Searching for the **Electric Dipole Moment of the Neutron**, the Holy Grail of Precision Measurements

Chen-Yu Liu  
Indiana University  
September 25, 2016  
SPIN Conference
Physics in the late 19th century

Albert A. Michelson, in 1894, stated: "... it seems probable that most of the grand underlying principles have been firmly established ... An eminent physicist remarked that the future truths of physical science are to be looked for in the sixth place of decimals."
Standard Model of Particle Physics (the bright side)
Standard Model of Particle Physics
(the dark side)
Precision Measurements

Muon Anomaly $\Delta a_{\mu} = a_{\mu}^{\text{exp}} - a_{\mu}^{\text{SM}} = 276(80) \times 10^{-11}$

$g = 2 + \frac{\alpha}{2\pi} + 6\times10^{-8} + \ldots + \gamma$

MuLAN & FAST experiments at PSI:
$\tau_{\mu^+} = 2.1969803(22) \times 10^{-6} \text{sec}$ MuLAN 2010
(Most precise lifetime measurement ever!)

*Improved Previous World Average by error/20!*

and many more...
Electric Dipole Moment (EDM) of the Neutron

Purcell and Ramsey, Phys. Rev. 78, 807 (1950)

- Neutron EDM ($d_E$): Permanent, net charge separation within the neutron volume

- Current limit [1]:
  
  $d_E < 2.9 \times 10^{-26} \text{ e-cm}$

- First experiment (1957):
  
  $d_E < 5 \times 10^{-20} \text{ e-cm}$

Charge separation for an earth-size neutron

Current limit: \( \Delta x < 3 \times 10^{-13} r_E \) (4 \( \mu \text{m} \))

Goal sensitivity: \( \Delta x < 3 \times 10^{-15} r_E \) (40 nm)

Electric Dipole Moment of polar molecules

NH₃ molecule has two (degenerate) ground states:

\[ \vec{d} = d \frac{\vec{J}}{|J|} \]

\[ \vec{d} = -d \frac{\vec{J}}{|J|} \]
Electric Dipole Moment of polar molecules

NH$_3$ molecule has two (degenerate) ground states:

\[ |\varphi_G\rangle_1 = \frac{1}{\sqrt{2}} \]

\[ |\varphi_G\rangle_2 = \frac{1}{\sqrt{2}} \]

\[ \varphi \rightarrow \varphi \]

\[ [H, T] = 0 \]

A permanent EDM is possible without violations in T (T&P).

NH$_3$: $d = 0.3 \times 10^{-8}$ e-cm
H$_2$O: $d = 0.4 \times 10^{-8}$ e-cm
NaCl: $d = 1.8 \times 10^{-8}$ e-cm
Electric Dipole Moment of fundamental particles

Fundamental particles don’t have degenerate ground state, so $\vec{d} = d\vec{f}$. Say, if the ground state (under fields) is

$$d s = B m d E$$

$$\varepsilon_{1/2} = dE + \left( \frac{1}{2} \frac{\hbar}{2m} \right) B$$

$$\varepsilon_{-1/2} = -dE + \left( -\frac{1}{2} \frac{\hbar}{2m} \right)(-B)$$

<table>
<thead>
<tr>
<th>C</th>
<th>P</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\vec{E}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$\vec{j}$</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>$d\vec{j}$</td>
<td>-</td>
<td>+</td>
</tr>
</tbody>
</table>

The ground state is not a T eigenstate! $\Rightarrow [H, T] \neq 0$
EDM is a sensitive probe for symmetry-violating physics.

nEDM: violates P and T

Suppressed 3-loop effect in the Standard Model

\[ d_n \sim 10^{-32} \text{ e-cm} \quad \text{(Khriplovich & Zhitnitsky 1986)} \]

Large effect in more comprehensive theories

\[ d \sim (\text{loop}) \frac{m_f}{\Lambda_{cp}^2} \]

\[ d < 10^{-26} \text{ e-cm} \rightarrow \Lambda_{cp} = 1 \text{ TeV} \]
fundamental CP-odd phases

$C_{qe}, C_{qq}$

$\theta, d \bar{q}, \tilde{d} q, w$

$g_{\pi NN}$

EDMs of diamagnetic atoms (Hg)

EDMs of paramagnetic atoms (Tl)

QCD

nuclear

TeV

Energy
We hate EDMs because:

Connecting EDMs to new physics is a challenging multi-scale problem: need RG evolution of effective couplings & hadronic / nuclear / molecular calculations of matrix elements.

