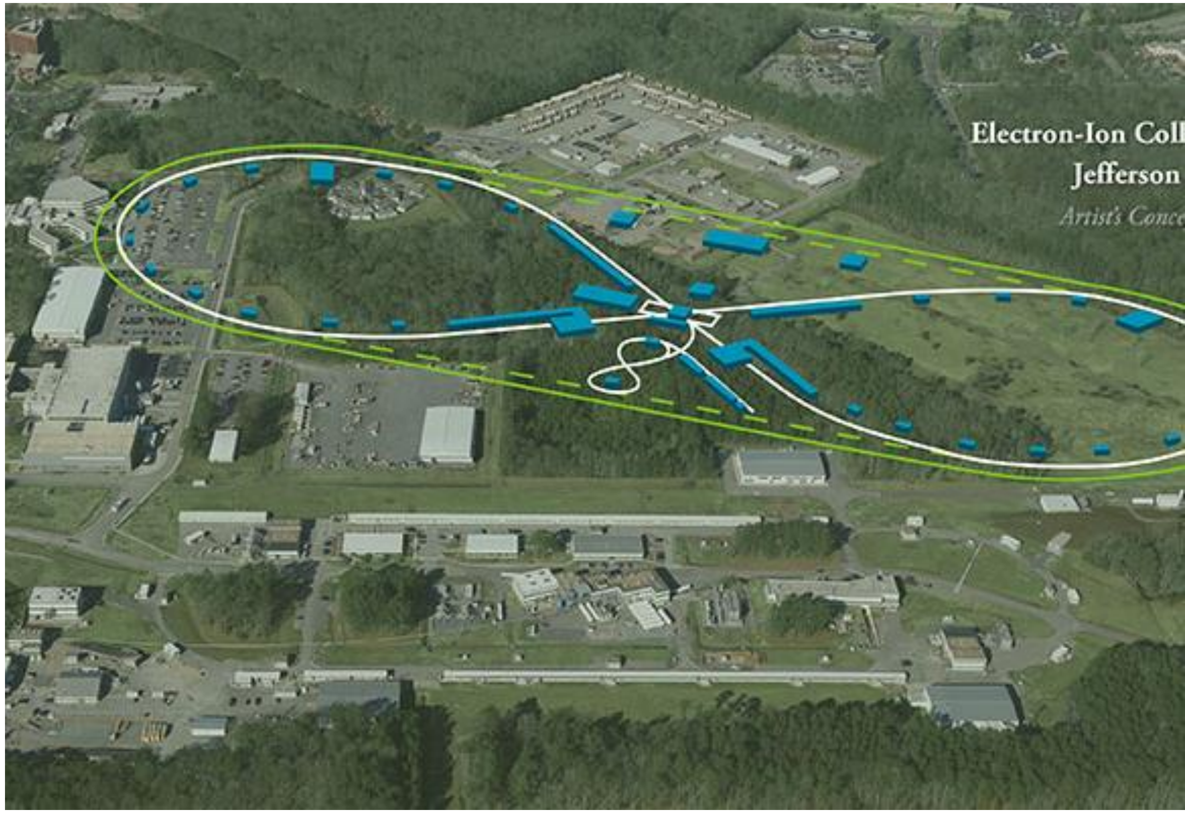
Measuring Charged Hadrons EDM in JLEIC Figure-8 Rings

LDRD proposal aims to enhance JLEIC physics reach by exploring possible measurements of proton and deuteron permanent Electric Dipole Moment (EDM) in JLEIC Figure-8



