Title: Superfluid Liquid Helium Scattering in Electric Fields

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Noon Seminar
Superfluid Liquid Helium Scintillation in Electric Fields

Abstract:

Physicists have been trying for 50 years now to detect the possible separation of positive and negative electric charges inside the neutron. This quantity, called the Electric Dipole Moment (EDM), is known to violate some of the basic symmetries, and if found to have a finite value, has a large implication for the fundamental theory of elementary particle physics. A new experiment to search for the neutron EDM with a sensitivity more than 2 orders of magnitude higher than the present limit is planned to run at the Fundamental Neutron Physics Beamline at SNS.

The experiment is currently in the design phase. Many design features have to be optimized by various R&D experiments and design optimization studies. One such study is a study of the superfluid liquid helium scintillation yield dependence on the strength of the electric field present. Liquid helium scintillation is used to measure the precession frequency of the neutrons with respect to that of the 3He atoms, which cohabit in the same measurement cell to monitor the magnetic field. The sensitivity of the experiment depends on the scintillation yield, therefore it is important to know how the scintillation yield is affected by a presence of electric fields.

In this talk, after a brief overview of the nEDM experiment, the experiment to study the liquid helium scintillation yield dependence on the electric field is discussed.
Superfluid Liquid Helium Scintillation in Electric Fields

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IUCF Noon Seminar

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Outline

- nEDM experiment overview
- Liquid helium scintillation
- Experiment at IUCF
Electric Dipole Moment

- EDM is a P and T (therefore CP) violating quantity
- Standard model value: $d_n \sim 10^{-32} - 10^{-31}$ e·cm
  (Small! Ideal probe for new Physics)
- Present limit: $d_n < 3.0 \times 10^{-26}$ e·cm (PRL 97, 131801 (2006))
Evolution of EDM Experiments

Theoretical Prediction:
- Electromagnetic
- Milliweak
- Weinberg
- Multi-Higgs
- Supersymmetry
- Superweak
- Standard Model

Evolution of EDM Experiments:
- 1950: PNPI
- 1960: ILL
- 1970: 
- 1980: 
- 1990: 

Neutron EDM Experimental Limit (c cm)

Year:
- 1950
- 1960
- 1970
- 1980
- 1990

K_{0}, Beams, UCN
Motivation for n-EDM searches

• n-EDM is a sensitive probe of new sources of CP violation
  - EDM due to the SM is small because in the SM, CP violation only occurs in quark flavor changing processes to the lowest order.
  - Most extension of SM naturally produce larger EDMs because of additional CP violating phases associated with additional particles introduced in the model.

• Strong CP problem
  - The limit on the CP violating term in the QCD Langrangian (from n-EDM) is very small
  - One proposed remedy, Peccei-Quinn symmetry, predicts axions. However, axions have not been observed.

• Baryon Asymmetry of the Universe provides additional motivation
CP violation and New Physics

- In SM, quark EDM is zero to first order in $G_F$ (one loop), and is also zero at the two-loop level (cancellation among diagrams).
- Many extensions of SM predict an extra set of particles and CP violating phases (eg SUSY, LR symmetric model).

![Diagram]

- These models predict substantially larger EDMs than SM.
- Neutron EDM is a very sensitive probe for new sources of CP violation.

Standard Model

SUSY
Principle of the Measurement

\[ \nu = -\left[2\mu_n B \pm 2d_n E\right] / h \]

\[ \Delta \nu = -4d_n / h \]

\[ \delta d_n = h \frac{\delta \Delta \nu}{4E} \]

For \( B \sim 10 \text{mG} \)
\( \nu = 30 \text{ Hz} \)

For \( E = 50 \text{kV/cm} \) and \( d_n = 10^{-28} \text{e}\cdot\text{cm} \)
\( \Delta \nu = 5 \text{nHz} \)
(corresponds to a change in magnetic field of \( 2 \times 10^{-12} \text{ gauss} \))
Experimental Consideration

• Statistical uncertainty goes as (for stored UCNs)

\[ \delta d_n \propto \frac{1}{|\vec{E}| \sqrt{N_{UCN} T_{storage}}} \]

• Therefore we need:
  - High UCN density
  - Long storage time
  - High electric field

• Systematic effects:
  - Non-uniformity and instability of magnetic field
  - Leakage current
  - Geometric effects
EDM Collaboration


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EDM Experiment at SNS
General strategy and goal

• General strategy
  – Perform the experiment in superfluid liquid $^4$He
  – Produce UCN in the measurement cell via superthermal process
  – Use polarized $^3$He as comagnetometer
  – Use $^3$He-n interaction as spin precession analyzer

• Figure of merit: $E\sqrt{NT}$

• Expected gain over the ILL measurement
  
  $E \Rightarrow 5E \quad T \Rightarrow 5T \quad N \Rightarrow 100N$

A 2 orders of magnitude overall gain in sensitivity is expected.