Slide: Vincenzo Cirigliano
We love EDMs because:

1. Essentially free of SM “background” (CKM)*

2. Probe very high-scales ($\Lambda \sim 10-100 \text{ TeV}$)

3. Probe key ingredient for baryogenesis (CPV in SM is insufficient)

* Observation would signal new physics or a tiny QCD $\theta$-term ($< 10^{-10}$). Multiple measurements can disentangle the two effects.
$\Lambda_{\text{CP}} > 200\ \text{GeV}$

$\Lambda_{\text{CP}} > 50\ \text{TeV}$
Traditional technique: Nuclear Magnetic Resonance (NMR)

\[ H = -\left(\mu B + d_n E\right) \cdot \frac{S}{|S|} \]

- Larmor frequency:
  \[ \omega_B = -\frac{2\mu_B B}{\hbar} \]
  (\(\sim 29.2\) Hz for \(B \sim 0.1\)G)

- \(d_n\): additional precession:
  \[ \omega_E = \frac{2d_n E}{\hbar} \]

\[ \omega_E\parallel_B - \omega_{E\text{anti-}}\parallel_B \equiv \Delta\omega = \frac{4d_n E}{\hbar} \]

- Apply static \(B, E\parallel B\)

- Look for \(\Delta\omega\) on reversal of \(E\)

If \(d_n = 5 \times 10^{-28}\) e cm, \(\Delta\omega = 12\) nHz.
Technique: The Ramsey’s Separated Oscillatory Field Method

5. Spin analyzer (only allows “spin up” UCN through to be counted)
Ultra-Cold Neutrons (UCN)

What are UCN?

Very slow neutrons

\( v < 8 \text{ m/s}; \quad \lambda > 500 \text{ Å} \)

that cannot penetrate into certain material.

- Long storage time
- Low radiation background
- 100% polarization

→ Precision measurements
Magnetic Field Fluctuations Corrected by “Co-magnetometer”

\[ H = -\left(\mu \vec{B} + d_n \vec{E}\right) \cdot \frac{\vec{S}}{|\vec{S}|} \]

If \( n\text{EDM} = 10^{-26} \text{ e}\cdot\text{cm} \),

10kV/cm \( \rightarrow \) 0.1 \( \mu \text{Hz} \) shift

\( \cong \) B field of \( 2 \times 10^{-15} \text{ T} \).

“Co-magnetometer”
Uniformly samples the B Field faster than its relaxation time.

Data: ILL nEDM experiment with \(^{199}\text{Hg}\) co-magnetometer

EDM of \(^{199}\text{Hg} < 10^{-28} \text{ e}\cdot\text{cm} \) (measured); atomic EDM \( \sim \alpha^2 Z^2 \rightarrow ^3\text{He} \) EDM \( \ll 10^{-30} \text{ e}\cdot\text{cm} \)

Under gravity, the center of mass of He-3 is higher than UCN by \( \Delta h \approx 0.13 \text{ cm} \), sets \( \Delta B = 30 \text{ pGauss} \) (1nA of leakage current). \( \Delta B/B = 0.001 \).
# Neutron EDM Searches

