ABSTRACT

EDM Collaboration Meeting

These viewgraphs are a record of the meeting held on July 19-20, 2002, for planning the EDM experiment.

The LANSCE experiment to search for the electric dipole moment (EDM) of the neutron proposes a sensitivity of $4 \times 10^{-28}$ e-cm. It uses the cold neutron beam from a coupled liquid hydrogen moderator and a 10-cm x 10-cm supermirror guide to illuminate a superthermal 4He source. Systematic errors are suppressed by the addition of trace amounts of 3He as a magnetometer. See the following web site for more information: http://p25ext.lanl.gov/edm/edm.html
Agenda for EDM Meeting
July 19-20, 2002

July 19

09:00 - Welcome - John McClelland (Los Alamos)
09:10 - Statement of purpose - Martin Cooper (Los Alamos)
09:20 - DOE reaction to the pre-proposal - Martin Cooper (Los Alamos)
09:30 - EDM project development in the next 1.5 years - Steve Lamoreaux (Los Alamos)
10:00 - Discussion
10:15 - A new measurement at NIST of the neutron storage time in a TPB coated cell - Jen-Chieh Peng (Illinois)
10:30 - Discussion
10:45 - Coffee

11:15 - New ideas regarding light collection and backgrounds - Paul Huffman (NIST)
11:30 - Discussion
11:45 - How well can we identify neutron beta decays? - Bob Golub (HMI)
12:00 - Discussion
12:15 - Monte-Carlo studies - Martin Cooper (Los Alamos)
12:30 - Discussion
12:45 - Lunch

13:45 - Fitting into LANSCE ER-2 - Jan Boissevain (Los Alamos)
14:00 - Discussion
14:15 - Tour of LANSCE ER-2 and Building 10 Lab - Seppo Penttila (Los Alamos)
15:15 - Separating the purifier from the dilution refrigerator, an alternate design - Paul Huffman (NIST)
15:30 - Discussion
15:45 - Coffee

16:15 - Proposed tests of SQUIDs - Michelle Espy (Los Alamos)
16:30 - Discussion
16:45 - Shortening the magnet by better matching of boundary conditions; magnetic shielding issues - Brad Filippone (Caltech)
17:00 - Discussion
17:15 - Modifications of the apparatus to incorporate the dressed-spin technique - Bob Golub (HMI)
17:30 - Discussion
19:00 - Dinner at ...
July 20

09:00 - Update on the HV-test apparatus - Debbie Clark (Los Alamos)
09:15 - Discussion
09:30 - Measuring the Kerr effect at cryogenic temperatures - Alex Sushkov (UC-Berkeley)
09:45 - Discussion
10:00 - Update on the polarized 3He source - Justin Torgerson (LANL)
10:15 - Discussion

10:30 - Coffee

11:00 - Experiences with hexapole state selectors - Janos Fuzi (Budapest)
11:30 - Discussion
11:45 - Experiments relevant to transporting 3He into the superfluid He and the 3He polarization lifetime - Mike Hayden (Simon-Fraser)
12:15 - Discussion

12:30 - Lunch

14:00 - Determining the projects to be undertaken at each institution - moderated by Steve Lamoreaux (Los Alamos)

15:15 - Coffee

15:45 - Future telephone conference calls - moderated by Martin Cooper (Los Alamos)
16:00 - Development of a financial strategy - moderated by Martin Cooper (Los Alamos)
16:45 - Adjourn
Welcome
John McClelland (Los Alamos)
Statement of purpose
Martin Cooper (Los Alamos)
MECHANICS

Agenda
Dinner at 7:00 PM (19:00) at the Central Avenue Grill
• Located on Central Avenue (1 block north of Trinity) across from the post office
• Must pre-order your meal and beverage by circling your choices and putting down your name
Sign into our visitor log during first coffee break
Attendance list
Telephone, FAX, and E-mail list plus institutional addresses
Turn in your badges to me at end of the meeting (Debbie will keep them)
PURPOSE

Exchange scientific ideas
Establish the R&D plan for the experiment
• Speakers should list tasks on blackboard
Establish who will work on what for the next 1.5 years
Open dialogue on long term commitments
Open dialogue on a funding plan
DOE reaction to the pre-proposal
Martin Cooper (Los Alamos)
DOE REACTION TO THE PRE-PROPOSAL

Jehanne Simon-Gillo / Gene Henry 18 July 2002

Next week in writing
Nice job on the physics case
Many external comments on how exciting the project is
Additions to make a real proposal
• Table of technical risks and how we are dealing with them
• Safety issues
• Order of magnitude and source of operating funds
• Potential commitment of physicists
• Facility modifications - their character and costs
• More detailed cost estimates -
  -- Rough breakdown into R&D, engineering, construction, pre-ops, TEC, and TPC
  -- Realistic contingency analysis - a repetitive effort for CDR

7/22/02
DOE REACTION TO THE PRE-PROPOSAL
Jehanne Simon-Gillo / Gene Henry 18 July 2002

• Milestones not understandable - "ready" means what, e.g. designed, constructed, installed, commissioned
• Breakout the cost of people from the cost of equipment
We should continue to work on the proposal
FY’05 funding still a possibility
We will need the upgraded proposal to establish “mission need”
Peter Rosen will want the upgrade for believability

Two conditions to proceed:
• Sorting out of the SNS beamline
• Integrated strategy for national neutron-physics program endorsed by the community

Community should take the initiative (in the form of a conference?)
EDM project development in the next 1.5 years
Steve Lamoreaux (Los Alamos)
The Neutron EDM Project over the Next 1.5 Years

S.K. Lamoreaux

1. Magnetic shielding; ferromagnetic vs. superconducting
   a. magnetic field generation
   b. RF coil
   c. Johnson noise etc. from materials

2. Studies of scintillation
   a. background
   b. cross effects (leakage currents, other cross effects with Larmor precession)
   c. event identification

3. Polarization of He-3

4. Transport and Storage of Polarized He-3

5. High Voltage Tests
   a. radiation effects
   b. wall coating stability
   c. measurements of field strength, uniformity
   d. effects on scintillation
   e. capacitive voltage multiplier

6. Cold neutron beam optics

7. General cryogenic design

8. Tests of SQUIDS in realistic environments

9. Investigation of incorporation of dress spin technique

10. 3-He diffusion at low concentrations
ASAP Tasks.