Superthermal Production of UCN

- 8.9 Å cold neutrons get down-scattered in superfluid $^4$He by exciting elementary excitation
- Up-scattering process is suppressed by a large Boltzmann factor
- No nuclear absorption

Expect a production of $\sim 0.3$ UCN/cc/s
With a 500 second lifetime, $\rho_{UCN} \sim 150$/cc and $N_{UCN} \sim 1.2 \times 10^6$ for an 8 liter volume
A dilute admixture of polarized $^3$He atoms is introduced to the bath of SF $^4$He ($x = N_3/N_4 \sim 10^{-10}$ or $\rho_{^3\text{He}} \sim 10^{12}/\text{cc}$)

$^3\text{He}$ as comagnetometer

Measurement cell filled with SF $^4$He

Neutron $\nu_n \sim 29$ Hz

$^3$He $\nu_3 \sim 32$ Hz

Change in magnetic field due to the rotating magnetization of $^3$He by SQUID magnetometers
\( ^3\text{He} \) as spin analyzer/ \( ^4\text{He} \) as a Detector

- \(^3\text{He}-\text{n} \) reaction cross section
  \[ ^3\text{He} + \vec{n} \rightarrow \vec{t} + p + 760 \text{ keV} \]
  \( \sigma (\text{parallel}) < 10^2 \text{ b} \)
  \( \sigma (\text{anti-parallel}) \sim 10^4 \text{ b} \)

- \(^3\text{He}-\text{UCN} \) reaction rate
  \[ 1 - p_3 \cdot p_n = 1 - p_3 p_n \cos[(\gamma_n - \gamma_3)Bt] \]
  \[ |\gamma_n - \gamma_3| = |\gamma_n| / 10 \]

- Detect scintillation light from the reaction products traveling in LHe
  - Convert EUV light to blue light using wavelength shifter
  - Detect the blue light with PMTs

- Signature of EDM would appear as a shift in \( \omega_3 - \omega_n \) corresponding to the reversal of \( E \) with respect to \( B \) with no change in \( \omega_3 \)
Alternative approach
Dressed spin technique

- By applying a strong non-resonant RF field, the gyromagnetic ratios can be modified or “dressed”

\[ \gamma' = \gamma J_0 \left( \frac{\gamma B_{rf}}{\omega_{rf}} \right) \]

\[ B_{rf} = B_{rf} \cos(\omega_{rf} t) \, e_\perp \]

- For a particular value of the dressing field, the neutron and \(^3\)He magnetic moments can be made equal \((\gamma_n' = \gamma_3')\)

\[ B_{rf} = 1 \text{ gauss}, \quad \omega_{rf} = 2\pi \times 3 \text{ kHz} \]

- Can tune the dressing parameter until the relative precession is zero. Measure this parameter vs direction of \(E\)
**Experiment Cycle**

- **$T = 0 - 100 \text{ s}$** Fill $^4\text{He}$ with $^3\text{He}$
  - L He
  - Fill Lines
  - $^3\text{He}$
  - E↑, B↑

- **$T = 100 - 1100 \text{ s}$** UCN from Cold n
  - Refrigerator
  - Phonon
  - L He
  - 8.9 Å neutrons
  - UCN $\lambda \sim 500$ Å
  - $\rho(\text{UCN}) = P_\tau$

- **$T = 1100 - 1110 \text{ s}$** $\pi/2$ pulse
  - L He
  - Fill Lines
  - E↑, B↑

- **$T = 1110 - 1610 \text{ s}$** Precession about E & B
  - L He
  - XUVγ
  - SQUID
  - Light to PMT
  - Deuterated TPB on Walls

