Measurement of Permanent Electric Dipole Moments of Proton, Deuteron and Light Nuclei in Storage Rings

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on behalf of the JEDI collaboration

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Outline

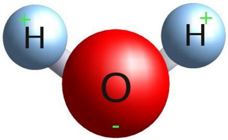
Electric Dipole Moments (EDMs)

- What is it?
- Why is it interesting?
- What do we know about it?
- How to measure it?

What is it?

Electric Dipole Moments: What is it?

- EDM: Permanent spatial separation of positive and negative charges
- Water molecule: $d = 2 \cdot 10^{-9} e \cdot$ cm



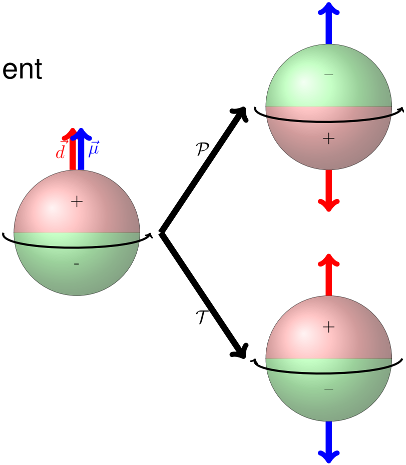
- Water molecule can have large dipole moment because ground state has two degenerate states of different parity
- This is not the case for proton.
  Here the existence of a permanent EDM requires both $\mathcal{T}$ and $\mathcal{P}$ violation, i.e. assuming $\mathcal{CPT}$ invariance this implies $\mathcal{CP}$ violation:

That makes it interesting!

$\mathcal{T}$ and $\mathcal{P}$ violation of EDM

$\vec{d}$: EDM

$\vec{\mu}$: magnetic moment

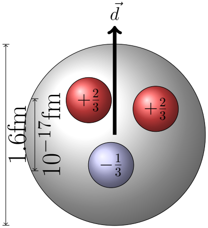


$\mathcal{T}$ violation $\overset{\mathcal{CPT}}{\rightarrow}$ $\mathcal{CP}$ violation

Why is it interesting?

Why is it interesting?

- $\mathcal{CP}$ violation of Standard Model predicts Proton EDM $< 10^{-31}\,e{\cdot}\mathrm{cm}$
- This corresponds to a separation of two $u-$quarks from a $d-$quark by $\approx 10^{-30}$cm, i.e 10^{-17} of the proton radius!



- Not reachable experimentally in foreseeable future
- Extensions of Standard Model predict EDM as large as $10^{-24}\,e{\cdot}\mathrm{cm}$
- Sources of $\mathcal{CP}$ outside the realm of SM are needed to explain matter/anti-matter imbalance in universe

What do we know about (hadron) EDMs?

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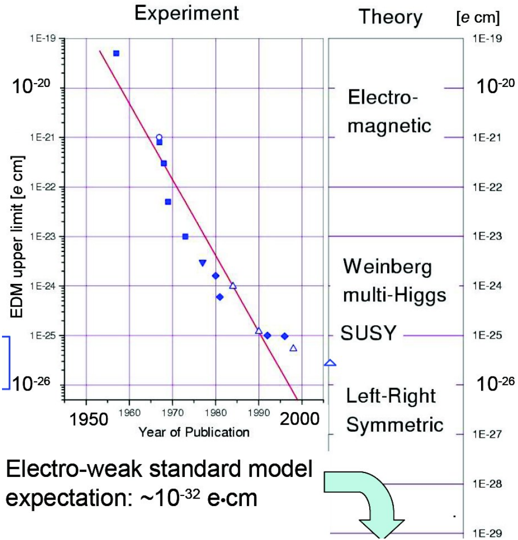
Particle/Atom	Current Limit/$e\cdot$cm
Neutron	$< 3 \cdot 10^{-26}$
^{199}Hg	$< 3.1 \cdot 10^{-29}$
$\to$ Proton	$< 7.9 \cdot 10^{-25}$
Deuteron	?
^{3}He	?