1. Ferromagnetic cryogenic shields
   + Transport
2. $^3$He $\ T_2$, $\ T_1$
3. Afterpulse study
4. HV effects on scintillations
   5. HV effects on cell

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General Technical Study

1. Measurement of E field
   - Dima et al, UCB
2. Valves
3. Cross effects in scintillation/
   - Larmor precession
   4. UCN polarization, lifetime in cell
5. Stray charge in cell
6. &He diffusion at low concentration
   - Spin diffusion
   - Temp gradient effects
7. Monte Carlo study of polarization
   - Spinning guide
8. Study of backgrounds
9. RF coil
10. Other wall coatings, Neon etc.
11. Study with Mike Haydari's technology
    + SQUIDS
    → Preliminary study in full apparatus
FIG. 1: Cosine magnetic field winding.
FIG 2.4: Behaviour of minor hysteresis loops with (a) steady field, $H_m$, and (b) the perturbation amplitude, $H_p$.

FIG 2.5: Anhysteretic magnetisation curve (for iron).
$D \propto T^{-7}$

$D = \frac{1}{L^2}$
Johnson Noise

\[ S \gg \tau \]

\[
\mathbb{E} [ \hat{J}_e (r) \hat{J}_k (r') ]_o = \left( \frac{k T}{\pi} \right) \sigma \delta_{ek} \delta (r - r')
\]

Rylov-Lifshitz

\[ B^2_w (r) = \frac{k T}{\pi} \sigma \left[ \frac{\mu_0}{4\pi} \right]^2 \int \frac{dV}{(r - r')^4} \]

\[ = \frac{k T}{\pi} \sigma \left[ \frac{\mu_0}{4\pi} \right]^2 \int 2\pi r'dr' \int_{-\infty}^{\infty} \frac{1}{\omega} \frac{1}{(r - r')^2 + \omega^2} d\omega \]

\[ = \frac{k T}{\pi} \sigma \left[ \frac{\mu_0}{4\pi} \right]^2 \frac{\pi^2}{R^2} \delta_1 \]

\[ B^2_w (0) = \frac{k T}{\pi} \sigma \left[ \frac{\mu_0}{4\pi} \right]^2 \frac{\pi^2}{R^2} \delta_1 \]

\[ R = 30 \text{ cm} \quad \text{Cu} \quad \sigma = 6 \times 10^{-7} \frac{\Omega}{\text{cm}} \]
A new measurement at NIST of the neutron storage time in a TPB coated cell
Jen-Chieh Peng (Illinois)
UCN PRODUCTION AND
STORAGE AT NIST

Jen-Chieh Peng
University of Illinois
Los Alamos, July 19, 2002

Outline

• Summary of existing measurements at NIST

• Ideas for a new NIST measurement
UCN production rate was recently verified at NIST.
UCN Losses in Superfluid $^4$He Bottle

1. Neutron beta decay

2. Wall absorption

3. Upscattering in superfluid $^4$He
   - Single-phonon upscattering rate $\propto e^{-1/KT}$
   - Multi-phonon upscattering rate $\propto T^7$

4. $n-^3$He absorption

$$n + ^3He \rightarrow p + t + 764KeV$$

  total spin  $\sigma_{abs}$ at $v = 5m/sec$

  $J = 0$  $\sim 4.8 \times 10^6$ barns

  $J = 1$  $\sim 0$

- The natural abundance of $^3He/^4He$ ($\sim 10^{-7}$) implies an absorption time of $\sim 0.4$ s

- Purified $^4$He with $^3He/^4He < 10^{-11}$ is required
UCN Production in Superfluid $^4He$

Magnetic Trapping of UCN
(Nature 403 (2000) 62)

$560 \pm 160$ UCNs trapped per cycle (observed)

$480 \pm 100$ UCNs trapped per cycle (predicted)

Measured neutron lifetime:
$750^{+330}_{-200}$ seconds

Peak UCN signal: 0.2/s
Peak Bkgrnd: 6.0/s
Neutron flux at NIST

\[ \frac{d\phi}{d\lambda} = 1.62 \times 10^6 \, \text{n cm}^{-2} \, \text{s}^{-1} \, \text{K}^{-1} \]

Net depth of B field trap = 1.04 Tesla

Trap UCN's of \( E < 60 \) nev with the correct spin orientation
PROPOSED NIST MEASUREMENTS

1. Use the new monochromatic neutron beam centered around 8.9 Å
   - ~ 80 percent transmission of 8.9 Å neutrons
   - A factor of 20 reduction of background-producing neutrons

2. Install a UCN storage cell coated with deuterated TPB
   - UCN confining potential is raised from ~ 60 nev to ~ 200 nev
   - UCN production rate is $\propto U^{3/2}$

3. Measure $n \rightarrow pe^{-}\bar{\nu}$ signals and upscattering UCN's as a function of $^{4}He$ temperature

GOALS

1. Study UCN production rate

2. Determine rates of UCN losses due to wall interaction and upscattering

3. Study of background
Monochromatic Neutron Beam at NIST

After adding graphite filter
Estimated rate for UCN signal

- Neutron flux: \( \frac{d\phi}{d\lambda} = 1.3 \times 10^6 \frac{n}{cm^2/s/K} \)
- UCN prod. rate = \( \frac{d\phi}{d\lambda} \times 10^{-7} \frac{UCN}{cm^3/s} = 0.13 \frac{UCN}{cm^3/s} \)
- Cell size: \(40cm \times 3.2cm\) diameter cylinder: \(320 \text{ cm}^3\)
- UCN production rate \( \sim 40 \text{ UCN/s} \)
- Effective storage time of UCN: \( \sim 100 - 500\text{ sec} \)
- Detector efficiency \( \sim 30\text{ percent} \)
- Initial UCN detection rate of \(1.2 - 6\text{ per second}\)