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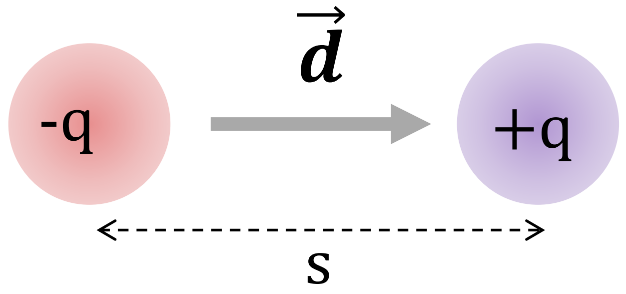
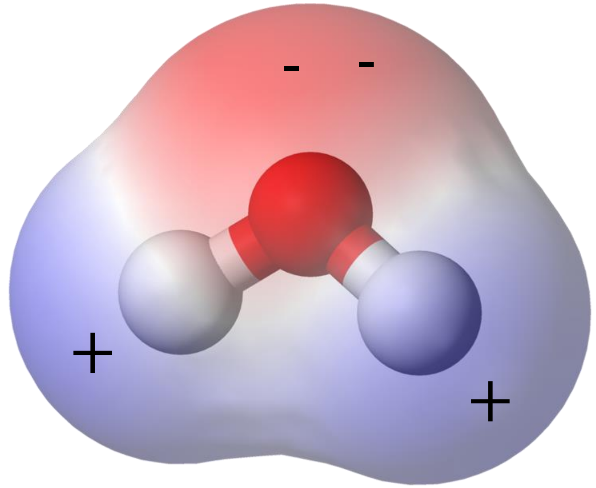
Electric Dipole Moment

Definition: Permanent spatial separation of positive and negative charges



$$\vec{d} = q \cdot \vec{s}$$



- Example: Water molecule has large permanent EDM because of degenerate ground state with different parity (not a parity eigenstate):

$$d_{H_2O} \sim 6.15 \times 10^{-30}\ \mathrm{C \cdot m} \sim 3.84 \times 10^{-9}\ \mathrm{e \cdot cm}$$

- This not true for electron, proton, deuteron, ...: existance of permanant EDM violates both T and P discrete symmetries and assuming $\mathbf{C}\mathbf{P}T$ invariance this would imply $\mathbf{CP}$ violation

$\mathbf{C}\mathbf{P}\boldsymbol{T}$ Invariance

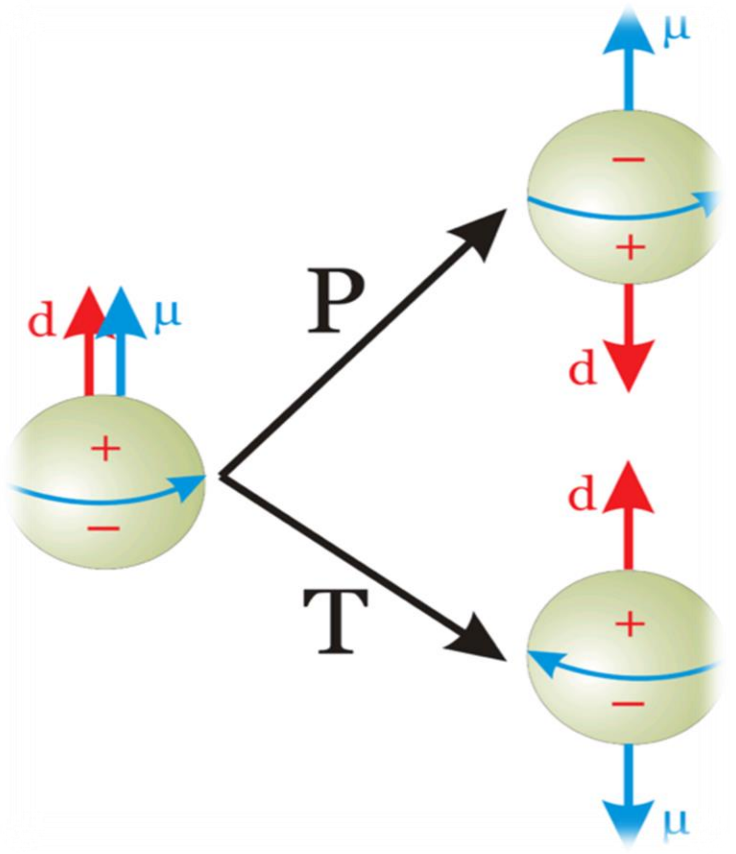
Parity (space inversion): $\boldsymbol{P}$: $\vec{\boldsymbol{x}} \rightarrow -\vec{\boldsymbol{x}}$

