Axion dark matter search with the storage ring EDM method

➢ **This work can be found in the arXiv: http://arxiv.org/abs/1710.05271**

Seongtae Park

Center for Axion and Precision Physics(CAPP)
of Institute for Basic Science (IBS), South Korea

On behalf of
Seung Pyo Chang, Selcuk Haciomeroglu, On Kim,
Soohyung Lee, Seongtae Park, Yannis K. Semertzidis

IBS conference on Dark World
Daejeon, Korea
Oct. 30-Nov. 3, 2017

Outline

1. About storage ring EDM experiment
2. About axion-coupled EDM
3. srEDM method for Axion search
4. About sensitivity of the experiment
5. Summary and conclusion

Introduction to EDM

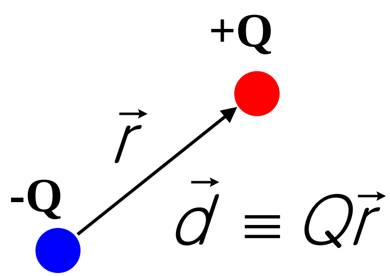
❖Motivation

✓Strong CP problem, Θ_{QCD}

✓Matter-antimatter asymmetry (Baryogenesis)

➢ P, T violation due to an EDM

Electric Dipole Moment



$$H = -\mu\vec{\sigma}\cdot\vec{B} - d\vec{\sigma}\cdot\vec{E}$$

$$T(\vec{B},\vec{\sigma}\ sign\ change): H = -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}$$

$$P(\vec{E}\ sign\ change): H = -\mu\vec{\sigma}\cdot\vec{B} + d\vec{\sigma}\cdot\vec{E}$$

$$\mu = g\frac{q}{2m}, d = \eta\frac{q}{2mc}$$

A nonzero particle EDM violates P, T, and assuming CPT conservation, also CP violation.

The first direct measurement of EDM in neutron and it's sensitivity improvement

PHYSICAL REVIEW VOLUME 108, NUMBER 1 OCTOBER 1, 1957

Experimental Limit to the Electric Dipole Moment of the Neutron

J. H. SMITH,* E. M. PURCELL, AND N. F. RAMSEY
Oak Ridge National Laboratory, Oak Ridge, Tennessee, and Harvard University, Cambridge, Massachusetts
(Received May 17, 1957)

1957

An experimental measurement of the electric dipole moment of the neutron by a neutron-beam magnetic resonance method is described. The result of the experiment is that the electric dipole moment of the neutron equals the charge of the electron multiplied by a distance $D=(-0.1\pm2.4)\times10^{-20}$ cm. Consequently, if an electric dipole moment of the neutron exists and is associated with the spin angular momentum, its magnitude almost certainly corresponds to a value of D less than 5×10^{-20} cm.

PRL **97,** 131801 (2006) PHYSICAL REVIEW LETTERS week ending 29 SEPTEMBER 2006

Improved Experimental Limit on the Electric Dipole Moment of the Neutron

C. A. Baker,[1] D. D. Doyle,[2] P. Geltenbort,[3] K. Green,[1,2] M. G. D. van der Grinten,[1,2] P. G. Harris,[2] P. Iaydjiev,[1,*] S. N. Ivanov,[1,†] D. J. R. May,[2] J. M. Pendlebury,[2] J. D. Richardson,[2] D. Shiers,[2] and K. F. Smith[2]
[1]*Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom*
[2]*Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom*
[3]*Institut Laue-Langevin, BP 156, F-38042 Grenoble Cedex 9, France*
(Received 9 February 2006; revised manuscript received 29 March 2006; published 27 September 2006)

2006

An experimental search for an electric dipole moment (EDM) of the neutron has been carried out at the Institut Laue-Langevin, Grenoble. Spurious signals from magnetic-field fluctuations were reduced to insignificance by the use of a cohabiting atomic-mercury magnetometer. Systematic uncertainties, including geometric-phase-induced false EDMs, have been carefully studied. The results may be interpreted as an upper limit on the neutron EDM of $|d_n| < 2.9\times10^{-26}e$ cm (90% C.L.).

DOI: 10.1103/PhysRevLett.97.131801 PACS numbers: 13.40.Em, 07.55.Ge, 11.30.Er, 14.20.Dh

Current EDM bounds and plan

- Current EDM bounds
  - ✓ SM predicts non-vanishing EDM
    - $|d_e| < 10^{-38}$ e.cm
    - $|d_{n,p}| < 10^{-31}$ e.cm
    - Beyond current experiment limit
  - ✓ SUSY prediction: 10^{-25}~10^{-28} e·cm (nEDM limit)
  - ✓ Neutron EDM bound: $|d_n|<2.9\text{x}10^{-26}$ e.cm ('06, ultracold neutrons)
  - ✓ Proton EDM bound: $|d_p| <7.9\text{x}10^{-25}$ e.cm ('09, ^{179}Hg)
  - ✓ Electron EDM bound: $|d_e| <8.7\text{x}10^{-29}$ e. cm ('14, ^{205}Tl)
- Target sensitivity level in the storage ring pEDM experiment
  - ✓ High statistics (10^{11} protons/store) is achievable using storage ring
  - ✓ Goal **10^{-29} e·cm** (statistical limit in about one year)
  - ✓ → 10^{-30} e·cm (with an upgrade)
- Physics reach $>10^3$ TeV

EDM and spin precession

❖ **Spin dynamics (with EDM and MDM) in magnetic+electric field (T-BMT equation)**

$$\frac{d\vec{s}}{dt} = \vec{\mu} x \vec{B} + \vec{d} x \vec{E} = \vec{s} \times (\vec{\omega}_s + \vec{\omega}_{edm})$$ (for particle at rest)

$$\mu = (ge/2m)s = ge\hbar/4m, \ d = (\eta e/2mc)s = \eta e\hbar/4mc$$

$$with \ \vec{\beta} \cdot \vec{E} = \vec{\beta} \cdot \vec{B} = 0$$

(T-BMT equation: for moving particle)

$$\vec{\omega} = -\frac{e}{m}\left[a\vec{B} - \left(a - \frac{m}{p} \right) \frac{\vec{\beta} \times \vec{E}}{c} + \frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta} \times \vec{B} \right) \right], a = \frac{g-2}{2}$$