Background reduction

- Monochromatic beam near \(8.9 \text{Å}\)
- Transparent beam stop and better light transmission for higher threshold to reject background
New ideas regarding light collection and backgrounds
Paul Huffman (NIST)
Detection of Neutron Capture

\[ n + ^3He \rightarrow p + ^3H + 764 \text{ keV} \]

- Recoil proton and/or triton creates an ionization track in the helium.

- Helium ions form excited \( \text{He}_2^* \) molecules (ns time scale) in both singlet and triplet states.

- \( \text{He}_2^* \) singlet molecules decay, producing a large prompt (< 20 ns) emission of extreme ultraviolet (EUV) light.

- EUV light (80 nm) converted to blue using the organic fluor dTPB (deuterated tetraphenyl butadiene).
Light Guide Detection System

d'HPB Doped Polystyrene

Clear Acrylic

liquid helium

PMTs

He$_2^+$

p$_3^H$

γ - 430nm
**BEAM STOP**
1. Placement of beam stop
2. Material (clear, opaque)
3. Pass thru design?

**CELL WALLS**
1. How thick?
2. dTPB coatings (thickness, concentrations, application technique)

**LIGHT GUIDES**
1. How many? (≥2)
2. Breaks at 4K, 50K, etc.

**ENTRANCE WINDOW**
1. How much scattering?
2. Thickness
3. Need to make? test
Where do we stop the beam?

a). End of cell

**Requirements**

1). Clear
2). Minimal luminescence

**Advantages**

1). Considerably more light
   - amount depends on wall thickness, but could be a factor of 2-3 more
2). Could consider evaporated TPE which gives ~x3 more light. Must be tested in this geometry.

**Materials of Choice**

B₂O₃

b). Beam passes thru.

**Disadvantages**

1). Lower light collection effic. - relies on total internal reflection within the walls

**Materials of Choice**

By C, BN (shielded in graphite), etc..
Detection Efficiency.

Parameters

1). Wall thickness
2). Surface quality of dTPB/polystyrene coating
3). dTPB concentration
   - Know efficiency for TPB - is it the same?
4). # of PMT's
   - Need at least two/cell for coincidence detection
5). Light extraction from apparatus
   - Need breaks in light guides for thermal isolation
   - Acrylic is poor thermal conductor - need other windows
to minimize black-body radiation

Tests must be done to opt. these for our setup!
Beam Stop:

Materials: $^3$He, Boron, Lithium, Cadmium, Gd. compounds.

$^3$He - too complex to deal with
  - probably most attractive otherwise
    (no luminescence, impurities, activation, etc... $^3$, CLEAR!

should re-visit

$^7$Li - some isotopes activate into 3 emitters 1/24 hours
  - GD - same as Cd.

$^6$Li - produces $\gamma \rightarrow ^3$He
  - bad for lifetime measurement - probably OK here.

B - produces $\gamma \rightarrow ^3$He prompt $\gamma$

\[ \text{LiF, BN, } B_2O_3, B_4C \]
\[ \rightarrow \text{ LiF, BN luminescence} \]

\[ \text{LiF \& } B_2O_3 \text{ optically clear, but hydroscopic} \]

\[ B_4C \text{ (hot pressed)} \text{ - expensive, not easily machined} \]

All cryogenically OK

All can be obtained with low impurity elements

All have some activation problems
Problems to consider

1. 300-77K lightguide
   - Poor thermal conductivity → center of lightguide is "warm"
   - Large blackbody heat leak onto 4K → high helium boiloff
   - Sapphire window used as thermal anchor

2. 77K Blackbody to cell
   - Quartz window: carries away most of heat & blackbody
   - Acrylic provides vacuum seal & blocks remaining blackbody. 
     (Acrylic alone won't work due to poor thermal conductivity)
\[
\text{LiF} \\
\text{F activates} - {}^{20}\text{F}, \tau_{1/2} = 11\text{sec.} \\
\text{short, but a lot of it!} \\
\text{can it cause gain shift problems in PATT?}
\]

\underline{Boron / Lithium loaded glasses}

has both \(^{6}\text{Li}\) and \(^{16}\text{O}\).

\[
\begin{align*}
n + {}^{6}\text{Li} & \rightarrow T + \alpha \\
T + {}^{16}\text{O} & \rightarrow n + {}^{18}\text{F} \\
\text{positron emission} & \quad \tau_{1/2} = 1.8\text{h} \\
\alpha + {}^{10}\text{B} & \rightarrow n + {}^{13}\text{N} \\
\text{positron decay} & \quad \tau_{1/2} = 10\text{min}
\end{align*}
\]

\underline{Boron compounds}

\[
\begin{align*}
n + {}^{10}\text{B} & \rightarrow \alpha + {}^{6}\text{Li} \\
\alpha + {}^{10}\text{B} & \rightarrow n + {}^{13}\text{N} \\
\text{positron decay} & \quad \tau_{1/2} = 10\text{min}
\end{align*}
\]

\[10^7 \text{n/s}\]

\[\Rightarrow 20 \text{ } {}^{13}\text{N} \text{ produced/second} \times 10^6 \text{s} = 6 \times 10^4 \text{ } {}^{13}\text{N}\]

\[\Rightarrow 15 \text{ Hz of events}\]

\text{NEED TO DECIDE HOW MUCH ACTIVATION/BACKGROUNDS}

\text{WE CAN LIVE WITH.}

\text{EXPECT ~ 10 Hz just from surroundings.}
How well can we identify neutron beta decays?

