GEM-based polarimeter detector development for storage ring EDM experiment

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AFAD2018
Daejeon Convention Center, Daejeon, South Korea
Jan. 28-31, 2018
Outline

1. Introduction to storage ring EDM search
2. Polarimeter for EDM search
3. CAPP GEM detector development
4. COSY beam test results
5. Summary and plans
About IBS/CAPP

- Center for Axion and Precision Physics Research (CAPP) at Institute for Basic Science (IBS) (Director: Yannis Semertzidis)
- Located at KAIST Munji campus in Daejeon, South Korea

We are working on:

- Axion-dark matter search
  - Cavities, Cryogenics, Electronics, Super conducting magnet, SQUID, etc.
  - ARIADNE, GNOME

- Storage ring Proton/Deuteron/electron EDM
  - Polarimeter, Beam position monitoring (with magnetic shielding), Beam dynamics, etc.

- Axion-coupled oscillating EDM search using storage ring method

- Muon g-2 experiment
  - System design, Systematics

- Others (COMET, etc)
Introduction to EDM

Motivation
- Strong CP problem, $\theta_{QCD}$
- Matter-antimatter asymmetry (Baryogenesis)

P, T violation due to an EDM

Electric Dipole Moment

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

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

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

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

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

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 \( D = (0.0.11-2.4) \times 10^{-8} \) 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 \( 5 \times 10^{-8} \) cm.

Improved Experimental Limit on the Electric Dipole Moment of the Neutron

Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 0QX, United Kingdom
Department of Physics and Astronomy, University of Sussex, Falmer, Brighton BN1 9QH, United Kingdom
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)

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 co-habiting atomic-susceptibility 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 \( |d_n| < 2.9 \times 10^{-59} \) e cm (90% C.L.).

DOI: 10.1103/PhysRevLett.97.131801
PACS numbers: 13.40.Em, 07.55.Ge, 11.30.Er, 14.20.Dn
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: $|d_n| < 2.9 \times 10^{-26}$ e.cm (’06, ultracold neutrons)
    - Proton EDM bound: $|d_p| < 7.9 \times 10^{-25}$ e.cm (’09, $^{199}$Hg)
    - Electron EDM bound: $|d_e| < 8.7 \times 10^{-29}$ e·cm (’14, ThO)

- **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)
  - $\Rightarrow 10^{-30}$ e·cm (with an upgrade)

- **Physics reach $>10^3$ TeV**
How to measure EDM?

You need...

Particles(EDM) + Electric field → Spin precession! (how fast?)

\[ \frac{d\vec{s}}{dt} = \vec{dx} \vec{E} \]

Where are my protons?
You need storage ring! (high statistics!)

Charged particle in an electric field?

\[ F = qE \]

Lost from the observation area
MDM, EDM and spin precession

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

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

\[ \mu = (ge/2m)s = g\hbar/4m, \quad d = (\eta e/2mc)s = \eta\hbar/4mc \]

with \( \vec{\beta} \cdot \vec{E} = \vec{\beta} \cdot \vec{B} = 0 \)

(T-BMT equation: for moving particle)

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

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

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

The equation for the spin dynamics in an electromagnetic field is given by

\[ \frac{d\vec{s}}{dt} = \vec{\mu} \times \vec{B} + \vec{\alpha} \times \vec{E} = \vec{s} \times (\vec{\omega}_s + \vec{\omega}_{edm}) \]

where \( \vec{\mu} \) is the magnetic moment, \( \vec{B} \) is the magnetic field, \( \vec{\alpha} \) is the electric dipole moment, \( \vec{E} \) is the electric field, \( \vec{s} \) is the spin vector, \( \vec{\omega}_s \) is the precession due to the magnetic field, and \( \vec{\omega}_{edm} \) is the precession due to the electric field.

For a particle at rest, the magnetic moment \( \mu \) is given by

\[ \mu = (g e / 2m) s = g \hbar / 4m \]

and for a moving particle, the charge \( d \) is given by

\[ d = (\eta e / 2mc) s = \eta \hbar / 4mc \]

where \( \eta \) is the electric charge, \( c \) is the speed of light, and \( s \) is the spin of the particle.

The equation simplifies to

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

where \( a = \frac{g - 2}{2} \) is the anomalous magnetic moment.
Storage ring technique for EDM search

g-2 precession in pure electric ring

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

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

\[ \vec{\omega}_a = 0 \quad \text{at} \quad p = \frac{m}{\sqrt{a}} = 0.7007400 \text{ GeV/c} \quad \text{: magic momentum} \]

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

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

- **Storage ring EDM collaboration is trying to establish the experiment at CERN**
  - \( \checkmark \) EDM Kick-off meeting at CERN in Mar. 2017
  - \( \checkmark \) 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

- For spin 1/2 particle
  \[
  \sigma(\theta) = \sigma_{\text{unpol}}(\theta) [1 + P_y A_y]
  \]
  \[
  \frac{L - R}{L + R}
  \]
  \[
  P_y = \frac{1}{A_y} \frac{L - R}{L + R}
  \]

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

Simulation by Hoyong Jeong
COSY ring and EDDA polarimeter

COSY ring (Juelich, Germany)

COSY carbon tube target

COSY EDDA detector
FZJ, Juelich, Germany
CAPP GEM detectors
for Asymmetry measurement, Tracking
CAPP GEM detectors

2x2 cm$^2$ GEM (double GEM, single channel)

100 channel pad board (10x10 cm$^2$ active area)

$^{55}$Fe test result

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CAPP GEM detectors

512 channel X_Y strip board
(R~115 μm), CERN PCB workshop

10x10 cm² GEM detector assembly
to beam test at COSY, Germany
**DAQ system for GEM test**

- **SRS**: Scalable Readout System
- Developed and distributed by the RD51 collaboration
- FE Hybrid+ adapter card+FEC+DAQ PC
  - Hybrid: **APV25**, **VMM**, GEMROC, Beetle, etc
  - APV: analog chip
  - VMM: digital chip with peak detection and time information

- Special thanks to CERN GDD lab. for providing SRS system (Hans Muller, Eraldo Oliveira)
Beam test setup at COSY (Big Karl room)
Deuteron beam profile

Hit map for detector GEM0

- X Position [mm]
- Y Position [mm]

Triple GEM detector
512 channel X-Y strip board
270 MeV Deuteron beam
Deuteron beam spread by materials

No target, ~4.5 m from the beam exit

Carbon target (t=5 mm)

Carbon target (t=5 mm) + plastic scintillator (t=10 mm)

Beam pipe SC Target GEM

~0.5 m ~4 m
GEM response to Deuteron beam

Total charge for detector GEM0

- 200 MeV, No target
- 270 MeV, No target
- 100 MeV, Sn target (t=5 mm)

Table:

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<th>GEM0TotalCharge</th>
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Detection efficiency

200 MeV Deuteron

- Detection efficiency: ~99.97%

270 MeV Deuteron

- Detection efficiency: ~99.2%
GEM digital imaging

Cupper rod

Without target

With Sn target
Summary and Plans

- IBS/CAPP is developing GEM-based polarimeter detectors for storage ring proton EDM experiment
- Successful beam test at COSY, Germany

Plans:
- Asymmetry measurement with polarized proton/deuteron beams
- Tracking test with multiple GEM planes (3~4)
  - Beam profile monitor during the measurement
- More test at KOMAC(Gyeongju, Korea)
  - In the second half of 2018?
Thank you!