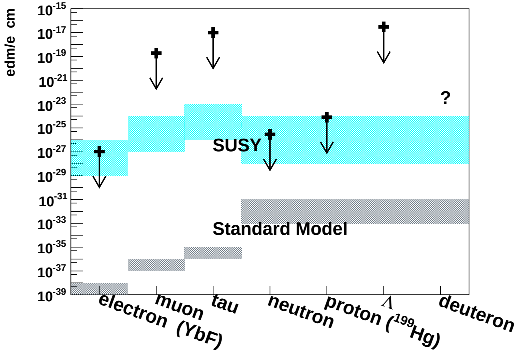
- charged particle EDM measurements less precise

What do we know about EDMs?



- charged particle EDM measurements less precise
- To measure EDMs one needs large **electric** fields. Charged particles are accelerated 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 $10^{-29}\,e\,\mathrm{cm}$

How to measure charged particle EDMs?

Measurement of charged particle EDMs

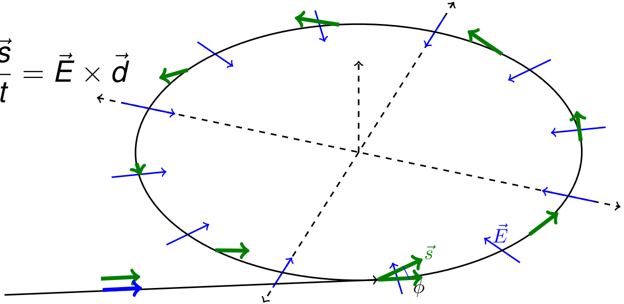
Generic Idea:

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:

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



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

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

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 $G > 0$

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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**

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

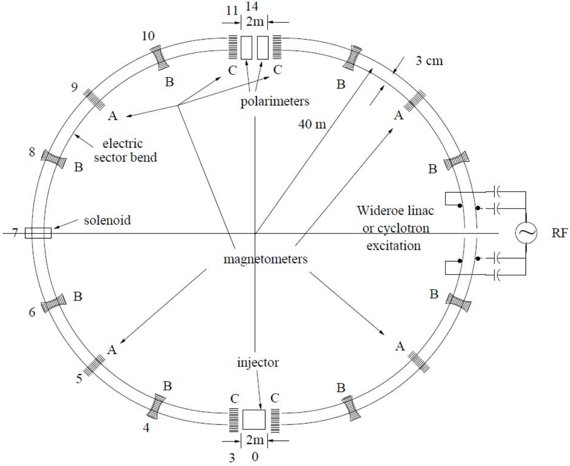


Figure 3: An all-electric storage ring lattice for measuring the electric dipole moment of the proton. Except for having longer straight sections and separated beam channels, the all-in-one lattice of Fig. 1 is patterned after this lattice. Quadrupole and sextupole families, and tunes and lattice functions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

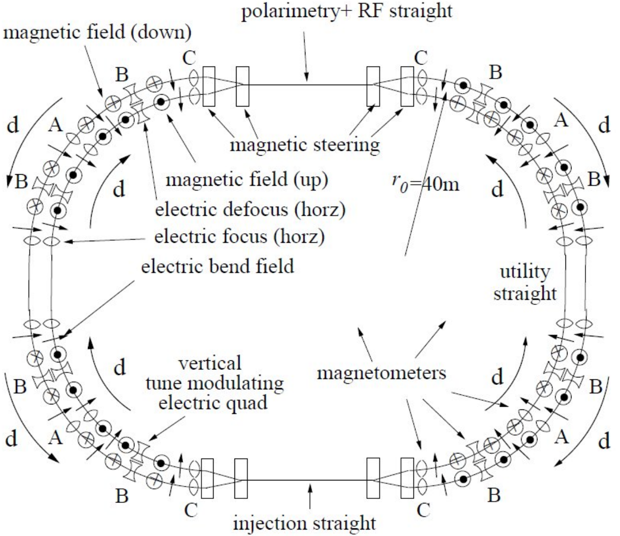


Figure 1: "All-In-One" lattice for measuring EDM's of protons, deuterons, and helions.

