The nEDM Project: A new cryogenic measurement of the electric dipole moment of the neutron

David Haase
NC State University and
The Triangle Universities Nuclear Laboratory
Overview

• Motivation for EDM measurements
• Description of the nEDM experiment
• Cryogenic issues in the nEDM project

Local collaborators –
NC State - Bob Golub, David Haase, Paul Huffman, Albert Young, Ekaterina Korobkina, Chris Swank, David Kendellen, Graham Medlin
Other institutions include ORNL, Caltech, UIUC, U. Va., MIT, Boston U., UC Berkeley, Harvard, ASU, U. Ky., LANL, IU, Miss. St., Simon Fraser
Physics Motivation

• Significant discovery potential in search for EDMs
  - If particle EDMs are observed in the next round of experiments, a new source of CP violation will have been discovered.

  - Such CP violation could play a role in explaining the observed excess of matter over anti-matter in the Universe.

  - The neutron is a key component of understanding new CP violation should it be observed in any EDM.

  - EDM searches will continue to be compelling even after LHC produces new physics results.
Context with other EDM Searches

• Three classes of observable EDMs that presently provide complementary constraints at similar levels of precision:
  – paramagnetic atoms and molecules (i.e. thallium)
  – diamagnetic atoms (i.e. mercury)
  – neutron
• Paramagnetic systems are primarily sensitive to the EDM of the unpaired electron.
• Diamagnetic systems are considerably more complicated; they depend on a combination of parameters $S[g_{\pi NN}, d_N], C_S, C_P, C_T, d_e$.
• Neutron EDM has no additional atomic and much simpler nuclear physics to deal with, and one can compute the dependence of $d_n$ on CP-odd sources at the quark-gluon level.
Overview of nEDM @ SNS

• Our goal is to measure the neutron electric dipole moment with a sensitivity of $d_n < 4 \times 10^{-28} \text{ e} \cdot \text{cm}$ (90%).
  – *the current experimental limit is* $d_n < 3 \times 10^{-26} \text{ e} \cdot \text{cm}$ (*Institut Laue Langevin*).

• Collaborative effort based at Oak Ridge National Laboratory (ORNL), that includes 21 institutions and more than 67 individuals.
“The subcommittee finds that the scientific motivation for EDM searches remains as compelling as ever. In particular, a measurement with sensitivity at the anticipated reach of the US nEDM experiment (~4 x 10^{-28} e-cm) would have a profound impact on nuclear physics, particle physics and cosmology, even in the event of a negative result.”
Goal Relative to Existing Measurements
<table>
<thead>
<tr>
<th>Exp</th>
<th>UCN source</th>
<th>cell</th>
<th>Measurement techniques</th>
<th>(d) (10(^{-28}) e-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ILL CryoEDM</strong></td>
<td>Superfluid (^4)He</td>
<td>(^4)He</td>
<td>Ramsey technique for</td>
<td>Phase 1 ~ 50 Phase 2 &lt; 5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>External SQUID magnetometers</td>
<td></td>
</tr>
<tr>
<td><strong>PNPI – ILL</strong></td>
<td>ILL turbine</td>
<td>Vac.</td>
<td>Ramsey technique for</td>
<td>Phase 1 &lt;100 &lt; 10</td>
</tr>
<tr>
<td></td>
<td>PNPI/Solid D(_2)</td>
<td></td>
<td>E=0 cell for magnetometer</td>
<td></td>
</tr>
<tr>
<td><strong>ILL Crystal</strong></td>
<td>Cold n Beam</td>
<td>solid</td>
<td>Crystal Diffraction</td>
<td>&lt; 100</td>
</tr>
<tr>
<td><strong>PSI EDM</strong></td>
<td>Solid D(_2)</td>
<td>Vac.</td>
<td>Ramsey for (</td>
<td>), external Cs &amp; (^3)He magnetometer. Possible Xe or Hg comagnetometer</td>
</tr>
<tr>
<td><strong>SNS EDM</strong></td>
<td>Superfluid (^4)He</td>
<td>(^4)He</td>
<td>(^3)He capture for</td>
<td>&lt; 4</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(^3)He comagnetometer SQUIDS &amp; Dressed spins</td>
<td></td>
</tr>
<tr>
<td><strong>TRIUMF</strong></td>
<td>Superfluid (^4)He</td>
<td>Vac.</td>
<td>Under Development</td>
<td>&lt; 10</td>
</tr>
<tr>
<td><strong>JPARC</strong></td>
<td>Solid D(_2)</td>
<td>Vac.</td>
<td>Under Development</td>
<td>&lt; 5</td>
</tr>
<tr>
<td><strong>Munich FRMII</strong></td>
<td>Solid D(_2)</td>
<td>Vac.</td>
<td>Under Development</td>
<td>&lt; 5</td>
</tr>
<tr>
<td><strong>NIST</strong></td>
<td>Crystal</td>
<td>Solid</td>
<td>R &amp; D</td>
<td>~ 5 ?</td>
</tr>
</tbody>
</table>
8.9 Å (12 K or 0.95 meV) neutrons can scatter in liquid helium to near rest by emission of a single phonon.