Time Reveral (reverse time derivative): $\boldsymbol{T}$: $\boldsymbol{t} \rightarrow -\boldsymbol{t}$

Charge Conjugation: **Change sign of electrical charge (particle to anti-particle)**

- All interactions described by a local Lorentz invariant gauge theory must be invariant under combined $\mathbf{C}\mathbf{P}\boldsymbol{T}$ transformation
- New sources of $\mathbf{C}\mathbf{P}$ violation (beyond that present in CKM quark weak mixing matrix) are needed to explain matter-antimatter asymmetry in universe

T and P Violation of Permanent EDM



$\vec{d}$: EDM (aligned with spin)

$$\vec{d} = G_E \frac{e\hbar}{mc} \vec{S}$$

$\vec{\mu}$: Magnetic Dipole Moment

$$\vec{\mu} = (G_M + 1) \frac{e\hbar}{mc} \vec{S}$$

Spin precession for particle at rest ($\vec{v} = 0$):

$$\frac{d\vec{S}}{dt} = \frac{e\hbar}{mc}\left((G_M + 1)\vec{S} \times \vec{B} + G_E \vec{S} \times \vec{E}\right)$$

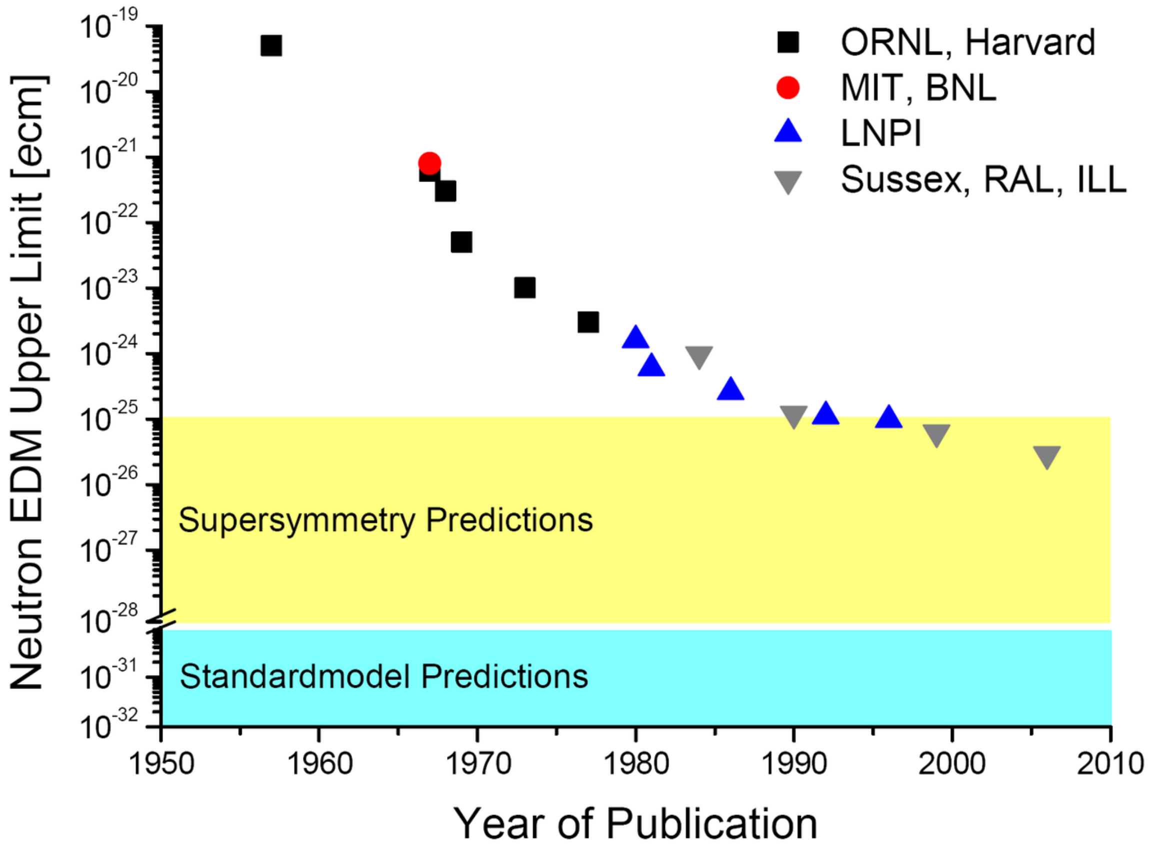
$\boldsymbol{P}$	$\vec{E} \to -\vec{E},$	$\vec{B} \to +\vec{B},$	$\vec{S} \to +\vec{S}$
$\boldsymbol{T}$	$\vec{E} \to +\vec{E},$	$\vec{B} \to -\vec{B},$	$\vec{S} \to -\vec{S}$

