Research and Development towards a Neutron EDM Experiment at the SNS

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Outline

- Introduction to the Experiment
- Currently Envisioned Apparatus
- Neutrons
- 3He
- Magnetic Field
- Electric Field
EDM Collaboration

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A New Search for the Neutron Electric Dipole Moment

Funding Pre-proposal

submitted to

The Department of Energy

prepared by

The EDM Collaboration

March 28, 2002

Recent Progress and Design Changes

February 1, 2005
The Permanent EDM of the Neutron

- A permanent EDM $\vec{d}$

\[ \vec{d} \cdot \vec{E} \]

$s = 1/2$

- The current value is $< 6 \times 10^{-26} \text{ e}\cdot\text{cm}$ (90% C.L.)

- We hope to obtain roughly $< 10^{-28} \text{ e}\cdot\text{cm}$ with UCN in superfluid He
The Basic Technique

Look for a precession frequency $\omega_d$

$s = 1/2$ dipole moment $d_n$

Figure of Merit for EDM Experiments $\sim E \sqrt{N \tau} \rightarrow 125$

$E \rightarrow 5E$  $\tau \rightarrow 5\tau$  $N \rightarrow 125N$
$^{3}\text{He}$ Magnetometry

Look for a difference in precession frequency $\omega_n - \omega_3 \pm \omega_d$ dependent on $E$ and corrected for temporal changes in $\omega_3$
3He-Dopant as an Analyzer

\[ ^{3}\text{He} + n \rightarrow t + p \]

\[ \sigma(\text{parallel}) < 10^2 \text{ b} \]

\[ \sigma(\text{opposite}) \sim 10^4 \text{ b} \]

UCN loss rate \sim

\[ 1 - \mathbf{p}_3 \cdot \mathbf{p}_n = 1 - p_3 p_n \cos(\gamma_n - \gamma_3) B_0 t \]

\[ |\gamma_n - \gamma_3| = |\gamma_n|/10 \]

3He concentration must be adjusted to keep the lifetime \( \tau \) reasonable for a given value of the 3He polarization.

The proper value for the fractional concentration \( x = \text{Atoms}^{-3}\text{He}/\text{Atoms}^{-4}\text{He} \sim 10^{-10} \).
$^4$He as a Detector

$^3$He + n $\rightarrow$ t + p

t + p share 764 keV of kinetic energy.

The emitted light (~3 photons/keV) is in the XUV ~ 80 nm.

A wavelength shifter (TPB) is used to change it to the blue, where it can be reflected and detected. The walls and the wavelength shifter must be made of materials that do not absorb or depolarize neutrons or $^3$He.
$^3\text{He}(n,p)t$ Scintillation Light 
$\nu \sim (\gamma_3 - \gamma_n)$

SQUID $\nu \sim \gamma_3$ 

$\sim d_n E$
EDM Experiment - Vertical Section View

- Dilution Refrigerator (DR: 1 of 2)
- Upper Cryostat Services Port
- DR LHe Volume 450 Liters
- \(^3\)He Polarized Source
- Central LHe Volume (300mK, ~1000 Liters)
- He Purifier Assembly
- Re-entrant Insert for Neutron Guide
- \(^3\)He Injection Volume
- \(^3\)He Injection Volume \(\cos\theta\)
- Magnet
- Lower Cryostat
- Upper Cryostat
- 5.6m

4 Layer \(\mu\)-metal Shield
Dilution Refrigerator

Up to 5 mW at 120 mK
EDM Experiment - Horiz. Section View

- Light Guide
- Measurement Cell
- Ground Electrode
- Electric Field Return

 HV Generator
 HV Electrode
 Support
Coil and Shield Nesting

- Inner-Dressing & Spin-Flip Coil
- Outer Dressing Coil
- 50K Shield
- 4K Shield
- Superconducting Lead Shield
- Ferromagnetic Shield
- \( B_0 \cos \theta \) Magnet
Neutron State Selector - Splitter

- Natural Nickel Guide - m=1
- Supermirror Guide - m=3
- Polarizing Beam Splitter - m=2 used at BENSNC

Unpolarized neutron m=1
Spin up neutron
Spin down neutron

Ballistic guide
25 cm
7.5 cm wide
50 cm long

EDM cells
25 cm
Lifetime $\tau$ in a Bottle

$$\frac{1}{\tau} = \frac{1}{\tau_n} + \frac{1}{\tau_w} + \frac{1}{\tau_{\text{hole}}} + \frac{1}{\tau_3} + \frac{1}{\tau_{\text{up}}}$$

where
- $\tau_n$ is the neutron lifetime,
- $\tau_w$ is the wall lifetime,
- $\tau_{\text{hole}}$ is the losses through a hole
- $\tau_3$ is absorption lifetime,
- $\tau_{\text{up}}$ is upscattering lifetime.