- direct measurement only for neutron
- proton deduced from atomic EDM limit
- no measurement for deuteron (or other nuclei)

History of Neutron EDM



from K. Kirch

50 years of effort

Extensions of SM allow for large EDMs

Sources of $\mathcal{CP}$ violation

$\mathcal{CP}$ can have different sources

- Weak Interaction (unobservably small)
- QCD θ term (limit set by neutron EDM measurement)
  ——— Part of Standard Model ———
- sources beyond SM

$\Rightarrow$ It is important to measure neutron **and** proton **and** deuteron **and** . . . EDMs in order to disentangle various sources of $\mathcal{CP}$ violation.

How to measure it?

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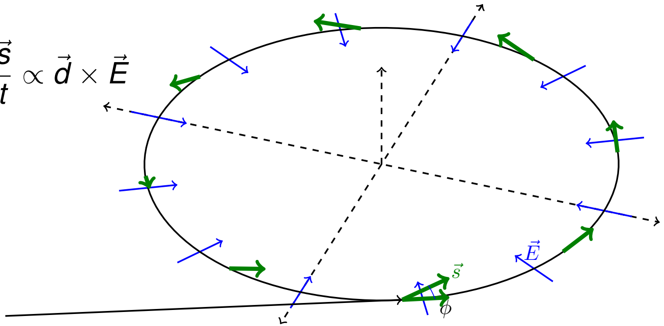
General Idea:

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:

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



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

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

"Thomas-BMT" formula

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

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

Several Options:

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Several Options:

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

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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

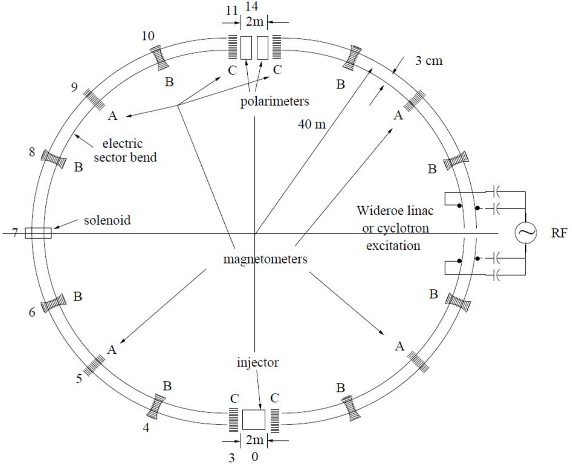


Figure 3: An all-electric storage ring lattice for measuring the electric dipole moment of the proton. Except for having longer straight sections and separated beam channels, the all-in-one lattice of Fig. 1 is patterned after this lattice. Quadrupole and sextupole families, and tunes and lattice functions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

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

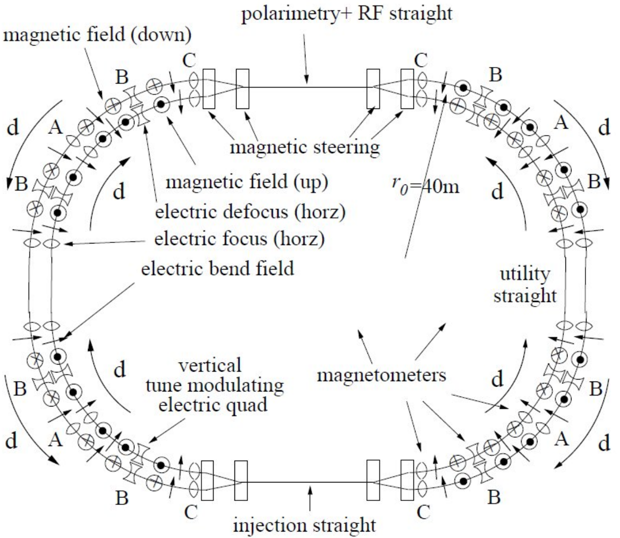


Figure 1: "All-In-One" lattice for measuring EDM's of protons, deuterons, and helions.