Permanent EDMs violate both $\boldsymbol{P}$ and $\boldsymbol{T}$ symmetry, therefore $\boldsymbol{CP}$ must be violated

Measured EDMs

- Electron and Proton EDMs are deduced from neutral atom/molecule measurements
- Direct measurement only for neutron and muon
- Muon EDM limit is from muon $g-2$ expreiment
- No measurement of deuteron or any other nuclei

Particle/Atom/ Molecule	Current Limit $(e \cdot cm)$	Standard Model $(e \cdot cm)$
ThO → Electron	$< 1.1 \times 10^{-29}$	10^{-40}
Muon	$< 1.8 \times 10^{-19}$	10^{-36}
^{199}Hg → Proton	$< 5.4 \times 10^{-24}$	10^{-32}
Neutron	$< 3.0 \times 10^{-26}$	10^{-32}



(1) Nature **562**, 355–360 (2018)
(2) Phys. Rev. D **80**, 052008 (2009)
(3) Phys. Rev. Lett. **116**, 161601 (2016)
(4) Phys. Rev. D **92**, 092003 (2015)

Charged Hadrons EDM

- For all EDM experiments (neutron, proton, atom, molecule), measure interaction of $\vec{d}$ with electric field $\vec{E}$

- For charged particles: use a storage ring
  - Wait for build-up of vertical polarization $s_\perp$
  - Measure $s_\perp$ using polarimeter
  - Must suppress G_M spin precession

- Among charged hadrons, deuteron has smallest anomalous magnetic moment:
  - Deuteron EDM: $d_d = d_p + d_n + \theta_{QCD}$
  - Theoretical value: $d_d = 2.8 \times 10^{-31}\ e \cdot cm$
  - If deuteron is size of Earth, this corresponds to charge separation of up and down quarks of size of an atom

Nuclei	g-Factor	Anomalous Magnetic Moment (μ_N) $G_M = \frac{g-2}{2}$	Spin - Parity
n	-3.83	-2.91	$\frac{1}{2}^+$
p	5.59	1.79	$\frac{1}{2}^+$
d	1.72	-0.14	1^+
^{3}H	5.96	1.98	$\frac{1}{2}^+$
^{3}He	-2.26	-2.13	$\frac{1}{2}^+$

CP-violating strong interaction term

(1) Nuclear Physics A **963**, 33 (2017)

Generalized Thomas-BMT Spin Precession Equation

$$\frac{d\vec{S}}{dt} = \frac{e\hbar}{mc}\vec{S} \times \left[G_M\vec{B} + (G_M - \frac{1}{\gamma^2 - 1})\vec{v} \times \vec{E} + \ G_E(\vec{E} + \vec{v} \times \vec{B} \right]$$

- Three choices for storage rings:
  1. Electric Ring:
     with $\vec{B} = 0$, $\left(G_M - \frac{1}{\gamma^2-1}\right) = 0$, works only for $G_M > 0$
     Brookhaven proposal to measure d_p
  2. Combined Electric/Magnetic Ring:
     with $G_M\vec{B} + \left(G_M - \frac{1}{\gamma^2-1}\right)\vec{v} \times \vec{E} = 0$
     Jülich proposal to measure d_p and d_d
  3. Magnetic Ring:
     with Spin Transparency mode
     JLEIC Figure-8