<table>
<thead>
<tr>
<th>Experiment</th>
<th>UCN source</th>
<th>cell</th>
<th>Measurement techniques</th>
<th>$\sigma_d$ Goal $(10^{-28} \text{ e-cm})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ILL-PNPI</td>
<td>ILL turbine PNPI/Solid D$_2$</td>
<td>Vac.</td>
<td>Ramsey technique for $\omega$ E=0 cell for magnetometer</td>
<td>Phase 1 &lt; 100 &lt; 10</td>
</tr>
<tr>
<td>ILL Crystal</td>
<td>Cold n Beam</td>
<td>solid</td>
<td>Crystal Diffraction Non-Centrosymmetric crystal</td>
<td>&lt; 100</td>
</tr>
<tr>
<td>PSI EDM</td>
<td>Solid D$_2$</td>
<td>Vac.</td>
<td>Ramsey for $\omega$, external Cs &amp; Hg comag. Xe or Hg comagnetometer</td>
<td>Phase 1 ~ 50 Phase 2 &lt; 5</td>
</tr>
<tr>
<td>Munich FRMII</td>
<td>Solid D$_2$</td>
<td>Vac.</td>
<td>Room Temp., Hg Co-mag., also external 3He &amp; Cs mag.</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>RCNP/TRIUMF</td>
<td>Superfluid $^4$He</td>
<td>Vac.</td>
<td>Small vol., Xe co-mag. @ RCNP Then move to TRIUMF</td>
<td>&lt; 50 &lt; 5</td>
</tr>
<tr>
<td>SNS nEDM</td>
<td>Superfluid $^4$He</td>
<td>$^4$He</td>
<td>Cryo-HV, $^3$He capture for $\omega$, $^3$He co-mag. with SQUIDS &amp; supercond.</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>JPARC</td>
<td>Solid D$_2$</td>
<td>Vac.</td>
<td>Under Development</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>JPARC</td>
<td>Solid D$_2$</td>
<td>Solid</td>
<td>Crystal Diffraction Non-Centrosymmetric crystal</td>
<td>&lt; 10?</td>
</tr>
<tr>
<td>LANL</td>
<td>Solid D$_2$</td>
<td>Vac.</td>
<td>R &amp; D, Ramsey SOF, Hg co-mag.</td>
<td>~ 30</td>
</tr>
</tbody>
</table>

Present neutron EDM limit < 300

= sensitivity < 5 x 10$^{-28}$ e-cm

Slide thanks to Brad Filippone
ILL Experiment:
- UCN in storage cell (Be electrode, BeO dielectric cell wall) at room temperature
- Ramsey’s separate oscillatory field method (interference in time domain)

PNPI Experiment:
Double cell configuration
→ double the signal and reduce the sensitivity to common mode magnetic field noise
The nEDM@PSI collaboration

Presently:
- 13 Institutions
- 7 Countries
- 48 Members
- 11 PhD students
The nEDM spectrometer

- Four-layer Mu-metal shield to shield the experiment from external magnetic fields
- Vacuum chamber
- Precession chamber where neutron precession is induced and measured
- Photomultiplier tube to detect the intensity modulation of the mercury light
- Mercury polarizing cell where the mercury is polarized
- Mercury lamp to polarize the mercury ultraviolet (253.7 nm)
- 5 tesla magnet to spin polarize the UCNs
- High voltage lead with a $1\,\Omega$ resistance
- Cesium magnetometer
- Electrode (upper) charged up to 150 kV electric field $= 10^3 \, \text{V/m}$
- Mercury lamp to read out the mercury polarization
- Magnetic field coils are wound around the vacuum chamber to generate the holding and compensating fields, as well as the spin flipping fields
- Switch to distribute the UCNs to different parts of the apparatus
- Spin analyzer
- Neutron detector

Klaus Kirch, NuPECC, Basel, June 12, 2015

Slide thanks to Klaus Kirch
Towards n2EDM

- Two UCN precession chambers with opposite electric field directions
- Improved magnetometry
  - Hg – laser read out of Hg-FID to avoid light shift
  - Cs – vectorial
  - 3He – free from geometrical phase shift

Status/Prospects:
Taking data at $\delta dn \approx 1 \times 10^{-26} e\text{-cm/yr}$
n2EDM hopes to reach $\delta dn \approx 4 \times 10^{-27} e\text{-cm/yr}$

Slide thanks to Klaus Kirch
Optimistic (but in principle possible) plan towards a physics result

- **Move Inner Shield to ILL (2016)**
  - Adapt/build new UCN components, mobile Cs magnetometers
  - No RF shield, only manual alignment control

