High Voltage studies with Xe-129 for an nEDM experiment at TRIUMF

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• Spin precession frequency of neutrons in the presence of magnetic (B) electric (E) fields
• Using $^{129}$Xe/$^{199}$Hg co-magnetometer to monitor the B-field changes
• Investigating the dielectric properties of $^{129}$Xe in the 1 mTorr range
• High voltage setup at TRIUMF
• Current status and next steps
• Summary
Spin precession frequency of neutrons in the presence of magnetic ($B$) and electric ($E$) fields

$$\omega_o = -2 \frac{\mu B}{\hbar}$$

\[ \mu : \text{magnetic dipole moment (MDM)} \]
\[ d : \text{electric dipole moment (EDM)} \]

\[ \omega_o : \text{Larmor frequency} \]

\[ \Delta B \neq 0 \]

\[ \delta \nu_o = \frac{-4 \, dE}{\hbar} \]

If $\Delta B = 0$

$$2 \mu \frac{\Delta B}{\hbar} = 4 \frac{dE}{\hbar} \Rightarrow \Delta B = 40 \, fT$$

(over 10,000 runs if $d = 10^{-27} \, e \cdot cm$ and $E = 10 \, kV/cm$)

Unknown magnetic field fluctuations can produce a false EDM signal
Using $^{199}$Hg co-magnetometer to monitor the B-field changes

- B-field fluctuations are one of the main sources of systematics.
- An atomic co-magnetometer occupies the same space with neutrons and can accurately monitor the magnetic temporal changes.


Absorption $\sim$ x-component of the spin polarisation (10-100 fT resolution).
Using $^{199}$Hg co-magnetometer to monitor the B-field changes

$^{199}$Hg co-magnetometer in the ILL/Sussex/RAL nEDM experiment

$^{129}$Xe compared to $^{199}$Hg has:

1. neutron absorption $\sigma_{Xe} = \frac{1}{100} \sigma_{Hg}$

2. same sign of gyromagnetic ratio

Dual $^{129}$Xe + $^{199}$Hg co-magnetometer

Improve systematics by data cross checking
Using $^{129}$Xe co-magnetometer to monitor the B-field changes

- Neutrons
- $^{129}$Xe atoms (spins precess on xy plane with $\omega_z$)

$^{204}$Hg discharge lamp (along x)

Magnetic shielding

Polarised light

$\pm V$

$V = 0$

$^{129}$Xe 2-photon emission

Detect a $\sim 900$ nm emitted photon
Investigating the dielectric properties of Xe

$^{129}$Xe density $\rightarrow$ Optical signal

$^{129}$Xe density $\rightarrow$ Neutron density $N$ (via absorption & up-scattering)

$^{129}$Xe density $\rightarrow$ Breakdown Voltage

Statistical sensitivity

$$\sigma_d \propto \frac{1}{E \cdot \sqrt{N}} \left( \frac{\hbar}{2 T_s} \right)$$

E = Electric field
N = neutron numb. density
$T_s$ = neutron storage time

Yamamoto 1977 Jpn. J. Appl. Phys. 16 343

P·d=0.1-5·10^{-2} [Torr · cm]

P·d=50·10^{-2} [Torr · cm]

F. Paschen 1889 (Wied. Ann., 37, 69)

http://commons.wikimedia.org/
High voltage setup at TRIUMF

Gas filling

Flat aluminum electrodes

100 kV feedthrough

High Voltage Power Supply

0 V

100 kV

V=0

OD=85 cm

V=0

~8 cm
Lessons learnt:

- Keep it simple by minimizing interfaces
- Maximize the distance of the grounded parts from the high voltage feed-through
- Eliminate sharp edges/holes
- Remove metal and carbon depositions from the ceramic (sandblasting) + smooth its surface
Incorporated the changes to a new setup

Gas filling inlet

Top electrode pusher.

Aluminum electrodes separated by a glass insulator

Ceramic support rods.

Wider support ring

High voltage setup at TRIUMF

88 cm

0 V

100 kV
Load Cell 0-500 lbs
(LCGB-500 Omega)
http://www.omega.ca/pptst/LCGB.html
Wider support alu ring. Ceramic support rods.