MDM in B-field — MDM in induced B-field — EDM term

MDM in B-field + MDM in induced B-field: $\vec{\omega}_a$

EDM term: $\vec{\omega}_{edm}$

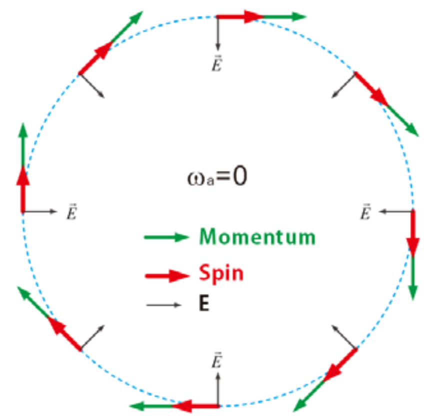
Storage ring technique for EDM search

g-2 precession in **pure electric ring**

$$\Rightarrow \vec{\omega}_a = \frac{e}{m}\left[a - \left(\frac{m}{p}\right)^2\right]\frac{\vec{\beta}\times\vec{E}}{c}$$

for the proton (a=1.792847357(23)) >0

$$\vec{\omega}_a = 0 \;\; at \;\; p = \frac{m}{\sqrt{a}} = 0.700740 \text{ GeV/c}$$: magic momentum



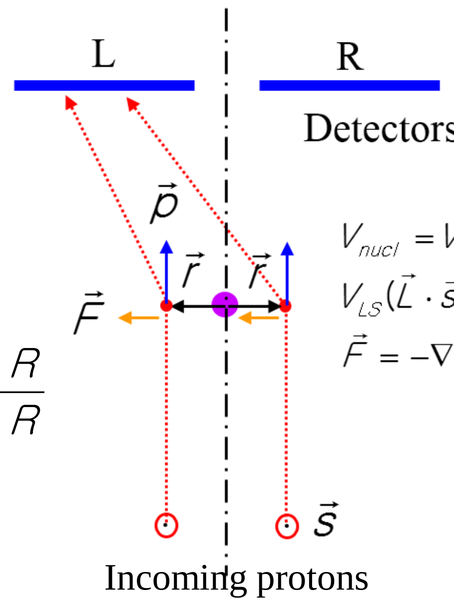
❖ **Use frozen spin method (static EDM measurement)**
- ✓ Spin freezes to the momentum direction
- ✓ a>0 particles (p,e, etc.): use magic momentum
- ✓ a<0 (deuteron) : use E+B field
- ✓ spin precesses only on the vertical plane!
- ✓ No precession on the ring plane

$$\vec{\omega}_{EDM} = -\frac{e\eta}{2m}\frac{\vec{E}}{c}$$

❖ Storage ring EDM collaboration is trying to establish the experiment at CERN
- ✓**EDM Kick-off meeting at CERN in Mar. 2017**
- ✓About 50 participants

Polarimeter and asymmetry

- **Use asymmetrical proton scattering on Carbon target**
  - Hadronic elastic scattering(spin-orbit interaction)
  - Asymmetrical proton hit distribution on the detector plane
  - L/R (U/D) asymmetry for vertical (horizontal) component of proton polarization



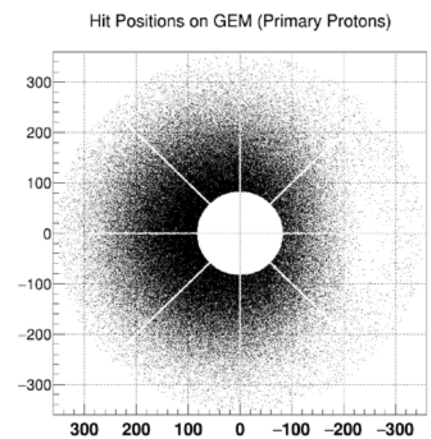
$$V_{nucl} = V_0 + V_{LS}(\vec{L}\cdot\vec{s})$$
$$V_{LS}(\vec{L}\cdot\vec{s}) = -\vec{\mu}\cdot\vec{B}$$
$$\vec{F} = -\nabla V_{nucl}$$

- For spin 1/2 particle

$$\sigma(\theta) = \sigma_{unpol}(\theta)\,[1 + P_y A_y]$$

$$L/R\ asymmetry\quad \varepsilon_{LR} = P_y A_y = \frac{L-R}{L+R}$$

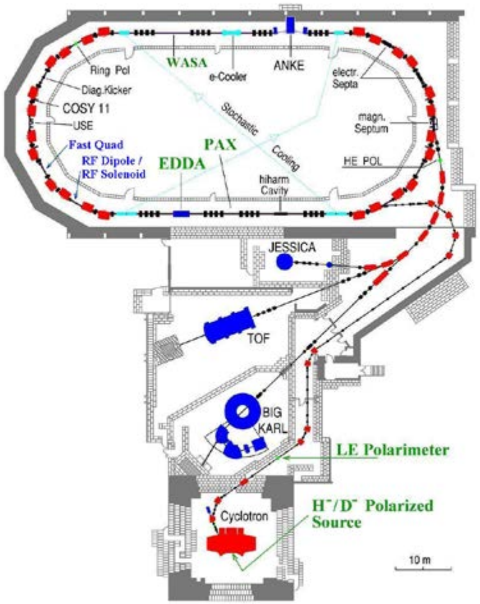
$$P_y = \frac{1}{A_y}\frac{L-R}{L+R}$$



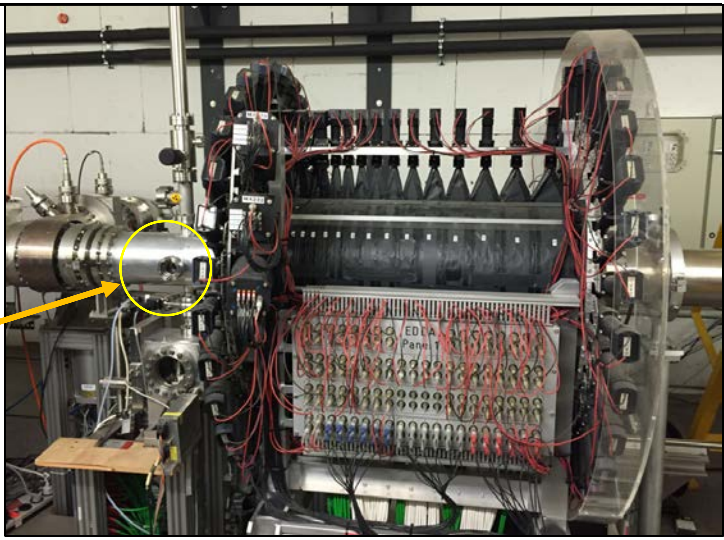
Simulation by Hoyong Jeong

- P_y is calculated from the asymmetry with known A_y
- P_y changes in time due to the precession in E field.