- **Outer Shield at TUM**
  - Outer magnetic shield
  - External field compensation
  - HV R&D and assembly

- **Development of cryogenic chambers**

- **Installation at new Super-SUN Stage 1 w/o magnet (2017+), no co-magnetometer**
  - Best possible results $\sim 3.10^{-27}$ ecm (stat, 1)

- **EDM runs at Super-SUN Stage 2 with magnet (2019+)**
  - Best possible result $\sim 8.10^{-28}$ ecm (stat, 1)

**Options**
(i) Assembly of Inner and Outer shield with RT chamber
(ii) Cryogenic chambers with Inner Shield
(iii) Cryogenic chambers with Outer and Inner Shield
(before $\sim 2022$ no UCN at FRM-II EDM position)
Sensitivity potential of nEDM @ SuperSUN at ILL

<table>
<thead>
<tr>
<th></th>
<th>SuperSun stage I</th>
<th>SuperSun stage II</th>
</tr>
</thead>
<tbody>
<tr>
<td>UCN density</td>
<td>333 1/cm³</td>
<td>1670 1/cm³</td>
</tr>
<tr>
<td>Diluted density</td>
<td>80 1/cm³</td>
<td>400,8 1/cm³</td>
</tr>
<tr>
<td>Transfer loss factor</td>
<td>3</td>
<td>1,5</td>
</tr>
<tr>
<td>Source saturation loss</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Polarization loss factor</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Density in cells</td>
<td>6,7 1/cm³</td>
<td>133,6 1/cm³</td>
</tr>
<tr>
<td>2 EDM chamber volume</td>
<td>33,2 l</td>
<td>33,2 l</td>
</tr>
<tr>
<td>Neutrons per chamber</td>
<td>110556</td>
<td>2217760</td>
</tr>
<tr>
<td>EDM sensitivity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>E</td>
<td>2,00E+04 V/cm</td>
<td>2,00E+04 V/cm</td>
</tr>
<tr>
<td>alpha</td>
<td>0,85</td>
<td>0,85</td>
</tr>
<tr>
<td>T</td>
<td>250 s</td>
<td>250 s</td>
</tr>
<tr>
<td>N after time T (1/e)</td>
<td>398000</td>
<td>794000</td>
</tr>
<tr>
<td>Number of EDM cells</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Sensitivity (1 Sigma, 1 cell)</td>
<td>3,9E-25 ecm</td>
<td>8,7E-26 ecm</td>
</tr>
<tr>
<td>Sensitivity (1 Sigma, 2 cells)</td>
<td>2,7E-25 ecm</td>
<td>6,1E-26 ecm</td>
</tr>
<tr>
<td>Preparation time</td>
<td>150 s</td>
<td>150 s</td>
</tr>
<tr>
<td>Measurements per day</td>
<td>216</td>
<td>216</td>
</tr>
<tr>
<td>Sensitivity (1 Sigma, 2 cells) per day</td>
<td>1,9E-26 ecm</td>
<td>4,2E-27 ecm</td>
</tr>
<tr>
<td>Sensitivity 100 days</td>
<td>1,9E-27 ecm</td>
<td>4,2E-28 ecm</td>
</tr>
<tr>
<td>Limit 90% 100 days</td>
<td>3,00E-27 ecm</td>
<td>7,00E-28 ecm</td>
</tr>
</tbody>
</table>

Slide thanks to Peter Fierlinger
The next version: Super-SUN (funded and under construction @ ILL)

For calculations of UCN storage see:

- Single-user facility
- Converter volume: 12 litres
- UCN production rate: $10^5$ s$^{-1}$ ($E < 230$ neV)
- UCN saturation number: $4 \times 10^6$ (2017, fomblin spectrum)
  $2 \times 10^7$ (2019, polarised, $E < 230$ neV)

R = 43 mm

Slide thanks to Peter Fierlinger
TRIUMF UCN Facility

Slide thanks to Jeff Martin
“Phase 1” – what will exist in 2017

- use existing EDM Ramsey apparatus from RCNP, Osaka
- exploit higher UCN density at TRIUMF (also more beamtime available)
- room temperature, 1 small cell, vertical loading, spherical $B_0$ coil
- small incremental improvements until replaced by Phase 2
  - Active magnetic compensation system
  - high voltage
  - comagnetometer
  - high-flux detector