Preliminary result $\tau > 100s$
Area B Setup

EDM TARGET CELL NEUTRON LIFETIME MEASUREMENT

TO UCN SPECTROMETER

UCN SWITCH

Diamond coated guide

SAMPLE CELL

SHUTTER

Switch

D2 WINDOW

VACUUM CHAMBER

Coat with UCN absorber

UCN DETECT

UCN GATE VALVE

UCN DETECT

UCN DETECT

PREPOLARIZER MAGNET

UCN GATE VALVE

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The cell - 90 cm x 19 cm ID
- 25.6 liters
- @10 UCN/cc gives $2.5 \times 10^5$
- acrylic coated with d-styrene
- can be cooled to ~4 K

Option for dTPB
Storage Time

1/Fill Time = Production Rate - Loss Rate

Absorption Time

1/Detector Loss Rate

Storage Time

Time from Switch Opening (min.)

Counts in n Detector/min.
β-decay and γ-ray Separation

Afterpulses per main pulse

Main Pulse area

n(³He,t)p

e

3.5 nVolt sec

90 mK, neutron count rate 700 Hz
Results

Diffusion Coefficient of $^3$He in $^4$He

Temperature (K)

$\tau_3 = \tau_n$

$T^{-7}$

Temperature (K)

(\text{cm}^2/\text{s})

$0.00001$ $0.0001$ $0.001$ $0.01$ $0.1$ $1$ $10$ $100$ $1000$ $10000$ $100000$ $1000000$ $10000000$ $100000000$
4He Purifier

First sample measured at ANL - $^{3}$He/$^{4}$He $< 10^{-12}$
$^4\text{He}$ Purification

$^3\text{He}$ velocity must be sufficient to overcome the binding energy to the superfluid $^4\text{He}$, i.e.

\[0.3 \, \text{K} < T < 0.5 \, \text{K}\]

based on the diffusion coefficient measurement.

The pump is a charcoal trap.
Device commissioned

Flux $4 \times 10^{14}$ atoms/s

Average velocity
~150 m/s

Polarization measurements
$(99.6 \pm 0.25)\%$

Loading time
300 s
$^3$He Relaxation
Magnetic Materials

Magnetic Field Uniformity

Room Temperature

Hysteresis of METGLAS at 290K (f=152Hz, R=103.1ohm)

Hysteresis Curve of METGLAS 2714A at 1.2K (f=152Hz, R=103.1ohm)

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Magnetic Materials

Metglas Magnetization vs. Temperature

Inductance (mH) vs. Temperature (K)

- Metglas 2714A
- Metglas 2705M

Required $\mu$

$\mu = 10^6$
Saddle cos\( \theta \) Coil

Shield dimensions (identical):
\( r = 9.33\text{cm}, \ell = 91.44\text{cm}, t = 60\text{ mils} \)
SQUIDs

M. Espy, A. Matlachov

~100 cm² superconducting pickup coil

Flux = 2 \times 10^{-16} \text{Tm}^2 = 0.1 \Phi_0

Noise = 4 \text{m}\Phi_0/\text{Hz}^{1/2} \text{ at } 10 \text{ Hz} \sim T^{1/2}
SQUID Low-Field NMR

\[ \text{Low field NMR (water, 01/16/04 12:50:35, } F = 449.26 \text{ Hz, } T2^* = 0.65 \text{ s)} \]
Summary

- The EDM-Collaboration R&D program has made considerable progress in defining the apparatus as well as understanding and overcoming the experimental challenges.
- The collaboration is poised to start construction in 2007, begin data taking in 2011, and have final results in 2016.
$^3$He Relaxation
$^3$He Distributions in Superfluid $^4$He

Dilution Refrigerator at LANSCE Flight Path 11a

Position

Neutron Beam

Resistive Heater

$^3$He
$^4$He

Counts

Position (cm)

$\begin{align*}
\text{Counts} & : 160000 \\
\text{Position (cm)} & : -3 -2 -1 0 1 2 3
\end{align*}$
**EDI**

**Diffusion Coefficient**

- $^3\text{He}(n,p)t$ measures path length of $^3\text{He}$ from scintillations from stopping $p$ and $t$
- More heat implies smaller path length

Three component Liquid: Superfluid $^4\text{He}$, normal $^4\text{He}$, concentration $X$ of $^3\text{He}$

\[ X\vec{v}_n - D\nabla X = 0 \]

\[ \tau = \frac{L^2}{2D} \]
Dimensional Requirements

\( \frac{\delta B}{B} < 10^{-3} \quad \text{Depolarization} \quad \text{Length} > 2.5 \text{ m} \)

\( E > 50 \text{ kV/cm} \quad \text{Sensitivity} \quad \text{Radius} > 0.3 \text{ m} \)

\[ V > 0.7 \text{ m}^3 = 700 \ell \]