(1) Brookhaven EDM:
https://www.bnl.gov/edm/

(2) JEDI Collaboration:
http://collaborations.fz-juelich.de/ikp/jedi/

EDMs at JLEIC Figure-8

$$\vec{d} = G_E \frac{e\hbar}{mc} \vec{S}$$

$$\frac{e\hbar}{mc} \sim 10^{-14} e \cdot cm$$

- Rely on Spin Transparency mode of Figure-8:
  → (almost) perfect cancellation of MDM spin precession

- Initial estimate of proton EDM limit in JLEIC Figure-8:
  — $G_E \sim 10^{-5}$ or $d_p < 2 \times 10^{-19}\ e \cdot cm$

- Initial estimate of deuteron EDM limit in JLEIC Figure-8:
  — $G_E \sim 10^{-6}$ or $d_d < 1 \times 10^{-20}\ e \cdot cm$

(1) A. Kondratenko *et al*, Proceedings of XXIV International Baldin Seminar on High Energy Physics Problems "Relativistic Nuclear Physics and Quantum Chromodynamics", Dubna, Russia (2018)

- To enhance EDM limit:
  — Complete detailed analysis of spin resonance strength
  — Increase sensitivity to EDM signal

Main Challenges: Statistical Sensitivity and Systematics

- Suppress MDM spin precession
  - Study impact of ring element alignment and strength errors on spin dynamics, *i.e.*, coherent part of zero-integer spin resonance strength
  - Investigate compensation of coherent part of resonance strength by small fields
  - Study impact of betatron and synchrotron particle motion on spin dynamics, *i.e.*, incoherent part of zero integer spin resonance strength
  - Investigate suppression of incoherent part of resonance strength by lattice design
  - Explore further suppression of MDM signal by symmetries and techniques such as spin flip
- Measure EDM polarization build-up
  - Explore possibility of enhancing EDM signal by lattice design
  - Explore possibility of enhancing EDM signal by electric or combined electric and magnetic elements such as a Wien filter
  - Explore polarimetry options, *e.g.*, work done at COSY in Jülich
  - Specify polarimetry requirements
- Explore parameters and design a prototype Figure-8 ring dedicated to EDM experiment
- Validate experimental design by spin tracking simulations
- Evaluate what can be done in a Figure-8 of JLEIC

Polarimetry

- Proton and deuteron standard polarimetry using carbon targets
- Must be capable of continuous monitoring of vertical polarization build-up
- Works best at < 1 GeV/c
- Real time observation of vector polarization changes smaller than 10^{-6} could be possible

(1) Nucl. Instr. and Methods A **664**, 49 (2012)

- EDM limit:

$$G_E^{limit} \sim \Delta\theta_{s_\perp}$$

- Explore possibility of developing RF polarimetry to provide continuous non-invasive polarization measurement

EDM LDRD

- Deliverables – Refereed paper that summarizes:
  - Achievable charge hadrons EDM limit (sensitivity) in JLEIC Figure-8
  - Systematics and EDM signal measurement via polarimetry

- Budget:

Scenario I	**Scenario II**
Three-year LDRD Suleiman: 20% Morozov: 20% PhD Student ~ $100k per year	Three-year LDRD Suleiman: 10% Morozov: 10% PhD Student Postdoc ~ $170k per year

- LDRD Letter of Intent (deadline: March 14, 2019)
- LDRD Proposal (deadline: April 29, 2019)

LDRD Milestones

- Year 1:
  - Proton and deuteron polarimetry
  - Systematic errors
  - Spin dynamics in Figure-8

- Year 2:
  - d_d sensitivity
  - Proton, ^{3}H, and ^{3}He EDM limits
  - Write paper

- Year 3:
  - Write paper
  - Write paper
  - Write paper