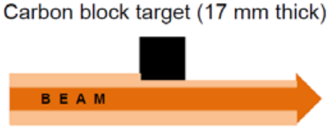
COSY ring and EDDA polarimeter

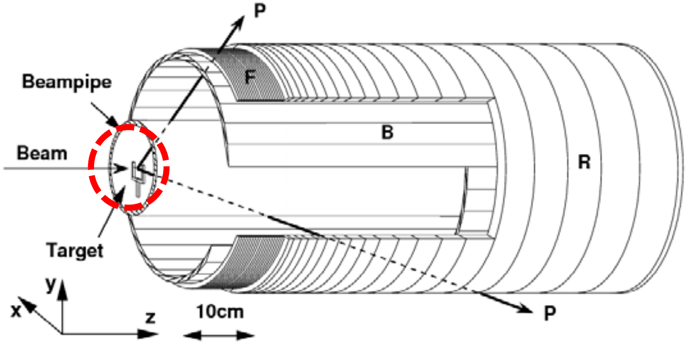


COSY ring (Juelich, Germany)



COSY carbon tube target





COSY EDDA detector
FZJ, Juelich, Germany

About Axion-coupled oscillating EDM

❖ The oscillating axion field is coupled with

✓ Photon

$$P_{sig} = \eta^2_{g_{a\gamma\gamma}} \left(\frac{\rho_a}{m_a}\right) B_0^2 V C Q_L \quad a \rightarrow \gamma\gamma$$

Searched by **resonance microwave cavity** experiment (IBS/CAPP, ADMX)

✓ **gluons**, fermions, nucleon, etc. → Oscillating EDM

$$d_n = 2.4\times10^{-16}\frac{a}{f_a} e\cdot cm \approx 9\times10^{-35}\cos(m_a t)[e\cdot cm]$$

$$a(t) = a_0\cos(m_a t) \Rightarrow d(t) = d_{DC} + d_{AC}\cos(m_a t + \varphi_x)$$

Axion coupled EDM measurement using storage ring method

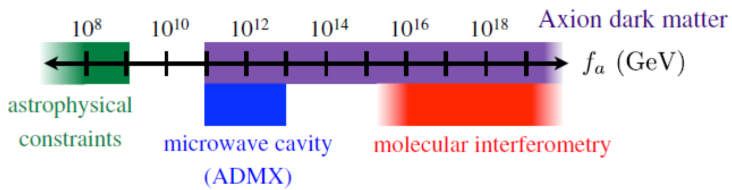
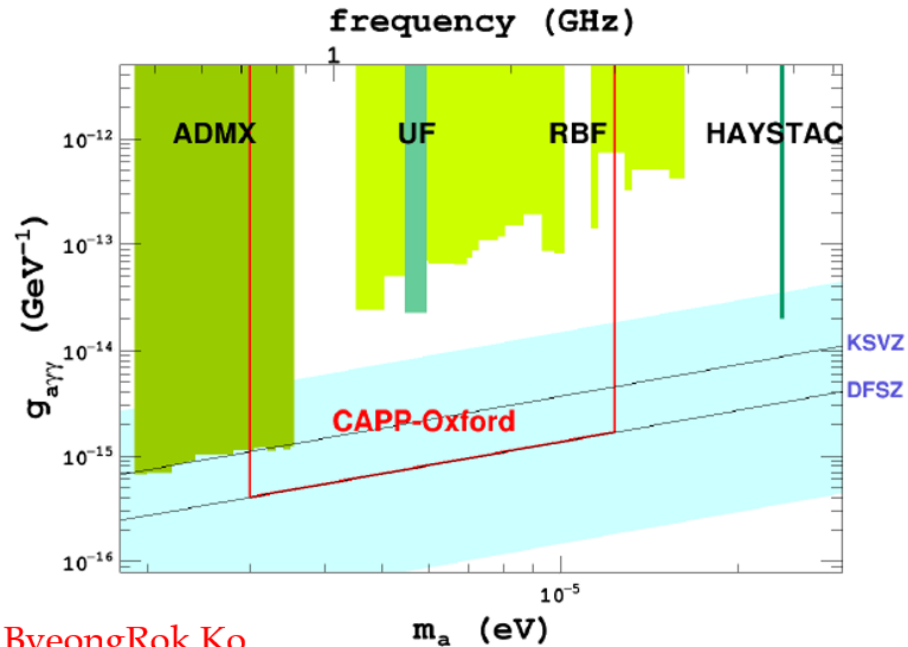


FIG. 1 (color online). (Color Online) The parameter space of the axion in f_a (GeV). Values of $f_a < 10^9$ GeV are ruled out by astrophysical constraints (green). Values of $f_a \gtrsim 10^{11}$ GeV allow the axion to be the dark matter (purple). The (blue) region labeled "microwave cavity" shows the region of parameter space that is potentially observable with microwave cavity experiments, e.g. ADMX. The (red) region labeled "molecular interferometry" shows the range of f_a which is potentially observable with the experiments proposed here. The lower limit on this region may in fact be lower than shown, depending on technological advances.

Peter W. Graham, Surjeet Rajendran,
Phys. Rev. D 84, 055013 (2011).