Under discussion in Jülich (design: R. Talman)

3. Pure Magnetic Ring

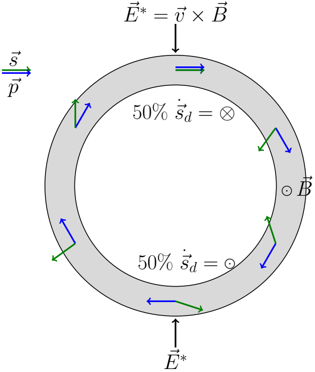
Main advantage:
Experiment can be performed at the existing (upgraded) COSY (COoler SYnchrotron) in Jülich on a shorter time scale!

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

3. Pure Magnetic Ring

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

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



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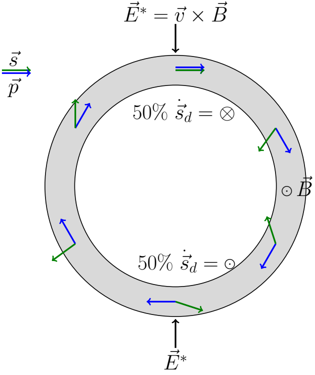

E^* field in the particle rest frame tilts spin due to EDM up and down
$\Rightarrow$ **no net EDM effect**

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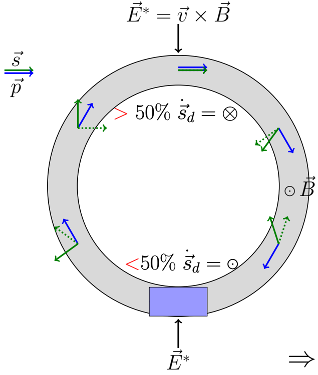

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Use resonant "magic Wien-Filter" in ring ($\vec{E} + \vec{v}\times\vec{B} = 0$):
$E^* = 0 \rightarrow$ part. trajectory is not affected but
$B^* \neq 0 \rightarrow$ mag. mom. is influenced

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

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

$$\sigma \approx \frac{\hbar}{\sqrt{N f T \tau_p} P E A}$$

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

$\Rightarrow \sigma \approx 10^{-29} e\cdot$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)

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

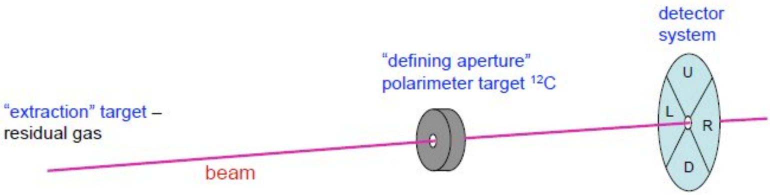
Solution: Use two beams running clockwise and counter clockwise, Separation of the two beams is sensitive to B_r

Main Challenges

- Spin Coherence Time (SCT)$\approx$ 1000s
- Beam positioning $\approx$ 10nm (relative between CW-CCW)
- Polarimetry on 1 ppm level
- Field Gradients $\approx$ 10MV/m

Polarimeter

Principle: Particles hit a target:
Left/Right asymmetry gives information on EDM
Up/Down asymmetry gives information on g-2