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

3. Pure Magnetic Ring

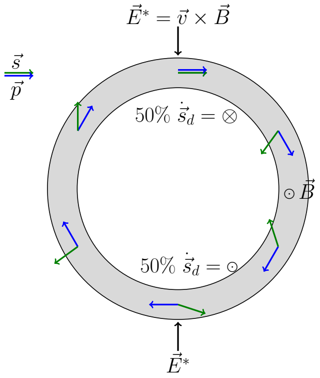
Main advantage:
Experiment can be performed at the existing (upgraded) COSY (COoler SYnchrotron) in Jülich on a shorter time scale!

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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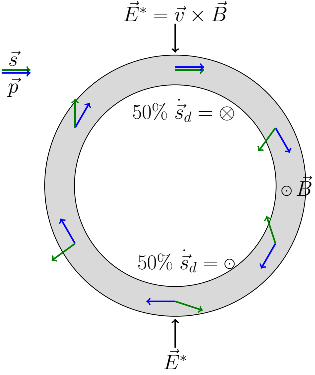

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$\Rightarrow$ **no net EDM effect**

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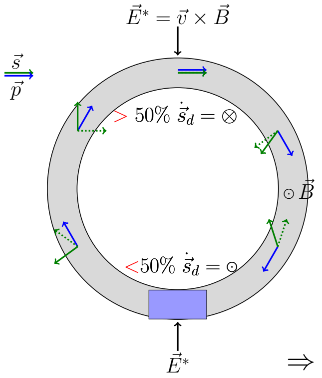

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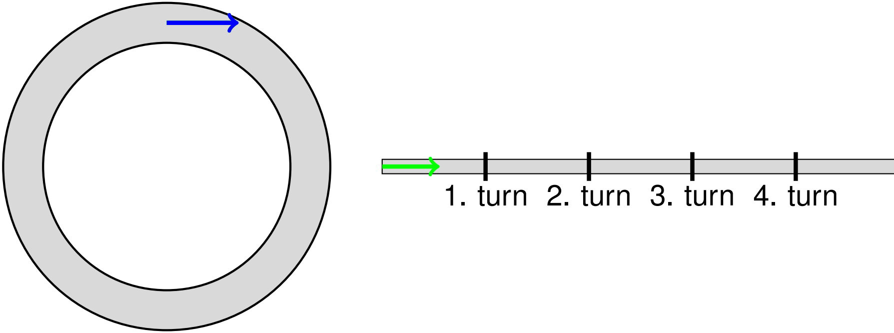
Use resonant "magic Wien-Filter" in ring ($\vec{E} + \vec{v} \times \vec{B} = 0$):
$E^* = 0 \rightarrow$ part. trajectory is not affected but
$B^* \neq 0 \rightarrow$ mag. mom. is influenced

$\Rightarrow$ **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

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

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

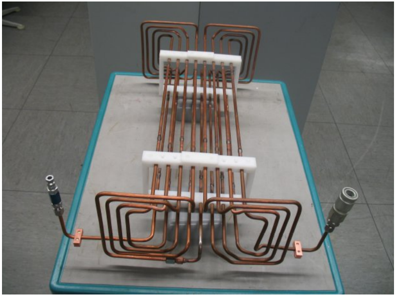
$\Rightarrow \sigma \approx 10^{-29} e\cdot$cm/year (for magnetic ring $\approx 10^{-24} e\cdot$cm/year)
Expected signal $\approx$ 3nrad/s (for $d = 10^{-29} e\cdot$cm)
(BNL proposal)

JEDI

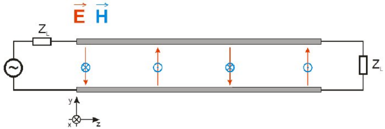
Electrostatic Deflectors

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

Wien filter



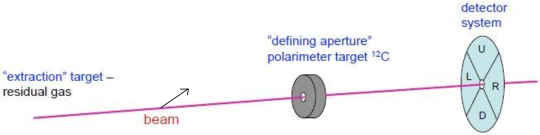
Conventional design
R. Gebel, S. Mey (FZ Jülich)

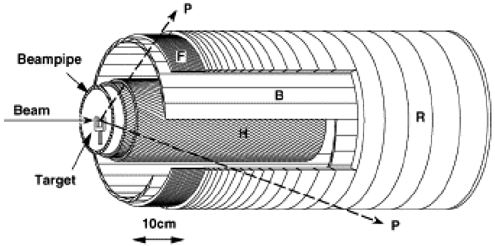


stripline design
D. Hölscher, J. Slim
(IHF RWTH Aachen)