"Use molecular interferometry"



ByeongRok Ko

Experiments on axion search

- ❖ **Our proposal: "Use storage ring"**
  - ➢ **Scan frequency range up to 0.1 kHz~100 MHz** using storage ring method.
  - ➢ axion parameter space: 10^{13} GeV $\leq f_a \leq 10^{19}$ GeV

Axion + Storage ring EDM method

Using storage ring EDM method for Axion search

Spin tracking for AxionEDM search

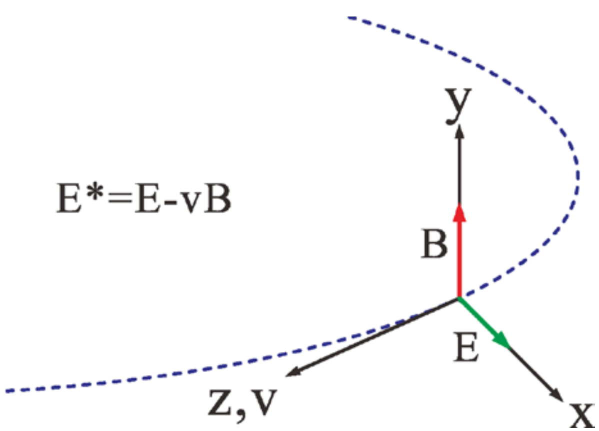
In particle rest frame

$$\frac{d\vec{s}}{dt} = \vec{\mu} x \vec{B} + \vec{d} x \vec{E} = \vec{s} \times (\vec{\omega}_a + \vec{\omega}_{edm})$$

$$\mu = (ge/2m)s = ge\hbar/4m, \; d = (\eta e/2mc)s = \eta e\hbar/4mc$$

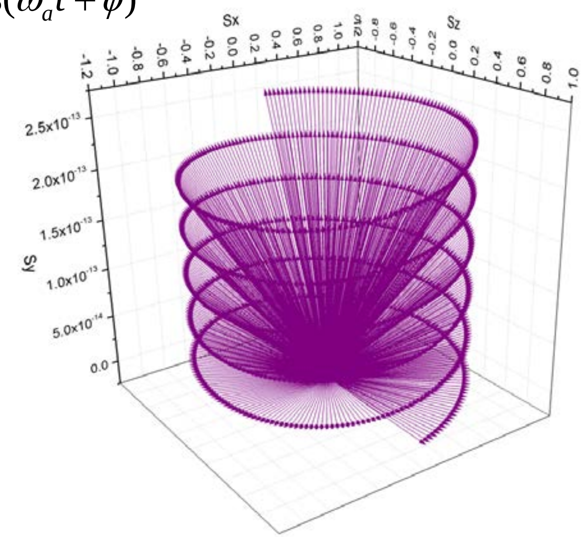
$$\frac{d\vec{\beta}}{dt} = \frac{e}{\gamma m}\left[\vec{\beta} \times \vec{B} + \frac{\vec{E}}{c} - \vec{\beta}\frac{\vec{\beta}\cdot\vec{E}}{c}\right]$$

$$\frac{d\vec{s}}{dt} = \frac{e}{m}\vec{s} \times \left[\left(\frac{g}{2} - \frac{\gamma-1}{\gamma}\right)\vec{B} - \left(\frac{g-2}{2}\frac{\gamma}{\gamma+1}\right)(\vec{\beta}\cdot\vec{B})\vec{\beta} - \left(\frac{g}{2} - \frac{\gamma}{\gamma+1}\right)\frac{\vec{\beta}\times\vec{E}}{c} + \frac{\eta}{2}\left(\frac{\vec{E}}{c} - \frac{\gamma}{\gamma+1}(\frac{\vec{\beta}\cdot\vec{E}}{c})\vec{\beta} + \vec{\beta}\times\vec{B}\right)\right]$$

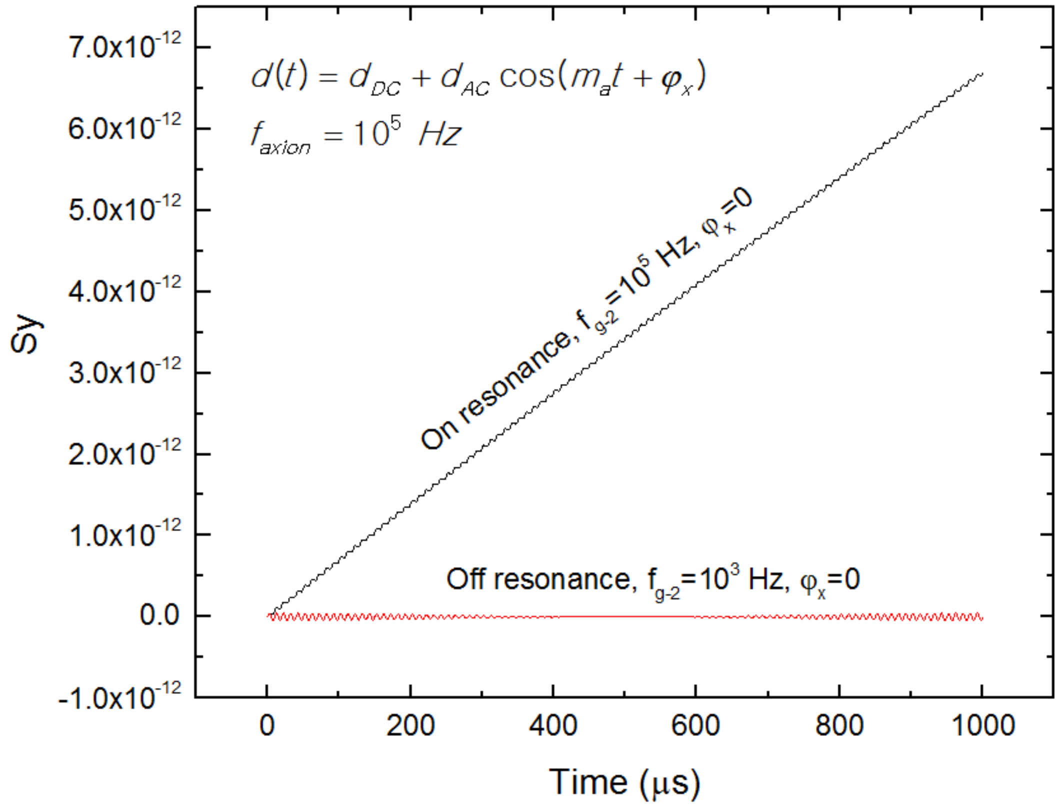


$$d(t) = d_{DC} + d_{AC}\cos(\omega_a t + \phi)$$

$$\eta(t) = \frac{d(t)4mc}{e\hbar}$$



Resonance of Axion induced oscillating EDM with g-2 precession in storage ring



$$\frac{d\vec{s}}{dt} = \vec{\mu}\times\vec{B} + \vec{d}\times\vec{E} = \vec{s}\times(\vec{\omega}_a + \vec{\omega}_d)$$