Slide thanks to J. Martin
“Phase 2” – to implement by 2020

R&D on Hg and Xe co-magnetometers is underway

Phase 2 sensitivity \( \delta d_n \sim 10^{-27} \text{ e-cm} \)

- LD\(_2\) moderator, to increase cold flux entering the superfluid
- New high-quality guides.
- World-competitive nEDM experiment apparatus

CFI Innovation Fund application in progress, in Canada. Scale $16M.
Concept for nEDM experiment at LANL

- A neutron EDM experiment with a sensitivity of $\delta d_n \sim O(10^{-27})$ e-cm based on already proven room temperature Ramsey’s separated oscillatory field method could take advantage of the existing LANL SD$_2$ UCN source
  - nEDM measurement technology for $\delta d_n \sim O(10^{-27})$ e-cm exists. What is holding up the progress is the lack of UCN density.
  - The LANL UCN source currently provides a UCN density of $\sim 60$ UCN/cc at the exit of the biological shield
  - A 5-10 fold improvement in the delivered UCN density is required for an nEDM experiment with $\delta d_n \sim O(10^{-27})$ e-cm

- Such an experiment could provide a venue for the US nEDM community to obtain physics results, albeit less sensitive, in a shorter time scale with much less cost while development for the SNS nEDM experiment continues.
Expected achievable statistical sensitivity with the current LANL UCN source without the upgrade

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E$ (kV/cm)</td>
<td>12.0</td>
</tr>
<tr>
<td>$N$ (per cell)</td>
<td>14,700</td>
</tr>
<tr>
<td>$T_{\text{free}}$ (s)</td>
<td>180</td>
</tr>
<tr>
<td>$T_{\text{duty}}$ (s)</td>
<td>300</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>0.80</td>
</tr>
<tr>
<td>$\sigma$/day/cell ($10^{-25}$ e-cm)</td>
<td>0.93</td>
</tr>
<tr>
<td>$\sigma$/year/cell ($10^{-27}$ e-cm)</td>
<td>4.8</td>
</tr>
<tr>
<td>$\sigma$/year* ($10^{-27}$ e-cm) (for double cell)</td>
<td>3.4</td>
</tr>
<tr>
<td>90% C.L./year* ($10^{-27}$ e-cm) (for double cell)</td>
<td>5.6</td>
</tr>
</tbody>
</table>

This estimate is based on the following:

- The estimate for $N$ is based on the results of the UCN storage test performed in January 2016 and is not assuming the source upgrade.
- The estimate for $E$, $T_{\text{free}}$, $T_{\text{duty}}$, and $\alpha$ is based on what has been achieved by other experiments.

* "year" = 365 live days. In practice it will take 3+ years to achieve this.

- Present - August 2016: Installation of the new UCN source and guides
- September 2016-January 2017: Commissioning and operation of the new UCN source

Slide thanks to Takeyasu Ito
Area B layout with the proposed nEDM Experiment

New nEDM experiment

UCNτ experiment

UCNA/B experiment

Slide thanks to Takeyasu Ito
nEDM@SNS

Neutron electric-dipole moment, ultracold neutrons and polarized $^3$He

R. Golub$^a$ and Steve K. Lamoreaux$^b$

$^a$Hahn–Meitner Institut, Postfach 390128, Glienicker Strasse 100, 14109 Berlin, Germany

$^b$University of Washington, Department of Physics FM-15, Seattle, WA 98195, USA

Physics Reports 237, 1 (1994)

** “The Miracle of Helium”**

Improve statistical precision by x100.