- Upscattering (by 12 K phonon absorption)
- \( \sim \) Population of 12 K phonons
  \( \sim e^{-12 \text{ K}/T_{\text{bath}}} \)

Co-Magnetometry

• Look for a difference in precession frequency
  \[ f_n - f_3 = \left( \gamma_n - \gamma_3 \right) B \pm 2 \, d_n E = (0.1 \, \gamma_n) B \pm 2 \, d_n E \]

• Detect precession of \(^3\text{He}\) magnetization by SQUIDS which serves as a direct magnetometer \(d_{3\text{He}} \ll d_n\)
Measurement Cycle

• Load collection volume with polarized $^3$He atoms
• Transfer polarized $^3$He atoms into the measurement cell
• Illuminate measurement cell with polarized cold neutrons to produce polarized UCN
• Apply a $\pi/2$ pulse to rotate spins perpendicular to $B_0$
• Measure precession frequency
• Remove reduced polarization $^3$He atoms from measurement cell
• Repeat (periodically reversing B and/or E)
$^3$He Transport - Heat Flush Technique

- Used to move $^3$He around in the apparatus
- Source of our isotopically pure $^4$He

McClintock, Cryogenics 18, 201 (1978)
Cryogenic Systems
Cryogenic Issues

- Cooling 1000 liters of superfluid helium to 0.25 K
- Injection of polarized $^3$He atoms into liquid helium
- Heat flush of polarized $^3$He into the target volumes
- Heat flush removal of depolarized $^3$He from the target volumes
- Purification of the liquid $^4$He to $X_3 \sim 10^{-12}$
- Construction using non-magnetic, non-conducting and non-activating materials
- Long-term operation, reliable cooldowns and acceptable maintenance and trouble-shooting
Configuration at completion of 1.03

- Cryovessel
- Valve Stack
- Dilution Refrigerator
- Vent Line
- 4 K Thermal Shield
- Re-entrant Thermal Shield
- 77 K Thermal Shield
- Helium Electrical Insulation Volume or “Central Volume”
Global View
Revisions of the Dilution Refrigerator

Old

New

Helium Supply

19” dia

16” dia. (65 liters)

27.5”

1K pot placeholder
Dilution Refrigerator

- Increase cooling power during cooldown
- Reduction of LHe entrainment volume to 80 l
  - Becomes part of DR installation
  - Reduces complexity of previous design
  - Removes large vacuum seal and metal
  - Allows simpler pre-installation testing

D. Haase and W. Yao
Operation as $^4$He refrigerator
$^3$He Volumes and Transfer

D. Beck and D. Kendellen
Thermal Modeling of $^3$He Cycles

\[ C_{IV1} \frac{dT_{IV1}}{dt} = \dot{Q}_{IV1} \]

\[ - \kappa_1 (T_{IV1} - T_0) \]
\[ - \kappa_F (T_{IV1} - T_{TGT}) \]
\[ - \kappa_F (T_{IV1} - T_{IV2}) \]
\[ - \kappa_F (T_{IV1} - T_{INJ}) \]

\[ \dot{Q}_{TOT} = \kappa_1 (T_{IV1} - T_0) + \kappa_{2b} (T_{INS} - T_0) + ... \]
Thermal Modeling of $^3$He Cycle

\[ T_{\text{TGP}} - T_{\text{INS}} (K) \]

\[ \dot{Q}_{\text{TOTIN}} \approx 26 \text{ mW} \]
Cryovessel re-entrant thermal shields