$$\vec{\omega}_a = -\frac{e}{m}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

$$\vec{\omega}_d = -\frac{e}{m}\left[\frac{\eta}{2}\left(\frac{\vec{E}}{c} + \vec{\beta}\times\vec{B}\right)\right]$$

$$\omega_d = \frac{d\theta}{dt} = -\frac{2d}{\hbar}E^*, \quad \boxed{E^* = E + c\beta B}$$

Benefit from large effective E field!

Static EDM and AxionEDM experiments

- **Static EDM measurement**
  - ✓ Use frozen spin method
  - ✓ Spin precesses only on the vertical plane
  - ✓ No precession on the ring plane

$$\vec{\omega}_{EDM} = -\frac{e\eta}{2m}\frac{\vec{E}}{c}$$

- **AxionEDM measurement uses non-zero g-2 precession**
  - ✓ Benefit from larger effective E-field ($\vec{v} \times \vec{B}$)
  - ✓ More sensitive

$$\omega_d = \frac{d\theta}{dt} = -\frac{2d}{\hbar}E^*, \boxed{E^* = E + c\beta B}$$ ←Also used for muon g-2/EDM experiment

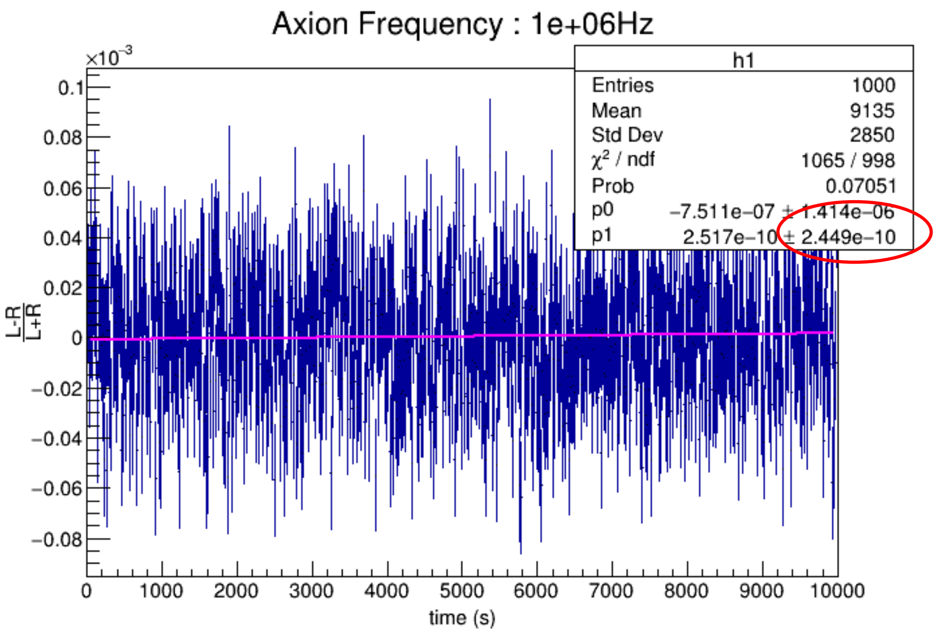
Asymmetry simulation and sensitivity calculation

Error for the EDM d

$$\omega_d = \frac{d\theta}{dt} = -\frac{2d}{\hbar} E^*$$

$$E^* = E + c\beta B \Leftarrow \text{E, B=?}$$

$$\sigma_d = \frac{\hbar}{2E^*} \sigma_{\omega_d}$$



Simulated L/R asymmetry with linear fit

$$L/R \text{ asymmetry} \quad \varepsilon_{LR} = P_y A_y = \frac{L-R}{L+R}$$

$$P_y = \frac{1}{A_y} \frac{L-R}{L+R}$$

EDM precession and statistical error

Statistical error for EDM *d* (sensitivity)
(static (DC) EDM measurement)

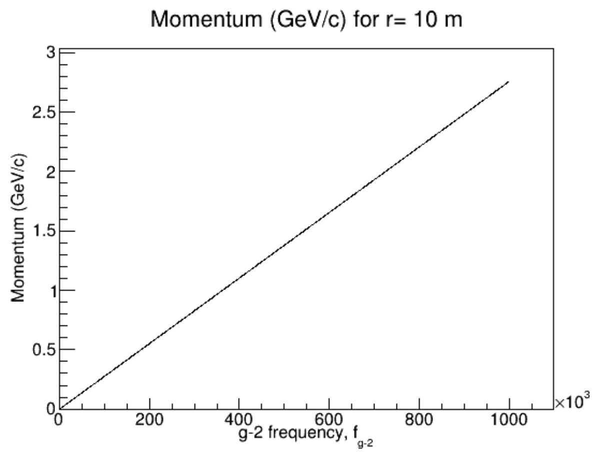
$$\sigma_d = \frac{2\hbar}{PAE\sqrt{N_{tot} f T_{tot} \tau_p}}$$

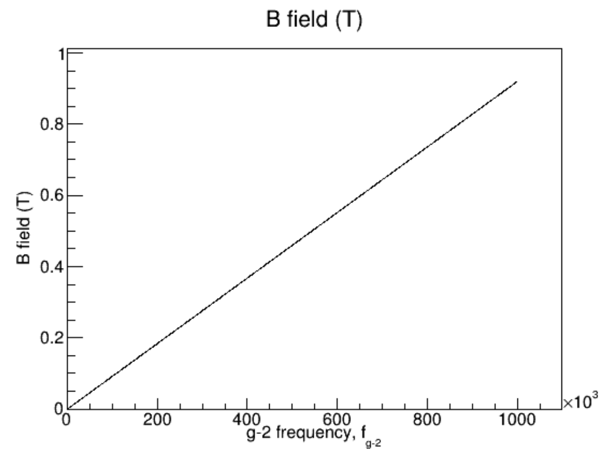
P: Degree of polarization (0.8)
A: Analyzing power (0.6)
E*: Effective electric field (8MV/m)
N_{tot} = Number of particles/storage (5×10^{10})
f : Effective detection efficiency of polarimeter (0.011)
T_{tot} : Total running time (10^7 s/year)
τ_p: Spin coherence time (10^3 s)