Bob Golub (HMI)
Detection of Neutrons in Liquid Helium

Neutrons inside the superfluid helium can be detected via the energetic charged particles which are produced in the beta decay:

\[ n \rightarrow p + e^- + \bar{\nu} + 783 \text{ keV} \]

or with a dilute solution of $^3\text{He}$ inside the $^4\text{He}$ volume:

\[ n + ^3\text{He} \rightarrow p + ^3\text{H} + 764 \text{ keV} \]

Travelling through the helium these charged particles loose their kinetic energy which is partially converted into scintillation light.

\[ \rightarrow \text{Scintillations with highest intensity in vacuum ultraviolet region (VUV) of the optical spectrum.} \]

Using a fluorescent wavelength shifter the VUV scintillation light is converted into visible light which can easily be detected by a photomultiplier.
Sketch of the experimental apparatus

Liquid Helium Experiments

- Vacuum
- Liquid nitrogen
- Main bath, liquid helium
- LN₂-shield
- LHe-shield
- Quartz sample chamber
- Aluminium reflector
- Plastic sheet coated with TPB
- Light pipe
- Cryostat window
- Photomultiplier
typical neutron scintillation event
Neutronensignal

- \( T = 4.2 \text{ K}, 500 \text{ mbar Gas} \)
- \( T = 4.2 \text{ K}, \text{LHe} \)
- \( T = 1.8 \text{ K}, \text{LHe} \)
If long time tail would vanish in gas ⇒ not from Tr13
I MeV Konversionselektronen in 2K LHe

signal / V

integrated signal

alle unter Lambda Punkt

1 MeV Konversionselektronen in 2K LHe

alle unter Lambda Punkt

1 MeV Konversionselektronen in 2K LHe

only 1 MeV

only 1 MeV
Abb. 4.22: Zeitliches Verhalten des durch monoenergetische Elektronen (\(E = 1\,MeV\)) induzierten Szintillationssignals innerhalb der ersten 4.5 μs nach dem Signalanstieg für flüssiges Helium bei \(T=4.2\,K\) und bei \(T=1.8\,K\). Rechts oben: Zeitskala von 450 ns bis 1 μs. Man beachte, daß das Maximum des Signals bei \(t=500\,ns\) liegt. Die Signale sind jeweils auf das Maximum normiert.
Kapitel 4 Experimente mit Helium als Szintillator

counts - normalized to one main pulse

- 500 keV electrons
- 1 MeV electrons
- neutrons

Normalization might be necessary.
\[ I(t) = A \cdot e^{-\frac{t}{\tau}} + \frac{B}{1 + \frac{t}{\tau_d}} \]

\( \tau \approx 1.5 \mu s \)
Vorzügliche Rate
Latenzrate ≈ 50%
\( a^{3\Sigma_u^+} \text{He}_2 \approx 20\% \) (für \( t > 1\) s)
\[ n + ^3 \text{He} \rightarrow p + t + 764 \text{ keV} \]

e\:^-\ : \quad 0.15 - 0.2 \text{ p.e. / keV}

\[ \alpha, n : \quad 0.035 - 0.04 \text{ p.e. / keV} \times \text{Faktor 4 - 5} \]

\[ \rightarrow \text{Quenching} \]
\[ t_T \approx 4.2 \text{ ns} \]
\[ t_f \approx 13.6 \text{ ns} \]

Für alle Teilchen → PSD

Modell: 2 exponentielle Zerfälle
Zeitauflosung: Gaß-Funktion

FWMH = 3.5 ns
\[ T_1 \approx 2.4 \text{ ns} \]
\[ T_1 \approx (\text{eln} - 1) (T - T_0) \]
Monte-Carlo studies
Martin Cooper (Los Alamos)
SIGNAL ANALYSIS

Scintillation Signal

\[ \Phi = \Phi_B + Ne^{-\Gamma_{AVe}t}\left[\frac{\epsilon_\beta}{\tau_\beta} + \frac{\epsilon_3}{\tau_3} \left[1 - P_3P_n e^{-\Gamma_p t} \cos(\omega_r t + \phi)\right]\right] \]

+ \frac{N_{Al}e^{-t/\tau_{Al}} + N_{Cu}e^{-t/\tau_{Cu}}}{\tau_{Al}}

measured for a time \( T_M \)

• How does the error in a least squares fit compare to the proposal?
• How does the error on \( \omega_r \) depend on other parameters?
• What is the optimal value of \( T_M \)?
• What is the optimal value of \( N_3 \) that sets \( \tau_3 \)?
• At what level can \( \Phi_B, N_{Al}, \) and \( N_{Cu} \) be ignored?
• What is to be gained by suppressing the \( \beta \) decays, i.e. \( \epsilon_\beta \rightarrow 0 \)?

SQUID Signal

\[ \Phi_S \propto \Phi_{BS} + N_3\left[1 - P_3 e^{-\Gamma_3 t} \cos(\omega_3 t + \phi_3)\right]\]
\( \nu_0 = 3 \text{ Hz} \quad N_n = 2 \times 10^6 \quad \sigma_{LS} = 1.20 \mu\text{Hz} \quad \sigma_{\text{rms}} = 1.25 \mu\text{Hz} \)
\[ v_0 = 3 \text{ Hz} \quad N_n = 2 \times 10^6 \]

![Graph showing efficiency for detecting neutron β-decays with frequency sensitivity on the y-axis and efficiency on the x-axis. The graph includes a label for the uncertainty principle and a proposal point.]