Polarimeter

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





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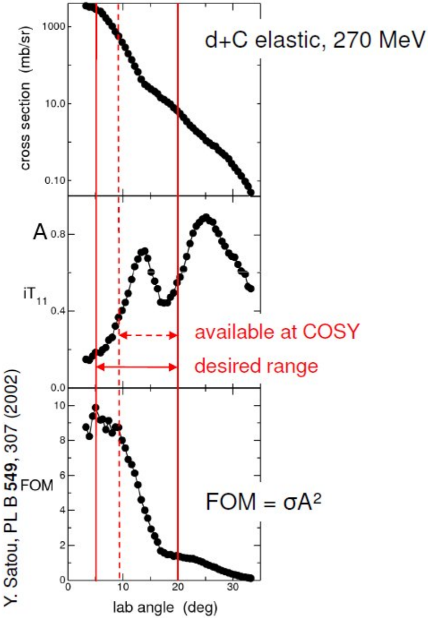
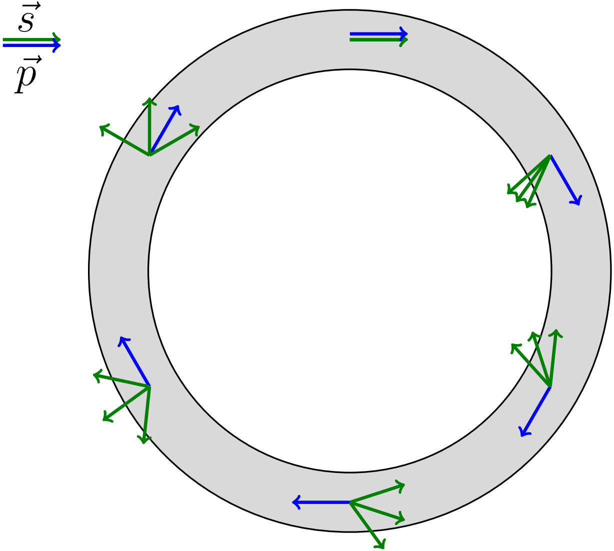


Cross Section &
Analyzing Power
for deuterons

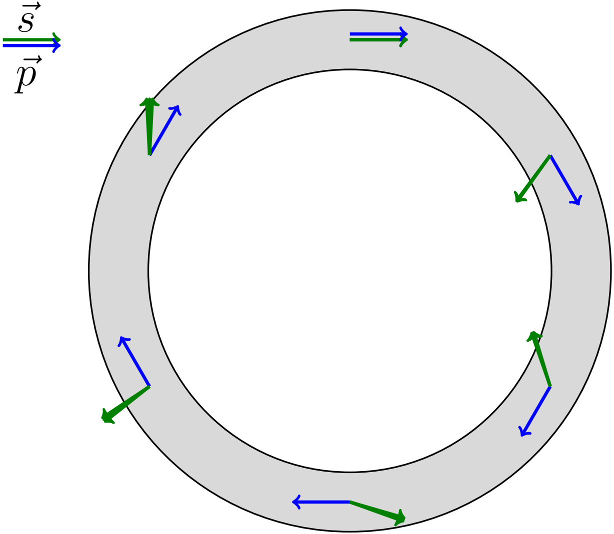
Spin Coherence Time (SCT)

Short Spin Coherence Time

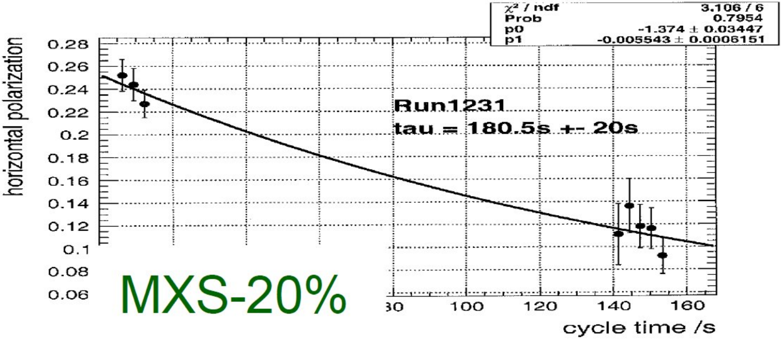


Spin Coherence Time (SCT)