ANSYS Stress simulations

Sealing force \(\sim 500\) lbs
Ceramic tensile yield = 1400 psi
Safety factor = 6.2
Current status:

- 100 kV with a steel ball in vacuum
- Most of the parts of the new setup are ready

Our next tests:

- Assembly and test in vacuum and with gas

Next R&D steps:

- Study different geometries and materials for the electrodes to deliver as high as possible electric field.
R&D work is carried out at TRIUMF to develop the high voltage system for the nEDM experiment which will deliver an electric field:

- $E \sim 12 \text{ kV/cm}$
- Uniform $[\left(\frac{E_{\text{transv}}}{E}\right)_{\text{max}} = 1\%]$  
- Stable  

..across the neutron storage cell in the presence of $^{129}\text{Xe}$ (and possibly $^{199}\text{Hg}$) co-magnetometer.
Backup slides
Next steps / Trench+O-ring groove geometry

For: \( d = s = b = \alpha = 0 \)

- \( 1 \text{ mm} < r < 10 \text{ mm} \)
- \( 1 \text{ mm} < d < 10 \text{ mm} \)
- \( 0 < s < 2 \text{ mm} \)
- \( 0 < b < 0.1 \text{ mm} \)
- \( 0 < \alpha < 10^\circ \)

M. Losekamm
B.Sc. Thesis

For: \( d = s = b = \alpha = 0 \)

- \( 1 \text{ mm} < r < 10 \text{ mm} \)
Next steps / Trench+O-ring groove geometry

For $r = 5$ mm:
1 mm < $d$ < 10 mm

For $r = 5$ mm, $d = 5$ mm: 0 < $s$ < 2 mm

For $r = 5$ mm, $d = 5$ mm, $s = 1$ mm: 0 < $\alpha$ < 10°
Initially neutron spin is aligned with $\mathbf{B}_0$.

RF pulse on xy-plane near Larmor frequency.

Accumulated phase: $\varphi = (\omega - \omega_o) t_{ph}$.

Depending on the accumulated phase the second RF pulse will turn the spin up or down.

N. F. Ramsey, Phys. Rev. 76 996 (1949)
A. $^{199}$Hg atoms are polarised along $z$.

B. A transverse RF pulse at $^{199}$Hg resonance frequency forces the spins to precess on the $xy$-plane (8 Hz at 1 μT).

C. A beam of polarised light from $^{204}$Hg discharge lamp traverses the cell in the $x$-direction. Its absorption depends on the $x$-component of the spin polarisation which varies sinusoidally with time at the Larmor frequency (10-100 fT resolution).

\( ^{129}\text{Xe} + ^{199}\text{Hg} \) dual co-magnetometer

\( ^{129}\text{Xe} \) compared to \( ^{199}\text{Hg} \) has:

1. 100 times smaller neutron absorption cross section
2. Same sign of gyromagnetic ratio with neutron
3. \( ^{129}\text{Xe} \) atomic EDM limit is very close to that of neutron (\( 2.9 \times 10^{-26} \text{ e} \cdot \text{cm} \)):

\[
 d_{\text{Xe}-129} < (0.7 \pm 3.3 \pm 0.1) \cdot 10^{-27} \text{ e} \cdot \text{cm}
\]

Needs to be improved by at least one or even better by two orders of Magnitude. Need to conduct \( ^{129}\text{Xe} \) atomic EDM measurement using the \( ^{199}\text{Hg} \) as co-magnetometer

Dual \( ^{129}\text{Xe} + ^{199}\text{Hg} \) co-magnetometer

1/ Improve systematics by data cross checking
2/ Easy implementation as the laser requirements are quite similar
   (the transition lines are \( ^{199}\text{Hg} \): 253.7 nm \( ^{129}\text{Xe} \): 252.4 nm)
High voltage setup at TRIUMF

1st attempt: lessons learnt

- Epoxy
- Nylon cylinder (metal coated inner+top surface for grounding)
- Aluminum shield (HV)
- To the Power supply
- High Voltage Power Supply
High voltage setup at TRIUMF

Proved not trivial to handle materials of different thermal expansion coefficient.
High voltage setup at TRIUMF

Dielectric Strength
Epoxy: 115 kV/cm
Air: 30 kV/cm

Epoxy
Nylon cylinder (metal coated inner+top surface for grounding) (V=0)
Aluminum shield (HV)

To the HV electrode
To the Power supply

FEMM simulations
High voltage setup at TRIUMF

Aluminum corona ring (not polished) in air within a wide Faraday cage \( (R_{\text{cage}} \sim 2.5R_{\text{cor. ring}}) \)

Reached feedthrough Voltage specification (100 kV)

To a GAMMA 125 kV Power Supply (neg. Voltage)

AIR (30 kV/cm)

Purple: \( E \sim 13 \text{ kV/cm} \)

\( V = 100 \text{ kV} \)

V = 0

FEMM simulations
High voltage setup at TRIUMF

Add an in-line 1 GΩ resistor to minimize energy dissipation in the event of a breakdown.

Stored energy @ 100 kV = 12.4 J
\[ h \delta \nu_o = -2 d_n (E(\uparrow\uparrow) - E(\uparrow\downarrow)) \]

\( \delta \nu_o \): resonance frequency shift

\( E \): applied electric field

\( d_n \): neutron edm

nEDM experiment layout

Neutron cell

ULTRA COLD POLARISED NEUTRONS

SPALLATION TARGET

PROTON BEAM