7/22/02

Los Alamos

Physics Division / P25
DEPENDENCE ON OTHER PARAMETERS

Free Variables

\[ f_0 = \frac{\omega_f}{2\pi} \]
\[ f_0, \tau \]
\[ f_0, \tau, N_n \]
\[ f_0, \tau, N_n, \phi \]

\[ \sigma_{LS} \]

\[ 1.2 \ \mu\text{Hz} \]
\[ 1.2 \ \mu\text{Hz} \]
\[ 1.2 \ \mu\text{Hz} \]
\[ 2.4 \ \mu\text{Hz} \]
LIGHT COLLECTION

Optimizing the light collection design
• What is the number of photoelectrons expected?
• How many PEs do we get versus integration time?
• How is the number of PEs influenced by compromises associated with HV, activation backgrounds, cryogenics, etc?
• Do fiber optics have a role?

GUIDE7 program as a starting place
Test code against NIST lifetime results
COLD NEUTRON TRANSPORT

Design the beam polarizing beam splitter
• How do we optimize polarization and transmission given the allowed length?
• Do losses in the splitter make backgrounds?

Minimizing beam activation
• Do we need a guide in the cryostat?
• What sort of collimation is useful?
• Do the entrance windows need to be Be?
• How can we minimize the activation on the electrodes?
• How should we dump the beam?

Minimize scattered-neutron activation
• Where do we want to place neutron absorbers?

Problems with trace elements
UCN IN THE TRAP

Should these considerations be part of the light collection Monte-Carlo? UV light in the trap also needs to be considered?
SPIN TRANSPORT OF THE $^3$He INTO THE CELL

Polarization losses in the transport into the cryostat
Polarization losses in the storage volume
Polarization losses in the transport from the storage volume to the measuring cell
Fitting into LANSCE ER-2
Jan Boissevain (Los Alamos)
Tour of LANSCE ER-2 and Building 10 Lab
Seppo Penttila (Los Alamos)
Separating the purifier from the dilution refrigerator,
an alternate design
Paul Huffman (NIST)
James Butterworth (ILL)
Figure 3.1  The Heat Flush

a) Flushing tube
b) Needle Valve
c) Heater
d) Helium of natural purity
e) Decreasing level of $^3$He

Graph to show $^3$He concentration in Flushing tube
Figure 4.4 Purifier Mk IV
McClintock apparatus

Photo 1  The Purifier Insert
Combined System (proposed design)

Advantages:
- compact design
- minimizes amt. of equipment used
- helium circulated at "low" (<2K) temperature

Disadvantages:
- problem with one system requires warming up both systems
  (turnaround for purifier ~ 1 day, for D.K. ~ 1 week)
- thermal fluctuations in one system may significantly affect the other system
- combining systems after independent development and testing may be difficult
- extra equipment needed during development
Two independent systems:

Advantages:

- Systems can be tested independently
- Helium could be accumulated prior to the run (for reserve)
- No interdependence between systems
  Instability in one system (or leak) does not prevent operation of other system

Disadvantages:

- Recovering used helium difficult
  (using "new" helium would be ~1000 l/day)
- Recovering helium must be cooled
  \[ (4.2K \rightarrow 9W) \]
  \[ (2.2K \rightarrow 3W) \]
Hybrid system: (compromise)
Proposed tests of SQUIDs
Michelle Espy (Los Alamos)
SQUIDs in the nEDM

• Introduction
• Temperature Effects
  – Survey of SQUIDs
• Upcoming tests
Motivation

- 3He comagnetometer reduces systematic errors due to instabilities in the magnetic field.

- SQUID provide direct measure of 3He precession frequency, \( \nu_3 = \gamma_{3\text{He}} B_0 \), thus a direct measure of \( B_0 \) averaged over cell volume and measurement period.

- SQUID could provide a measure of polarization of 3He introduced into the cell during the filling period.

- Monitor orientation of 3He magnetization.

- *Hopefully* simpler than dressed spin technique (no RF)
Fig IV-1. Experimental cryostat, length ~ 3.1 m. The neutron beam enters from the right. Two neutron cells are between the three electrodes. Scintillation light from the cells is monitored by the light guides and photomultipliers.
What does the FEM model say?

Without SIS = .002 $\Phi_0$ and with SIS = .02 $\Phi_0$.

Figure V.F.2. Predicted values of flux in the vertically oriented pick-up coils expected, both with and without the superconducting vessel.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SIS Cylinder</strong></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>1.34 m</td>
</tr>
<tr>
<td>Radius</td>
<td>0.3 m</td>
</tr>
<tr>
<td><strong>Target cells</strong></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>0.5 m</td>
</tr>
<tr>
<td>Inner Radius</td>
<td>0.04 m</td>
</tr>
<tr>
<td>Center from SIS axis</td>
<td>+/- 0.1 m</td>
</tr>
<tr>
<td>Magnetization</td>
<td>$5 \times 10^{-9}$ J/(T m$^3$) assuming $1.25 \times 10^{15}$ 3He/cell</td>
</tr>
<tr>
<td><strong>SQUID pickup coils</strong></td>
<td></td>
</tr>
<tr>
<td>Length</td>
<td>0.25 m</td>
</tr>
<tr>
<td>Width</td>
<td>0.04 m</td>
</tr>
<tr>
<td>Center from SIS axis</td>
<td>+/- 0.145 m</td>
</tr>
<tr>
<td>Coils #1,3 (Horizontal)</td>
<td>+/- 0.145 m</td>
</tr>
<tr>
<td>Coils #2,4 (Vertical)</td>
<td>+/- 0.175 m</td>
</tr>
</tbody>
</table>
Assume the target is a uniformly magnetized sphere:
M=magnetization=polarization*magnetic moment/volume
100% polarization
\[ \mu = 2.127 \mu_N = 2.127(5.05 \times 10^{-27}) \]
1.25e^{15} 3He and cell volume (2.5 liters) = 5e^{17} 3He/m^3

\[ M = 54e^{-10} \text{JT/m}^3 \]

\[ B_z = \frac{2}{3} \mu_o \frac{a^3}{z^3} M \]

radius of cell a~8.5cm and pick-up coil is z~1cm from surface.