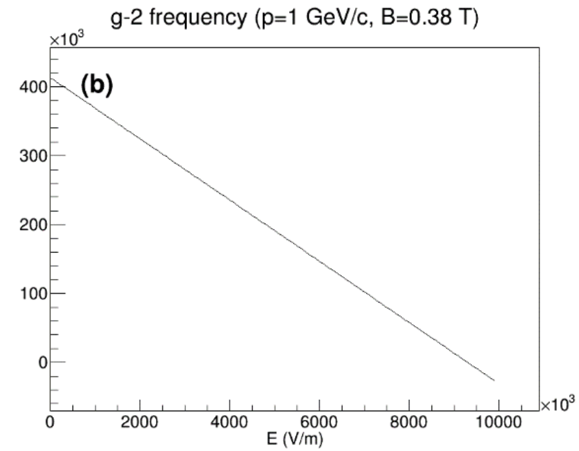
for storage ring proton EDM experiment
→ ~10^{-29} e·cm

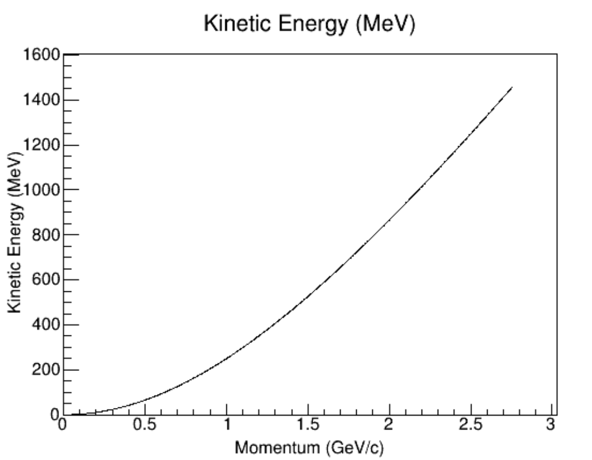
Determination of storage ring parameters

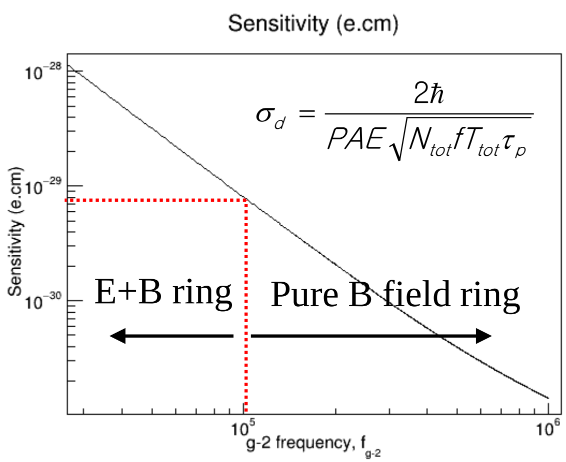
Pure magnetic ring for deuteron, a=-0.14
Ring bending radius r=10m

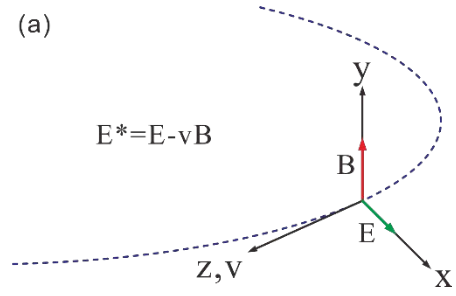












Use E+B combined ring to improve the sensitivity

$$E^* = E + c\beta B$$

Sensitivity calculation results for deuteron

B (T)	P (GeV/c)	f_G (Hz)	E_r (V/m)	E^* (V/m)	Sensitivity (e·cm)		Ring
					a	b	
0.38	0.9429	10^2	8.82×10^6	4.23×10^7	1.9×10^{-31}	1.9×10^{-31}	E/B ring (r = 10 m)
0.38	0.9433	10^3	8.80×10^6	4.24×10^7	6.0×10^{-31}	1.9×10^{-31}	
0.38	0.9473	10^4	8.65×10^6	4.27×10^7	1.9×10^{-30}	1.9×10^{-31}	
0.38	**0.988**	$\mathbf{10^5}$	$\mathbf{7.05 \times 10^6}$	4.60×10^7	5.5×10^{-30}	$\mathbf{1.8 \times 10^{-31}}$	
0.38	1.035	2×10^5	5.06×10^6	5.00×10^7	7.2×10^{-30}	1.6×10^{-31}	
0.38	1.133	4×10^5	3.47×10^5	5.86×10^7	8.7×10^{-30}	1.4×10^{-31}	
0.38	1.239	6×10^5	-5.47×10^6	6.83×10^7	9.1×10^{-30}	1.2×10^{-31}	
0.38	1.355	8×10^5	-1.26×10^7	7.93×10^7	9.1×10^{-30}	1.0×10^{-31}	
0.38	1.484	10^6	-2.14×10^7	9.21×10^7	8.8×10^{-30}	8.8×10^{-31}	
0.80	2.513	10^6	-9.13×10^6	2.01×10^8	4.0×10^{-30}	4.0×10^{-31}	
0.9198	2.7574	10^6	0	2.28×10^8	3.5×10^{-30}	3.5×10^{-31}	B ring (r = 10 m)
9.1977	27.574	10^7	0	2.75×10^9	9.3×10^{-31}	9.3×10^{-31}	

a : Axion $Q = 10^6$, Polarimeter Efficiency = 0.02,
Initial polarization = 0.8, Analyzing power A=0.36, SCT = 10^4 s.
b : Axion $Q = 10^{10}$, Polarimeter Efficiency = 0.02,
Initial polarization = 0.8, Analyzing power A=0.36, SCT = 10^4 s.