- Magnet package
- 4 K window
- Insulation Volume
- Target cell
- Re-entrant pressure vessel section
- Re-entrant 77 K shield
- 77 K window
Reentrant Thermal Shield

• Problem of radiative heat flow from shield to magnet package. Also radiative shielding for Central Volume

• Patterned mylar from VAST Films, Ltd. Aluminized hexagons 2 mm circumference separated by 80 μm. $2-$5/sq.ft.
Cryovessel re-entrant thermal shields
Cryovessel re-entrant thermal shields

DETAIL E
SCALE 1:1

PITCH OF SPACING BETWEEN ALUMINA RODS IS 1.19X ROD DIAMETER
Current nEDM activities

- Medium Scale High Voltage Tests (LANL)
- Tests of Electrode Coating Materials (IU and LANL)
- $^3$He Injection Process (UIUC and Harvard)
- nEDM Test Facility at PULSTAR (NCSU, UK)
Test Facility at PULSTAR

- Capture neutrons
- Measure n decays
- Optimize cell coatings
- Inject and remove $^3\text{He}$
Operating Cycle

• Dissolve polarized $^3$He into the sample cell from a storage volume. $X_3 \sim 10^{-10}$
• Perform experimental measurements
• Remove $^3$He by pumping with a charcoal adsorption pump
• When the pump surface is fully covered, close off the charcoal volume and regenerate by heating to $\sim 20$ K
Charcoal Adsorber and Valve (W. Yao)
Calculations of $^3$He and $^4$He Removal

- Approach – calculate orifice diameter required to remove the $^3$He within 16 hours.
- Then use that geometry to calculate flow rates for $^4$He through effusion and through film flow
- Compare rates to choose an optimum temperature for the purification
- An ideal situation would be to purify near the operating temperature and also extend the lifetime of the charcoal adsorber before regeneration
Gas Flow Rates vs Temperature

- 3He
- 4He vapor
- 4He film flow
Suppression of $^4$He Collection

- Deal with it – large charcoal adsorber and regular regeneration cycle
- Traditional film burner – causes a heat load of 0.1 to 1 mW
- Film “pinner” using sharp edged etched Si chip, which could also be used on fill line
Etched Silicon Film Suppressor

Processing of Etched Silicon

1. Deposit SiO₂ on both sides
2. Front-side photolithography
3. SiO₂ patterning with BHF
4. KOH etching (33 wt%, 80°C), remove SiO₂ with BHF
5. Back-side photolithography
6. Dry etching for central hole (Φ 1.5 mm)
7. Remove photoresist with ultrasonic cleaning machine and piranha etching

Fig. 3. Process flow for the production of knife edge devices. Cross-sectional views of the wafer are shown.
$^4$He film flow measurements

Heater

Copper Flange

Stainless Steel Tube

Fill Line

Attach to DR and Cool to \( \sim 0.45 \text{ K} \)
$^4$He film flow measurements

$T_0 = 0.3 \text{ K}, h = 0.7''$, $\dot{Q} = 20 \mu\text{W}$
Dilution Refrigerator at NCSU
Molded composite fixture
G-10 Test Volume and Kapton Seal
Room temperature diffusion test system

- Leak detector
- Roughing pump
- Sample Disk
Diffusion through 5 mil Kapton
Diffusion through G-10 (31 mil) at room temperature

G-10 Sample under ~1.3 bar He-4
Summary

• “…the US nEDM experiment (~4 x 10^{-28} e-cm) would have a profound impact on nuclear physics, particle physics and cosmology, even in the event of a negative result.”

• In the interim period the highest priority is confirming that the high voltage specifications can be met

• Additional R&D to prepare for full-scale efforts

• Project management status has been changed – to great advantage

• We look forward to return to construction, installation and testing
Cryogenic Test Facility at NCSU
Medium Scale High Voltage Tests

- Building smaller-scale test facility (~10 cm electrodes).
- Close oversight by the ITC
- Questions to be addressed
  - electrode material selection
  - pressurization requirements
  - acrylic cell and coatings
  - leakage current
  - SQUID survivability