Flux = B-field* area. Assume field constant over 100cm^2 area.
Peak-to-peak value of flux in pick-up coils: 0.04 \( \Phi_o \).
• 100 cm$^2$ pick-up $S=0.02 \Phi_0$.

• Flux actually coupled to the SQUID is

$$\Phi_s = \Phi_p M \over (L_p + L_i)$$

"typical" values $M=10$ nH, $L_i=600$ nH, 100 cm$^2$ loop $L_p=1.4$ $\mu$H. Roughly 1/100$^{th}$ of the signal gets to the SQUID.

At 4 K: $d\Phi_{SQ} \sim 3 \mu \Phi_0/\text{Hz}^{1/2}$ (measured) and should scale with $\sqrt{4K/0.3K}$.

• Experimental noise needs to be limited to as low as possible

• Possible sources: vibration in $B$ field, leakage current; Johnson noise, magnetic noise through penetrations, non-uniformity in $B$ field.
Noise vs. Temperature

Initial work was at 4 K. The nEDM will be at 0.3 K.

Wellstood, Urbina, Clarke

New Picovoltmeter built for tests at low temperatures

Data taken at NHMFL '01-'02
CC12 flux noise vs. Temp

Flux Noise $\mu\phi_0^2$/Hz vs. Temperature:
- Slope = 0.138
- Intercept = 0.008

$\mu^2$ vs. Temperature: with pick-up
- Slope = 0.81
- Intercept = 0.61

$\mu^2$ vs. Temperature: no load
- Slope = 1.0
- Intercept = 0.08
MAG8 flux noise vs. Temp

Flux Noise (μ0μ0/Hz)

T(K)

(1.50²)
(1.53²)
(1.66²)
(1.75²)
(1.97²)
(2.00²)

slope = 1.67
intercept = 0.54

Same SQUID as in full head MEG system.
Effective area is 2.5 mm²
Mag 8

.84nT/ $\Phi_0$ and $2 \times 10^{15}$ Tm$^2$ in flux quantum
2.4 mm$^2$ effective area

SQUID with big coil

.02nT/ $\Phi_0$ and $2 \times 10^{15}$ Tm$^2$ in flux quantum
100 mm$^2$ effective area

The ratio of areas is 40.

$200 \, \mu \Phi_0 / 40 = 5 \, \mu \Phi_0$

The signal-to-noise goes as $\sqrt{\text{# of SQUIDs}}$
Upcoming Tests

No plans to test SQUIDs in HV at this time

tests of gradiometer as function of temperature at NHMFL (from 4K to at least 1K)

Additional FEM modeling for optimization of SQUID position

detection of 3He
High voltage issues (constraints on leakage current)

1nA produces $10^{-15}$ T at 10cm

- Johnson Noise
  - Electrodes can’t superconduct
  - Must be high resistance material

\[
\langle I^2 \rangle = \frac{4kT\Delta f}{R}
\]

- Protection of SQUIDs
  - SQUIDs in some sort of Faraday cage?
Try a large area gradiometer.

We have obtained a 1st order gradiometer from IHPT Jena

Each coil is 19mm x 19mm

The chip is 60mm x 20mm x 5mm

Effective area (for one coil) is 7.5 mm^2

(sensitivity 0.28nT/Φ₀)
Modify FEM to reflect new coils and optimize their location

Petr Volegov UNM
Detection of $^3$He
Shortening the magnet by better matching of boundary conditions; magnetic shielding issues
Brad Filippone (Caltech)
EDM Magnetic Fields & Shielding:

Issues/Challenges:

- Will Superconducting Shield work?
  \( \rightarrow \) "No" EDM exp. has used inner SC shield
  Possible uncontrolled trapped flux
  Trapped flux may vary randomly
  \( \rightarrow \) increased B noise

- Can Ferromagnetic Shield work?
  \( \rightarrow \) Standard Mag. materials perform poorly at low T
  Reduced \( M \), T cycling worsens?
  \( \rightarrow \) Ferro. shield may allow smaller volume
  Boundary Conds. give better uniformity than SC shield

- Will external B leakage through penetrations compromise SQUIDs?
Present Baseline Design

Target region with magnet coil

Specs:

- $18 \text{1 mG}$
- Uniformity $\leq 10^{-3}$
- Time stab. $< 10^{-6}$s
Ferromag. vs. SuperCond. Shield

Boundary Cords. favor Ferromag.

\[
\begin{align*}
\text{Ferromag.} & \quad \mu \to \infty \\
\text{SC} & \quad \mu = 0
\end{align*}
\]

\[B_{\parallel} = 0 \text{ at Surface}\]

\[B_L = 0 \text{ at Surface}\]

\[r_c \to 0 \text{ at Surface}\]

Image Currents

\[r_c = \left( \frac{L}{I_c} \right) R\]

\[I_c = -I_c\]

As \( r_c \to R \) image current adds to coil

As \( r_c \to R \) image current cancels coil I
2D Analytic Calc.
Re = 35 cm
Rs = 45 cm
20 coils

Note:

\[
\frac{B_x(x)}{B_x(0)}
\]

Note:
\[
\frac{I_{sc}}{I_{FeGo}} = 4
\]

SC shield
No Shield
\( \mu = \infty \) Shield

X (cm)
Ferromag. shield may allow smaller cryo volume + meet uniformity spec.
Also no trapped flux problems

Glenn Strycker & Jan B. (LANL)
working on ANSYS calc. of ferromag. shield

But...
Low T favors SC shield
SC only works at low T
Ferromag. may not work at low T
Low T Ferromag. performance:

- "Mu-metal has $\mu = 3500$ at 4 K"
  $\rightarrow$ Amineal
  (Problems w/ T cycling?)