- g-2 frequency tune by E-field

Sensitivity calculation results for proton

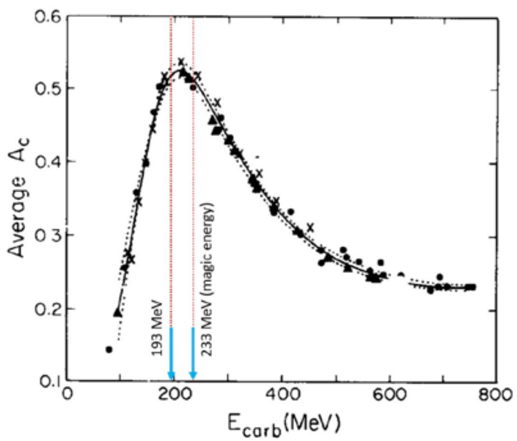
B (T)	P (GeV/c)	f_G (Hz)	E_r (V/m)	E^* (V/m)	Sensitivity (e·cm) a	Sensitivity (e·cm) b	Ring
0.00010	0.6984	10^2	-8.00×10^6	8.02×10^6	1.0×10^{-30}	1.0×10^{-30}	E/B ring ($r = 52$ m)
0.00008	0.6982	10^3	-8.00×10^6	8.01×10^6	3.2×10^{-30}	1.0×10^{-30}	
-0.00017	0.6964	10^4	-8.00×10^6	7.97×10^6	1.0×10^{-29}	1.0×10^{-30}	
-0.00243	0.6747	10^5	-8.00×10^6	7.57×10^6	3.4×10^{-29}	1.1×10^{-30}	
-0.00495	0.6519	2×10^5	-8.00×10^6	7.15×10^6	5.0×10^{-29}	1.1×10^{-30}	
-0.01523	0.7103	4×10^5	-1.10×10^7	8.24×10^6	6.2×10^{-29}	9.8×10^{-31}	
-0.02002	0.6711	6×10^5	-1.10×10^7	7.51×10^6	8.3×10^{-29}	1.1×10^{-30}	
-0.02666	0.6643	8×10^5	-1.20×10^7	7.38×10^6	9.8×10^{-29}	1.1×10^{-30}	
-0.03327	0.6583	10^6	-1.30×10^7	7.27×10^6	1.1×10^{-28}	1.1×10^{-30}	
0.36587	1.0968	10^7	0	8.33×10^7	3.1×10^{-29}	3.1×10^{-31}	B ring ($r = 10$ m)
3.65868	10.9684	10^8	0	1.09×10^9	7.4×10^{-30}	7.4×10^{-32}	

a : Axion $Q = 10^6$, Polarimeter Efficiency = 0.02, Initial polarization = 0.8, SCT = 10^4 s.
b : Axion $Q = 10^{10}$, Polarimeter Efficiency = 0.02, Initial polarization = 0.8, SCT = 10^4 s.
Analyzing power A : $A = 0.6$ for E/B ring, $A = 0.25$ for B ring

- g-2 frequency tune by B-field

$$\vec{\omega}_a = -\frac{e}{m}\left[a\vec{B} - \left(a - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