- *Increase E*: LHe permits very large electric fields; ~70 kV/cm in our measurement cell

- *Increase N*: LHe allows production of a high density of “ultracold” neutrons (UCN); ~few $10^2$ UCN/cc

- *Increase t*: With $T < 0.5$K UCN can be stored for ~ a thousand seconds

Additionally allows use of Helium-3 as a:

- *Spin analyzer*, providing continual measurement of the precession frequency

- *Co-magnetometer*, providing exquisite monitoring of the magnetic field

\[
\sigma \propto \frac{1}{E \sqrt{N \tau}}
\]
nEDM@SNS
Measurement Cycle

1. Load collection volume with polarized $^3$He atoms
2. Transfer polarized $^3$He atoms into measurement cell
3. Illuminate measurement cell with polarized cold neutrons to produce polarized UCN
4. Apply a $\pi/2$ pulse to rotate spins perpendicular to $B_0$
5. Measure precession frequency
6. Remove reduced polarization $^3$He atoms from measurement cell
7. Flip E-field & Go to 1.

Slide thanks to Vince Cianciolo
75 scientists from 19 institutions
UIUC Responsibilities

- **Test bed:**
  - 1K pot pump system,
  - $^3$He circulation pump stack,
  - Room-temperature vacuum plumbing,
  - Gas service plumbing,
  - Vibration-damping anchor block and wall,
  - Cryostat outer vacuum can,
  - Aluminum personnel support frame,
  - Vacuum can (and shield) lift mechanism.
  - $^3$He gas panel

- **Cryostat:**
  - Top flange
  - Insulating vacuum pump system
  - Heat shields (on order)

- **Slow Controls: National Instruments “cDAQ” front end**
  - Windows based
  - Autonomous
  - Data logged to “network shared variable” mechanism to server
  - Compatible with EPICS

- **500 l Helium Dewar**
  - New standard Dewar on order.

nEDM TRC Review, September 1-2, 2015
Look at me!
Look at me!
Look at me NOW!
It is fun to have fun
but you have to know how.

I can hold up the cup
and the milk and the cake!
I can hold up these books!
and the fish on a rake!
I can hold the toy ship
and a little toy man!
And look! With my tail
I can hold a red fan!
I can fan with the fan
As I hop on the ball!
but that is not all.
Oh, no
That is not all...
EDMs Worldwide

- **Neutrons**
  - @ILL
  - @ILL, @PNPI
  - @PSI
  - @FRM-2
  - @RCNP, @TRIUMF
  - @SNS
  - @J-PARC
  - @LANSCE

- **Molecules**
  - YbF@Imperial
  - PbO@Yale
  - ThO@Harvard
  - HfF+@JILA
  - WC@UMich
  - PbF@Oklahoma

- **Atoms**
  - Hg@UWash
  - Xe@Princeton
  - Xe@TokyoTech
  - Xe@TUM
  - Xe@Mainz
  - Cs@Penn
  - Cs@Texas
  - Fr@RCNP/CYRIC
  - Rn@TRIUMF
  - Ra@ANL
  - Ra@KVI
  - Yb@Kyoto

- **Ions-Muons**
  - @BNL
  - @FZJ
  - @FNAL
  - @JPARC

- **Solids**
  - GGG@Indiana
  - ferroelectrics@Yale

Rough estimate of numbers of researchers, in total ~500 (with some overlap)

K. Kirch, Proceedings CIPANP 2012

http://nedm.web.psi.ch/EDM-world-wide/
Why Do We Need So Many Experiments?

Electron EDM
TVPV pseudoscalar-scalar eN coupling
TVPV tensor eN coupling
Short-distance contribution to $d_n$
Short-distance contribution to $d_p$
TVPV isoscalar $πN$ coupling
TVPV isovector $πN$ coupling

$$d = \alpha_{d_e} d_e + \alpha_C C_S C + \alpha_{\bar{d}_n} \bar{d}_n + \alpha_{\bar{d}_p} \bar{d}_p + \alpha_{g^0} g^0 + \alpha_{g^1} g^1,$$

Paramagnetic Systems
Diamagnetic Systems

EDMs in SUSY

Compatable with baryon asymmetry

Bhattacharya, VC, Gupta, Lin, Yoon

Li, Profumo, Ramsey-Musolf 2009-10
Where Do We Come From? What Are We? Where Are We Going?