- Other materials may be promising
  
  Cryoperm 10 (high Ni)
  Claimed $\mu$ at 4K $\approx 75,000$
  (M. Snow (UCF studying))

  Metglas
  Amorphous metal (metal glass)
  Formed via rapid solidification $\sim 10^6$C/s

  2705M looks interesting
  $\rightarrow$ anti-theft tags

  (Steve L. has some of this ribbon)
Applications

- Flexible electromagnetic shielding
- Magnetic sensors
- High frequency cores

Benefits

- Near-zero magnetostriction
- High DC permeability at low fields without annealing
- High tensile strength

Typical Impedance Permeability Curves, Longitudinal Field Anneal

Physical Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (g/cc)</td>
<td>7.80</td>
</tr>
<tr>
<td>Vicker's Hardness (50g load)</td>
<td>900</td>
</tr>
<tr>
<td>Tensile Strength (GPa)</td>
<td>1.2</td>
</tr>
<tr>
<td>Elastic Modulus (GPa)</td>
<td>100-110</td>
</tr>
<tr>
<td>Lamination Factor (%)</td>
<td>&gt;75</td>
</tr>
<tr>
<td>Thermal Expansion (ppm/°C)</td>
<td>12.1</td>
</tr>
<tr>
<td>Crystallization Temperature (°C)</td>
<td>520</td>
</tr>
<tr>
<td>Continuous Service Temp. (°C)</td>
<td>90</td>
</tr>
</tbody>
</table>

Magnetic Properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Saturation Induction (Tesla)</td>
<td>0.77</td>
</tr>
<tr>
<td>Maximum D.C. Permeability (µ)</td>
<td>600,000</td>
</tr>
<tr>
<td>Annealed</td>
<td>0.290,000</td>
</tr>
<tr>
<td>As Cast</td>
<td></td>
</tr>
<tr>
<td>Saturation Magnetostriction (ppm)</td>
<td>&lt;&lt;1</td>
</tr>
<tr>
<td>Electrical Resistivity (µ-Ω-cm)</td>
<td>0.136</td>
</tr>
<tr>
<td>Curie Temperature (°C)</td>
<td>0.365</td>
</tr>
</tbody>
</table>
If suitable Ferromag. material can be identified, perhaps optimal soln. is

"Compact" Coi1 - Ferromag. - SC set

Coil coil SC Ferromag.
Possible Task List for next 1.5 yrs.

- Full 3D calc. of cosθ coil + Ferromag. Shield

- Study low T behavior of Ferromag. materials

- Build scaled (~ 1/4) prototypes?
  - Borrow cryostat (UIUC, LANL, ...?)
  - Wind coil (→ PIC)
  - Make shields
  - Install SQUID*/NMR

Fiscal/Manpower Impact
≈ 1 FTE + 10-20k$
Modifications of the apparatus to incorporate the dressed-spin technique
Bob Golub (HMI)
Polarization of UCN

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

\[ (\text{He}^4) \quad \vec{J} = J_{\text{He}^3} + J_n \]

experimentally \((J=0 \text{ resonance in } \text{He}^4)\)

\[ \frac{\sigma_{J=0}}{\sigma_{\text{tot}}} = 1.01 \pm 0.03 \]

\[ \vec{J} \parallel \vec{S} \quad \Rightarrow \quad \Gamma_{\text{He}^3} = 0 \]

polarized \(\text{He}^3\)

\[ \vec{S}_{n=+} = 0 \quad \vec{S}_{n=-} = 2 \vec{S}_0 \]

\[ \frac{1}{\tau_{\pm}} = \frac{1}{\tau_0} + (1 + P_3) \left[ n_3 \sigma_0 \left. \Gamma_{\text{UCN}} \right| \right] \Rightarrow \quad \frac{1}{\tau_{\text{He}^3}} \]

\[ \vec{S}_{\pm} = \frac{\Phi_{\pm}}{2} \tau_{\pm} \quad \vec{S}_0 = \text{UCN prod rate} \]

\[ \Phi_{\pm} = \int \phi(t) \left[ \varepsilon(E-E_{\text{He}^3}) \right] \text{d}E \]

\[ \Phi_{\pm} \]

\[ \text{UCN} = \frac{P_3}{1 + \tau_{\text{He}^3}/\tau_0} \]
For Polarized UCN

\[ \frac{1}{\lambda_{abs}} = N \sigma_0 \nu (1 - \hat{P}_n \cdot \hat{P}_3) \]

Absorptions \( \Rightarrow \) Scintillations
He\textsuperscript{5} co-magnetometer

Scintillation rate

\[ \frac{\text{Scintillation}}{\text{Counts}} \sim (1 - \vec{P}_n \cdot \vec{P}_3) \]

\[ (1 - \vec{P}_n \cdot \vec{P}_3 \cos \Theta_{n3}(t)) \]

\[ \Theta = (\chi_n - \chi_3) \vec{B}_0 \tau \pm \frac{ednE}{\tau} \]

\[ \chi_3 = 1.1 \chi_n \]

\[ \text{Weff} = 0.1 \chi_n \vec{B}_0 \] factor of 10 reduction in field sensitivity

Scintillation rate measures field shows edm
Further Development

Dressed Neutron (Muskat, Dubbers, Schädt)

\[ \mathbf{B}(t) = B_d \sin \omega_d t \]

\[ W_{prec} = x B(t) = \dot{B}(t) \]

\[ \Theta = \frac{x B_d}{\omega_d} \cos \omega_d t \]

\[ \langle \cos \Theta \rangle = \frac{1}{T} \int_0^T dt \cos \left[ \frac{x B_d}{\omega_d} \cos \omega_d t \right] \]

\[ = \frac{1}{2} \left( x \frac{B_d}{\omega_d} \right) = \int_0^x (x) = x_{eff} \]

\[ x = \text{dressing parameter} = x B_d / l \]
FIG. 3. Spin-precession measurements with dressed neutrons. At the critical rf-field strength $2B_1 = 1.7$ mT the $g$