- **$T = 1610 - 1710 \text{ s}$** Remove $^3\text{He}$
  - E↑, B↑
  - Emptying Lines
Spallation Neutron Source (SNS) at ORNL

1 GeV, 1.4 mA Proton Linac

- SNS construction completed: 2006
- SNS Total Project Cost: 1.411B$
SNS Fundamental Neutron Physics Beamline (FNPB)

Experiments expected to run

Cold neutron beamline
- Hadronic PV interaction
- $\beta$ decay correlation
- $\beta$ spectrum
- Neutron lifetime

UCN beamline
- Neutron lifetime
- Neutron EDM
EDM Experiment Schematic
Vertical Section View

Dilution Refrigerator (DR: 1 of 2)
Upper Cryostat Services Port
DR LHe Volume 450 Liters
3He Polarized Source

3He Injection Volume

Central LHe Volume (300mK, ~1000 Liters)
Re-entrant Insert for Neutron Guide

4 Layer μ-metal Shield

Upper Cryostat 5.6m
Lower Cryostat
Lower Cryostat Cutaway View

- PMTs
- Gain capacitor
- Light guides
- Measurement cells
- Electrodes

Cold neutron beam
Magnets and Magnetic Shielding

Inner Dressing Coil
\( r = 37 \text{ cm} \)

Outer Dressing Coil
\( r = 48 \text{ cm} \)

\( \mathbf{B}_0 \cos \theta \) Magnet
\( r = 61 \text{ cm} \)

50K Shield

4K Shield

Superconducting Lead Shield
\( r = 65 \text{ cm} \)

Ferromagnetic Shield
\( r = 62 \text{ cm} \)

Not shown: \( \pi/2 \) spin-flip coil and gradient coils

\( \mathbf{B}_0 \) field direction
SF Liquid Helium Scintillation

Ionization track

$\text{He}^+ + e \rightarrow (\text{He}_3^+)_{\text{snowball}} + (e^-)_{\text{bubble}} \rightarrow \text{He}_2^* + \text{He}$

- Singlet state: decays within $\sim 1\text{ns}$ emitting a 80 nm photon (prompt scintillation)

$$\text{He}_2\left(A^1\Sigma^+_u\right) \rightarrow \text{rad. decay}$$

- Triplet state: has a lifetime of $\sim 10\text{ s}$ in vacuum. Gives afterpulses through Penning ionization (destructive interaction with each other)

$$\text{He}_2\left(a^3\Sigma^+_u\right) \rightarrow \text{He}_2\left(A^1\Sigma^+_u\right) \rightarrow \text{rad. decay}$$
Schematic of the apparatus

- **ISI-Seal 5kV feedthrough** (part number 9421008)
  - Connected to the ground electrode (not shown)

- **ISI-Seal 20kV feedthrough** (part number 9441000)
  - Connected to the HV electrode

- **Heat exchanger**

- **Interface plate** (provides connection to DR mixing chamber)

- **4-1/2 CF flange** with 2.5” pipe

- **Ground electrode**

- **4-5/8” CF flange** with 3.0” pipe

- **UVT acrylic light guide**
  - (top surface coated with TPB-PS)
  - Sapphire view port
    - (CeramTec 18617-02-CF)

- **G10 sleeve**

- **4K heat shield for PMT**

- **Hamamatsu R7725mod PMT**
Schematic of the apparatus

- ISI-Seal 5kV feedthrough (part number 9421008) Connected to the ground electrode (not shown)
- ISI-Seal 20kV feedthrough (part number 9441000) Connected to the HV electrode
- Heat exchanger
- Interface plate
- 4-1/2 CF flange with 2.5" pipe
- Ground electrode
- He outlet
- 4-5/8" CF flange with 3.0" pipe
- UVT acrylic light guide (top surface coated with TPB-PS)
- Sapphire view port (CeramTec 18617-02-CF)
- 4K heat shield for PMT
- G10 sleeve
- HV electrode
- Hamamatsu R7725mod PMT
Schematic of the apparatus

He inlet

He outlet
Schematic of the apparatus

Heat exchanger
Schematic of the apparatus

ISI-Seal 20kV feedthrough
(part number 9441000) Connected to the HV electrode

Ground electrode

G10 sleeve
HV electrode
UVT acrylic light guide (top surface coated with TPB-PS)