From yeV to TeV: The neutron EDM experiment at the SNS

DHB/Illinois
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• Baryon asymmetry of the universe: CP violation
• Beyond S.M. physics: generically ‘large’ $\not{\mathcal{CP}}$

Outline

1. Introduction/history
2. Experiment overview
   • Unique features
3. Polarized $^3$He system

Physics: Neutron Electric Dipole Moment

- Neutron has spin $S$ (1/2)
  - has magnetic moment, $\mu$
  - electric dipole moment, $d$?
    - violates time reversal symmetry

- Time reversal is violated in standard model
  - we think CPT is conserved
  - CP (T) violation observed in K0, B0 decays
  - T violation observed in K0 decays
  - origin unknown!

- Theories beyond standard model predict CP violation
  - e.g. supersymmetry (SUSY): $d_n \neq 0$

- Most intriguing aspect – CP violation required to give observed baryon asymmetry in universe
  - must be some difference between interactions of, say, protons & antiprotons
Oak Ridge, 1943

• Fermi: first chain reaction U. Chicago, Dec. 2, 1942

• Graphite Reactor built in one year, power scaled up by $10^6$!
  – critical on Nov. 4 1943
  – world’s first production of electricity from nuclear energy (~1946)
  – neutron research
Purcell, Ramsey and Parity Violation

• 1949 – do strong interactions preserve parity?
  → Is $d_n$ non-zero?

• Motivation was Dirac’s work on magnetic monopoles!

• Method: early implementation of Ramsey’s method of separated oscillatory fields

$$\hbar \omega_{\text{prec}} = 2\left(\mu_n B \pm d_n E\right)$$

The First Modern Experiment

Jim Smith, ca. 1950

Neutron Polarizability

• What happens to the neutron when an electric field is applied?
  – E.g., imagine $\vec{E}$ and $\vec{B}$ are perpendicular
  – Neutron is polarized and
    $$\vec{d}_{tot} = \vec{d}_{int} + \vec{d}_{induced} = d_{int} \hat{z} + \chi_n \vec{E}$$
    need not point in the spin direction
  • Not to worry,* effectively compare energies for
    $\vec{E}$ up and $\vec{E}$ down

$$\frac{d\langle \vec{S} \rangle}{dt} = 2 \left( \langle \vec{S} \rangle \times \mu_n \vec{B} + \langle \vec{d}_{tot} \rangle \times \vec{E} \right)$$

Gordon Baym and DHB, PNAS 113 (2016) 7438.
What If We See Something?

• To lowest order: 12 independent contributions
  – light flavors only (u, d, e)
    – M. J. Ramsey-Musolf, EDMs13 (Fermilab, Feb. 2013)
      \[
      \begin{align*}
      \delta_f & \quad \text{fermion EDM} & 3 \\
      \varepsilon_q & \quad \text{quark color EDM} & 2 \\
      C_G & \quad \text{3 gluon (Weinberg)} & 1 \\
      C_{quqd} & \quad \text{non-leptonic} & 2 \\
      C_{lequ/d} & \quad \text{semi-leptonic} & 3 \\
      C_{\phi ud} & \quad \text{induced 4 fermion} & 1 \\
      \end{align*}
      \]
  – And QCD $\theta$ term!
    – $\theta E_a \cdot B_a$ (violates CP) is present in QCD Lagrangian
Beyond the Standard Model

• Generic SUSY edm

\[ d_n \sim 10^{-25} \left( \frac{1 \text{ TeV}}{m_{\text{SUSY}}} \right)^2 \sin \theta_{\text{SUSY}} \]

Amin Aboubrahim, Tarek Ibrahim, Pran Nath, Phys. Rev. D 91 (2015) 095017
Current Experimental Landscape

• **Present limit:** Sussex expt \( d_n < 3 \times 10^{-26} \text{ e}\cdot\text{cm} \)

• **New experiments**
  – PSI: new result soon: SD\(_2\)
  – panEDM (Munich/ILL) installing now in ILL 22: He II
  – LANL: improved cold source: SD\(_2\)
  – TRIUMF/RIKEN: He II
  – SNS: He II “in place”
Superfluid He nEDM: The Cartoon
Trapping Neutrons

Incident neutrons have same energy and momentum as phonons in superfluid helium: they interact and “stop”
Superfluid He nEDM: The Cartoon
Neutron Precession

\[ \hbar \omega = 2 \mu_n B_0 \]
Superfluid He nEDM: The Cartoon Precession Measurement (1)