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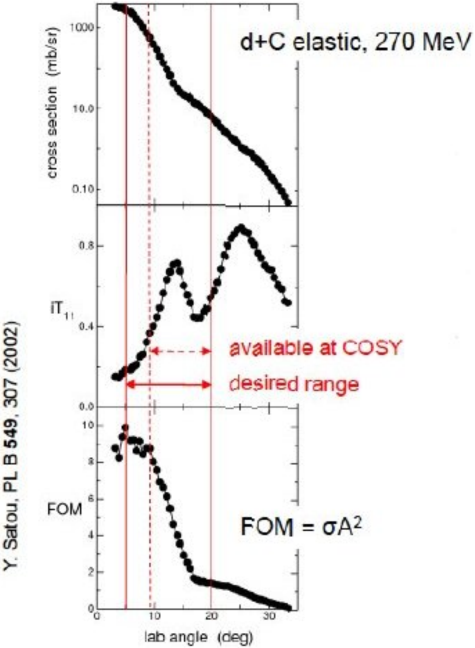
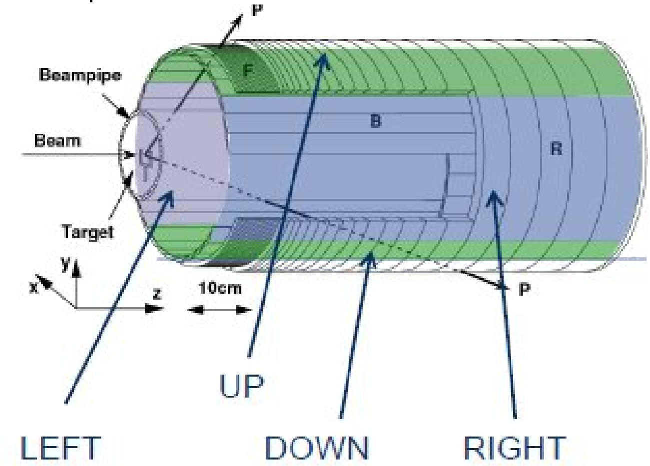


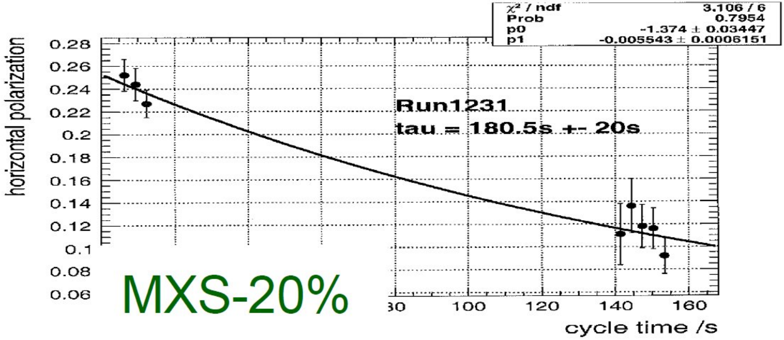
Cross Section &
Analyzing Power
for deuterons

Polarimeter

Available at COSY for tests:
EDDA polarimeter



Results on Spin Coherence Time (SCT)



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

⇒ SCT of ≈ 200s already reached

(Ed. Stephenson)

pEDM at Brookhaven

Time-lines:

2013-2014	R&D preparation
2014	final ring design
2015-2017	ring/beam-line construction
2017-2018	Installation

Stepwise approach of JEDI project in Jülich

JEDI = Jülich Electric Dipole Moment Investigation
(Collaboration since March 2012, $\approx$ 70 members, still growing)

1	Spin coherence time studies Systematic Error studies	COSY
2	COSY upgrade first direct measurement at $10^{-24} e\cdot$ cm	COSY COSY
3	Build dedicated ring for p,d and ^{3}He	
4	EDM measurement at $10^{-29} e\cdot$ cm	Dedicated ring

Time scales: Steps 1 and 2 $<$5 years
Steps 3 and 4 $>$5 years

Storage Ring EDM Efforts

Common R&D work

- Spin Coherence Time
- BPMs
- Spin Tracking
- Polarimetry
- . . .

BNL

- all electric ring (p)

Jülich

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

Summary

- EDM of (charged) hadrons are of high interest to disentangle various sources of $\mathcal{CP}$ violation searched for to explain matter - antimatter asymmetry in the Universe
- Measurements of p,d and ^{3}He needed in addition to neutron
- efforts at Brookhaven and Jülich to perform such measurements

EDM Workshop at ECT* Trento

EDM Searches at Storage Rings

October 1-5, 2012

http://www.ectstar.eu

Organizers:

Frank Rathmann (Jülich)
Hans Ströher (Jülich)
Andreas Wirzba (Jülich)

Mei Bai (BNL)
William Marciano (BNL)
Yannis Semertzidis (BNL)