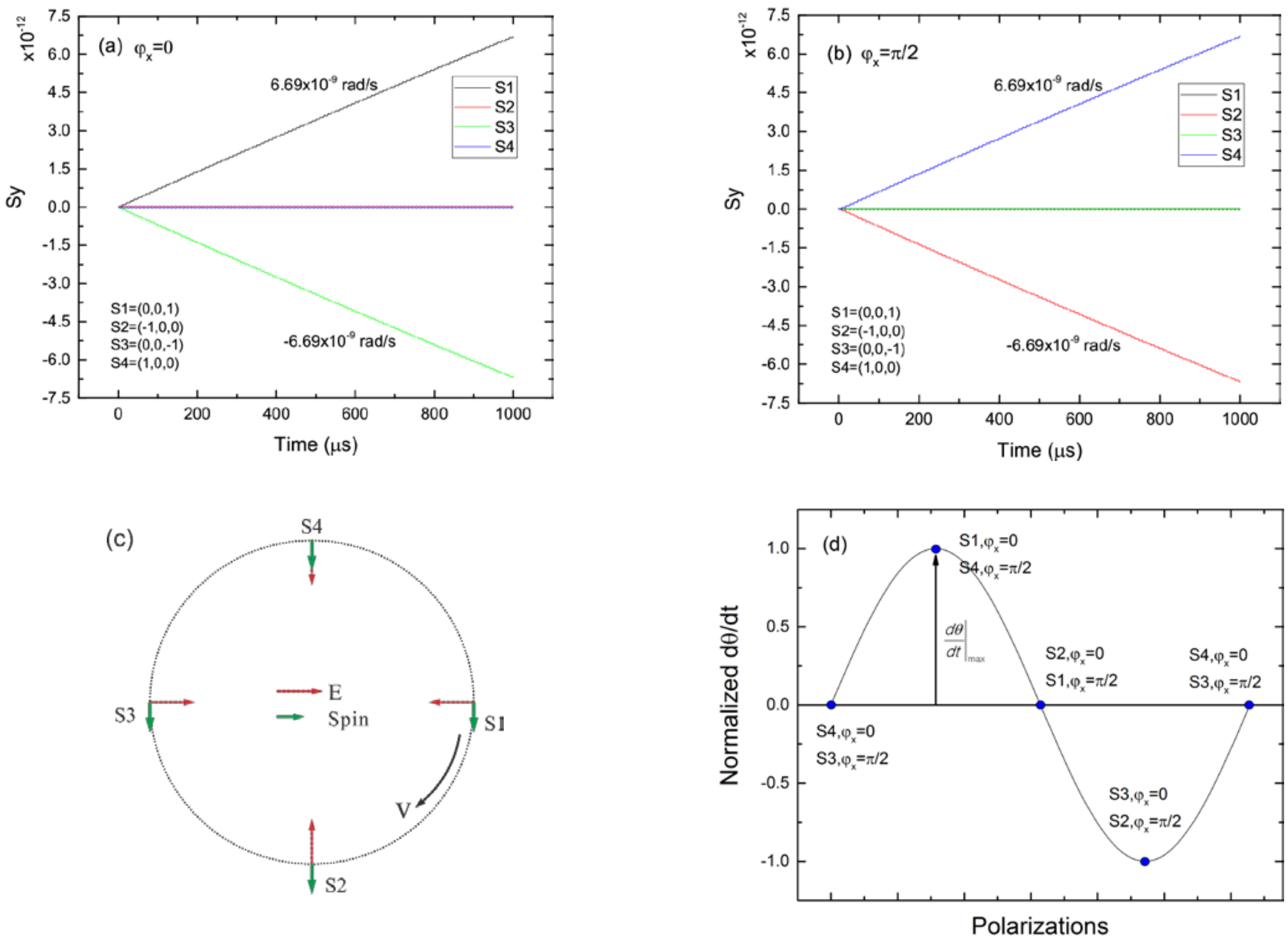
  - a_d=-0.14, a_p=1.79
  - m_d~$2m_p$



p-C analyzing power

Axion phase effect

$$d(t) = d_{DC} + d_{AC}\cos(\omega_a t + \varphi_x)$$ → φ_x=0 means d is parallel to s, positive and max.



• Axion phase is not an experimentally controllable parameter

Axion Q and sensitivity

- ❖ Resonance cavity experiment
  - ✓ No benefit from the high axion Q value if the cavity QL is smaller than the axion Q value.
  - ➢ P. Sikivie's Haloscope

    Axion conversion power (~10^{-24}W)

$$P_{a\to\gamma\gamma} = g_{a\gamma\gamma}^2 \frac{\rho_a}{m_a} B^2 V C_{mnp} \min(Q_L, Q_a)$$

- ❖ Storage ring method
  - ✓ No limit with axion Q_a value
  - ✓ Longer measurement time with larger axion Q_a → Higher sensitivity!

$Q_a=10^6$ $Q_a=10^{10}$

E* (V/m)	Sensitivity (e·cm) a	Sensitivity (e·cm) b	Ring
4.23×10^7	1.9×10^{-31}	1.9×10^{-31}	
4.24×10^7	6.0×10^{-31}	1.9×10^{-31}	
4.27×10^7	1.9×10^{-30}	1.9×10^{-31}	
4.60×10^7	5.5×10^{-30}	$\mathbf{1.8\times10^{-31}}$	
5.00×10^7	7.2×10^{-30}	1.6×10^{-31}	
5.86×10^7	8.7×10^{-30}	1.4×10^{-31}	E/B rin
6.83×10^7	9.1×10^{-30}	1.2×10^{-31}	(r = 10
7.93×10^7	9.1×10^{-30}	1.0×10^{-31}	
9.21×10^7	8.8×10^{-30}	8.8×10^{-31}	
2.01×10^8	4.0×10^{-30}	4.0×10^{-31}	
2.28×10^8	3.5×10^{-30}	3.5×10^{-31}	B ring
2.75×10^9	9.3×10^{-31}	9.3×10^{-31}	(r = 10

= 0.02,
wer A=0.36. SCT = 10^4 s.

Easy systematic error control

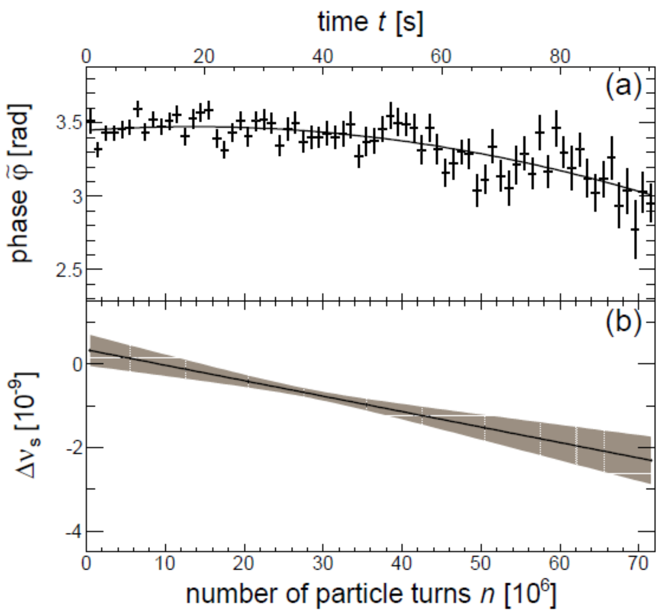


FIG. 3. (a): Phase $\tilde{\varphi}$ as a function of turn number n for all 72 turn intervals of a single measurement cycle for $\nu_s^{\text{fix}} = -0.160975407$, together with a parabolic fit. (b): Deviation $\Delta\nu_s$ of the spin tune from ν_s^{fix} as a function of turn number in the cycle. At $t \approx 38$ s, the interpolated spin tune amounts to $\nu_s = (-16097540771.7 \pm 9.7) \times 10^{-11}$. The error band shows the statistical error obtained from the parabolic fit, shown in panel (a).

D. Eversmann et al. *New method for a continuous determination of the spin tune in storage rings and implications for precision experiments.* Phys. Rev. Lett., 115, 094801, Aug 2015.

- Experiment at COSY (Juelich, Germeany)

Spin tune ν_s

$$\nu_s = \gamma G = \gamma (g-2)/2$$

- **Precise g-2 frequency tune is possible!**

Summary and conclusion

- We propose using the storage ring method to measure the axion induced oscillating EDM at the resonance conditions between the axion frequency and g-2 precession frequency.
- Calculated experimental conditions (E, B-field etc.) for deuteron and proton.
- The resulting sensitivity reaches up to ~10^{-32} e.cm for an oscillating EDM which have never been implemented so far. This assumes 0.3 GeV/cm^3 local axion dark matter density. The EDM amplitude depends on the square root of the local axion density. The local dark matter density may be enhanced by several orders of magnitude due to focusing effects due to planet motion.
- A wide range of frequency (0.1 kHz~100 MHz) of axion dark matter can be tested using both deuterons and protons in the same storage ring.

Thank you!