Add polarized $^3\text{He}$ atoms (nearly same magnetic moment as neutrons)

Superfluid helium
Superfluid He nEDM: The Cartoon Precession Measurement (2a)

\[ ^3\text{He}, \text{n spins parallel: “no” interaction} \]

Superfluid helium
Superfluid helium nEDM: The Cartoon

Precession Measurement (2b)

\[ ^3\text{He}, \text{n spins anti-parallel} \rightarrow p + ^3\text{H} \]

\[ ^p \text{and } ^3\text{H give off scintillation light} \]

Superfluid helium
Superfluid He nEDM: The Cartoon

EDM Measurement

\[ \hbar \omega = 2 \left( \mu_n B_0 \pm d_n E_0 \right) \]

\[ B = \frac{B_0}{40} \]

\[ d_n = 0 \]
**Experiment Statistics**

- **Incident neutron fluence**
  \[ \phi_{\text{cold}} \sim 3 \times 10^8 \text{n/s: } \Delta \lambda \sim 0.3 \text{ Å FWHM} \]

- **UCN density at beginning of measurement**
  \[ n_{\text{UCN}} \sim 100 \text{ cm}^{-3} \]

- **Polarized \(^3\)He density**
  (detector and co-magnetometer)
  \[ n_3 \sim 10^{12} \text{ cm}^{-3}, \quad n_3/n_4 \sim 5 \times 10^{-11} \]

- **Cell volume**
  \[ x \cdot y \cdot z = 7.6 \times 10 \cdot 40 \text{ cm}^3 = 3100 \text{ cm}^3 \]

- **Holding field**
  \[ B_0 \sim 30 \text{ mG} \]

- **Electric field**
  \[ E_0 \sim 75 \text{ kV/cm} \]

- **Precession frequencies**
  \[ f_n \sim 100 \text{ Hz}, \quad |f_n - f_3| \sim 10 \text{ Hz} \]

- **Operating temperature**
  \[ T_{\text{op}} = 0.45 \text{ K} \]

- **Refrigeration**
  \[ 2 \times 75 \text{ mW} @ 0.25 \text{ K} \]

- **Official sensitivity (300 live days)**
  \[ \Delta d = 5.5 \times 10^{-28} \text{ e \cdot cm (90% CL)} \]
A Unique Feature: Spin Dressing

• n and \(^{3}\text{He}\) precess at different rates

\[
\omega_{rel} = (\gamma_3 - \gamma_n) B_0 \pm 2d_n E
\]

\[
(\gamma_3 - \gamma_n) B_0 \sim 10^8 \times 2d_n E
\]

• Apply transverse, off (Larmor) resonance, a.c. B field

\[
B_d = B_{d0} \cos \omega_d t
\]

– At “critical” dressing, spins precess at same rate

\[
\gamma'_i = \gamma_i J_0 \left( \frac{\gamma_i B_{d0}}{\omega_d} \right); \quad \gamma'_n = \gamma'_3 @ \frac{\gamma_3 B_{d0}}{\omega_d} \approx 1.2
\]

and

\[
\omega_{rel, dressed} = \pm 2d_n E
\]

Spin Dressing: Measurement

1. Set critical dressing frequency, $\omega_{d,crit}$, at $E = 0$
2. Turn $E$ on
3. Modulate dressing frequency around $\omega_{d,crit}$: neutron spin moves slowly back and forth relative to $^3$He spin ... from $+\theta_0$ to $-\theta_0$
4. If $d_n = 0$, count rates at $\pm\theta_0$ are equal; $d_n \neq 0$ form asymmetry

$$A_{dress} = \frac{R_+ - R_-}{R_+ + R_-} \propto d_n$$

- non-EDM part of count rate oscillates at twice modulation frequency
An Insidious Systematic Error: 
“Geometric Phase”

• Consider circular motion of a spin in the magnetic field

\[ R \vec{\omega}_r \perp \vec{B}_0, \vec{E} \]

— Particle will see motional magnetic field \( \vec{B}_{\text{motional}} = R \vec{\omega}_r \times \vec{E} \)

• Suppose experiment has imperfection \( \frac{\partial \vec{B}_0}{\partial z} \neq 0 \Rightarrow \vec{B}_r = aR \)

• In frame moving with the ‘orbital’ motion

\[ B_{\text{tot}, r}^2 = \left( B_0 - \frac{\omega_r}{\gamma} \right)^2 + \left( aR + R \omega_r E / c \right)^2 \]