Paul Gauguin, 1897
Where Do We Come From? What Are We? Where Are We Going

The Standard Model of Cosmology

- The start: Big Bang Explosion
- The stage: Inflation
- Ingredients: Baryogenesis
- Cooking: Big Bang Nucleosynthesis (BBN); Stellar Nucleosynthesis

Pictures and diagrams showing the stages of the universe's expansion, including Afterglow Light Pattern, Dark Ages, Inflation, Development of Galaxies, Planets, etc., Quantum Fluctuations, 1st Stars about 400 million yrs., Expanding Homogeneous & Isotropic (CMB), Dark Energy Accelerated Expansion, and WMAP.
Big Bang | Baryogenesis | Today

$A_{BB} = 0$ | $A_{BB} \sim 10^{-10}$ | $A_{BB} \sim 1$

$A_{BB} = \frac{B - \bar{B}}{B + \bar{B}}$
Baryogenesis created more matter than anti-matter

- Sakharov’s criteria

  A.D. Sakharov, JETP 5 24 (1967).

  - Baryon number violation
    \[ \phi \rightarrow B; \phi \rightarrow \bar{B} \quad \Delta B \neq 0 \]

  - CP violation and C violation
    \[ R(\phi \rightarrow B) > R(\phi \rightarrow \bar{B}) \]

  - Departure from thermal equilibrium
    \[ R(\phi \rightarrow B) > R(B \rightarrow \phi) \]

left-handed particle under C → left-handed antiparticle
then \( P \rightarrow \) right-handed antiparticle
Experiment uses $^3$He as detector


- Inject small concentration ($\sim 10^{-11}$) of polarized $^3$He
- Look for reaction: $n + ^3$He $\rightarrow t + p + 764$ keV
  - $t, p$ scintillate in $^4$He
  - Pipe through light guides and detect with PMT
- $n + ^3$He $\rightarrow t + p$:
  - $\sigma (^3$He, n: ↑↓ singlet) $\sim 10^7$ b
  - $\sigma (^3$He, n: ↑↑ triplet) $< 10^4$ b
- $\mu_{He}/\mu_n = 1.11$
  - $^3$He spins will rotate ahead of $n$ spins in same $B$
  - Scintillation light according to $\Phi = \Phi_0 \sin (\omega_{He} - \omega_n) t \sim 1 - P_n P_3 \cos (\omega_{He} - \omega_n) t$
- Independent monitor of $^3$He spins with SQUIDs
Other Systematic Effects

Geometric Phase

In a rotating frame

$$\delta \omega = -\frac{\omega_1^2}{\gamma B_0 - \omega_r}$$

UCN rotates due to specular reflection

$$\omega_r \approx \frac{\nu}{R}$$

$$\omega_1 = \gamma (B_{mot} + B_r)$$

$$\frac{\delta \omega}{\gamma^2} = -\frac{B_mB_r}{\omega_o - \omega_r} = -\frac{B_r \nu E}{c(\omega_o - \nu/R)}$$

Sum UCNs moving in both clockwise & counterclockwise directions:

$$\delta \omega = -\frac{\gamma^2}{2} \frac{(\partial B_o/\partial z) E}{c} \frac{\nu^2}{\omega_o^2 - \omega_r^2}$$

Geometric Phase effect is significant at the level of $10^{-28}$ e·cm.
Dressed Spin Magnetometry

The magnetic moment of 3He can be altered through “spin dressing” with applied RF:

\[
\gamma' = \gamma J_0(\gamma B_{RF}/\omega_{RF}) = \gamma J_0(x)
\]

Effective dressed g factors:

\[
X = \gamma_n B_1/\omega_d
\]

The difference in the precession frequency between neutron and 3He:

\[
\delta \omega = \left[ \gamma_n J_0(\gamma_n x) - \gamma_3 J_0(\gamma_3 x) \right] = 0 \text{ with appropriate } x
\]

1kHZ, 100 mG RF field

All systematic effects and noises associated with the external magnetic field disappear!

EDM observable:

\[
\delta \omega = 2d_n EJ_0(\gamma_n x)
\]

modulate X to look for \( X_c \) which leads to \( \delta \omega = 0 \)