Large Spin Coherence Time



Results on Spin Coherence Time (SCT)



Spins decohere during storage time
results form Cosy run May 2012 using correction sextupole

⇒ SCT increase from a few s to ≈ 200s already reached

(Ed. Stephenson)

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:
  $$B_r = \frac{dE_r}{\mu_N} = \frac{10^{-22} e\mathrm{V}}{3.1 \cdot 10^{-8} e\mathrm{V}/\mathrm{T}} \approx 3 \cdot 10^{-17}\mathrm{T}$$
  (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

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)

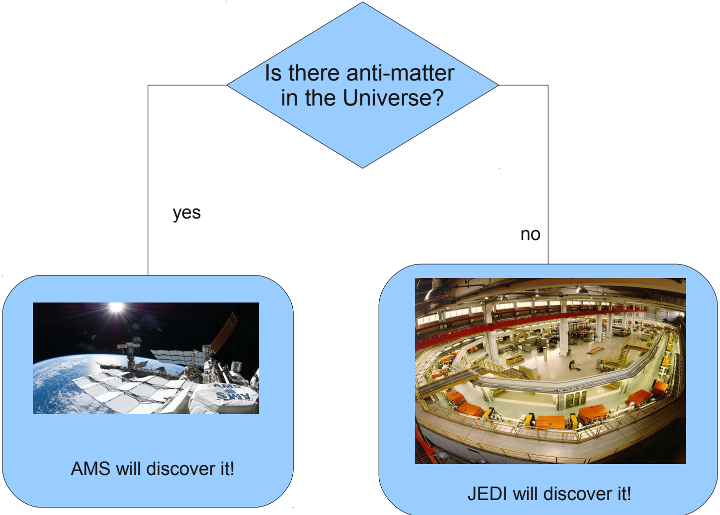
Jülich

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

JARA FAME

JARA=Jülich Aachen Research Alliance

New section founded: FAME (=Forces and Matter Experiments)



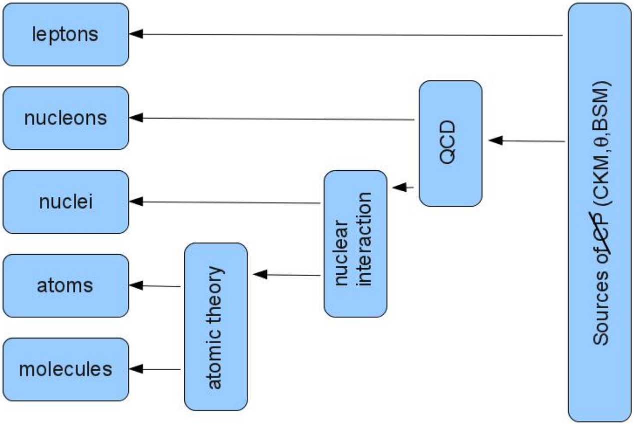
Summary

Summary

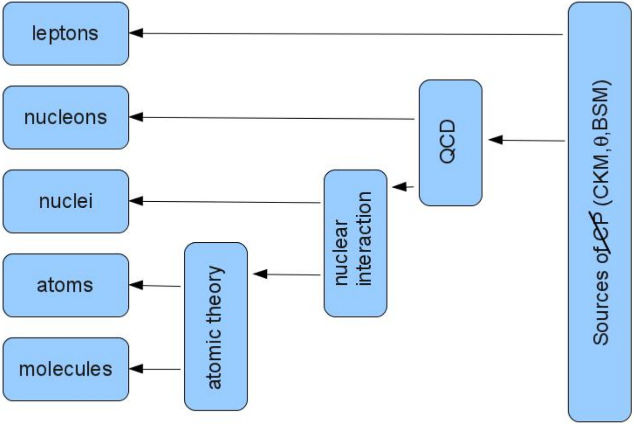
- EDM of charged particles can be measured in storage rings
- EDMs of elementary particles are of high interest to disentangle various sources of $\mathcal{CP}$ violation searched for to explain matter - antimatter asymmetry in the Universe
- Experimentally very challenging because effect is tiny
- Efforts at Brookhaven and Jülich to perform such measurements

Spare

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.