• Take relatively large \( B_0 \), transform back to lab, average over sign of \( \omega_r \), term linear in \( E \)

\[ \delta B = \frac{\delta \omega}{\gamma} = \frac{\gamma aR^2 \omega_r^2 E}{\left( \gamma B_0 \right)^2 - \omega_r^2} \]

Geometric Phase

- Problem for us is ‘high speed’ $^3$He (~60 m/s)
- We can enhance the effect by lowering temperature
  - Depends on $^3$He diffusion constant, $D_{34} \propto T^{-7}$
nEDM@SNS Status

- Ongoing development project
- Currently in year 4 (of 4) of “Critical Component Demonstration” phase
  - Successful completion of Critical R&D phase in Dec. 2013
  - Continued Annual Reviews, Technical Review Committee meetings
    - “It is the unanimous recommendation of the TRC Committee that the committee be abolished.”
  - 15 critical component activities
  - GOAL: reduce risk, build from inside out

- Equipment funding from NSF for He3 Services (UIUC), Magnet Systems (Caltech) at ~$1.4M/year
- Equipment funding from DOE for Central Detector System, Cryogenics, Neutronics at ~$1.8M/year

Lessons learned → modified design
**Experiment Overview**


- Measure neutron precession frequency in NMR-style experiment
- $\sigma (\vec{n} + \vec{^3He}) \sim 0$, $\sigma (\vec{n} + \vec{^3He}) \sim 2$ Mbars
- $^3$He co-magnetometer

**Measurement cell cutaway**

- HV
- Ground
- MC: Measurement Cells (7.6x10x40 cm)

**Graph:**
- hv=2($\mu$B±dE)
- Scintillation signal (B/40)
Current Status Highlights

• What is the breakdown field/voltage in superfluid He?
  – Extensive testing: bubbles are problematic
  – Smoothness of electrodes key

• First large parts of main cryostat

• First of two dilution refrigerators
Assembly and Commissioning

• Experiment to go on Fundamental Neutron Physics Beamline (ORNL)

• New building (EB2) downstream of existing experimental hall
He3 Services System

- Polarized atomic beam source (MIT)
- Injection into free surface of $^4$He
  - Requires control of film
- Transfer to measurement cells
- Transfer to purifier

\[\text{“heat flush”}\]

- Dilution refrigerator
  - ~75 mW at 250 mK
Getting $^3$He In

- Atomic beam source: quadrupole polarizer
- Problem: superfluid creeps and evaporates
- Design: reentrant ‘film burner’
  - condense vapor away from $^3$He path
- Test transmission: use $^4$He ‘beam’
Getting $^3$He In

- Test transmission: use $^4$He ‘beam’

Getting $^3$He Out: “Heat Flush”

• Use phonon – $^3$He scattering (reminder: Golub)
• Create phonons in superfluid with heater
  – phonon ‘wind’

• Basic physics worked out long ago (~1965)
  – $^3$He concentration, $\rho_3$, in degenerate regime
  – now need to understand process at relative densities $\sim 10^{-4}, 10^{-10}$ (natural: $10^{-7}$)

Transport in Solutions of $^3$He in Superfluid $^4$He

• Goal to determine dynamics of heat flush
  – Calculate thermal conductivities, diffusion coefficients

• Calculation based on
  – Phonon-$^3$He scattering cross section$^1$
  – Phonon-phonon scattering mean free path$^2$
  – $^3$He-$^3$He scattering cross section$^3$
  – Relaxation approximation for scattering from walls

Evolution for Low $x_3$

• Generically, evolution equations are just continuity

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0
\]

Temperature:

\[
C_{ph} \frac{\partial T}{\partial t} + \frac{\partial}{\partial z} \left(-K_{ph} \frac{\partial T}{\partial z} \right) = 0
\]

Concentration:

\[
\frac{\partial x_3}{\partial t} + \frac{\partial}{\partial z} \left(D \frac{\partial x_3}{\partial z} + D_T \frac{\partial T}{\partial z} - x_3 \nu_{ph} \right) = 0
\]
Heat Flush Demonstration

T. Rao, DHB, J. Koivuniemi, I. Silvera, S. Williamson, W. Yao, to be published
Summary

• Cryogenic nEDM experiment
  – Seek $\sim x100$ improvement in sensitivity
  – Systematics will be key: $\sigma_d(1 \text{ day}) \sim 3 \times 10^{-27} \text{ e-cm}$
    – Lots of interesting physics along the way

• If we see EDM in next decade or two it will signal new physics
• If we don’t, strong constraints on new physics