Dressed the 'cont- searches. earth's $n$
neutrons effective not help decouple: again be discussed basis, with the neutron sight.
FIG. 5. Variation of the dressed-neutron's $g$ factor with rf-field strength ($\omega_1 = \gamma \beta_1$).
Magnetic Moment

Dressing

\[ W = (\gamma_3^\text{eff} - \gamma_n^\text{eff}) B_0 \]

\[ \kappa_i^\text{eff} = \kappa_0 (X_i) \kappa_e \]

\[ X_i = \kappa_i B_d / \nu_d \]

\[ \gamma_3 / \gamma_n = 1.1 \]

\[ \left[ \gamma_3 J_0 (\gamma_3) - \gamma_n J_0 (\gamma_n) \right] = 0 \]

1.1 \( J_0 (1.1X) = J_0 (X) \) ?

Yes!

\[ X_c = 1.19 \]

Critical dressing \( \Rightarrow \)

constant scintillation rate independent of DC magnetic field

corrections \( \sim \frac{B_{dc}}{B_d} \)
\[ \text{edm} \text{ apply electric field} \quad \vec{B}, \vec{E} \]

\[ \omega_n = \frac{X_{\text{eff}} B_0 + e d_n E J_0 (X_c)}{\hbar} \]

\[ \theta_{03} = e d_n E t \]

shows up in scintillation rate.

with \( \overrightarrow{S}, \overrightarrow{I} \) parallel

absorption \( \sim 0 \)

modulate \( X \)

\[ x(t) = X_c + E \cos \omega_m t \]

\[ 8 \omega_{03} \sim E \cos \omega_m t \pm k \frac{d n}{d E} \]

\[ \delta \theta = \frac{e}{\omega_m} \sin \omega_m t \pm k \frac{d n}{d E} E t \]
Scintillation rate \( S \)

\[ \frac{\partial S}{\partial \theta_{\alpha \beta}} = 0 \Rightarrow \text{2nd harmonic} \]

\[ (\partial \theta)^2 \pm \partial \theta (\omega_n t) \text{ growing with } t \text{ due to} \]

\[ \Rightarrow \text{2nd Harmonic for calibration} \]
$B_{dc} = 10^{-3}$ gauss  \hspace{1cm} f_0 = 3 \text{ Hz} \hspace{1cm} \omega_0 = 20 \text{ rad/sec}$

$\omega_i = \frac{\omega_i}{\omega_i} \hspace{1cm} x = \frac{\omega_i}{\omega_i} = 1.19 = x_c$

$\omega_i \gg \omega_0 \hspace{1cm} \omega_i \sim 200 \text{ rad/sec} \hspace{1cm} \omega_i \sim 2000 \text{ rad/sec}$

$B_{rf} = 10^{-2} \text{ g} \hspace{1cm} (30 \text{ Hz})$

$10^{-1} \text{ g} \hspace{1cm} (300 \text{ Hz})$

Shaking Field
Shaking - Keep domains moving

\[ \text{Material} \rightarrow \text{Field} \rightarrow \text{Freq} \]

<table>
<thead>
<tr>
<th>Material</th>
<th>Field (mT)</th>
<th>Freq (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>G-metal</td>
<td>50</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Metglas 2705H</td>
<td>30</td>
<td>1 kHz</td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>200 Hz</td>
</tr>
<tr>
<td>Multilayer Slic</td>
<td>10</td>
<td>200 Hz</td>
</tr>
<tr>
<td>Shield</td>
<td>25</td>
<td>536 Hz</td>
</tr>
</tbody>
</table>

up to 500 Hz with 0.5
FIG. 1. Frequency dependence of the permeability, where values are normalized by $\mu_1$ (permeability at 1 Hz); $\mu_1 = 5.27 \times 10^5$ under magnetic shaking, $\mu_1 = 3.41 \times 10^4$ under normal condition.

$\Delta B = 10\text{mT}$
- shaking
- without shaking

5584   J. Appl. Phys., Vol. 67, No. 9, 1 May 1990

Hetglas 27 CSM

$2.1 \times 10^{-4} \text{J/kg/cycle} \times 500 \text{Hz}$

$\Rightarrow 100 \text{mmHg}$

say 1 watt

$2.1 \times 10^{-4} \text{J} \times 500 \text{Hz}$
was used to cancel the horizontal component of the earth's field. Before each measurement, the shielding case was demagnetized using the shaking coil.

**RESULTS AND DISCUSSION**

It was found that the leakage field into the shielded space increased gradually after applying the disturbing field and then reached steady state. The increase in leakage field was at most 14% within 2 h of observation. However, this phenomenon is not taken into account in the following data.
and shows a broad peak for $H_s = 2.0-3.0 \text{ A/m}$. The effective permeability decreases with decreasing $\Delta H$, however, it is still high. The maximum value even for $\Delta H = 0.002 \text{ A/m}$ (rms) is higher than $3.5 \times 10^5$. The maximum value, for example, obtained with Mumetal by shaking is $8.9 \times 10^4$ under no dc field. In that case, the value goes down to almost one when a dc bias field increases up to $0.5 \text{ A/m}$. A similar phenomenon was also found with the Metglas 2705M ribbon; however, the decrease in the effective permeability due to

![Diagram](image)

FIG. 3. Effective permeability vs shaking field strength (single layer).

5697 J. Appl. Phys., Vol. 64, No. 10, 15 November 1988
ing magnetic field leaking from shells #1–#4. The total weight of the tapes used was 15 kg. Nominal diameters of the shells are 56 cm for #1, 55.3 cm for #2, 54.6 cm for #3, 52.6 cm for #4, and 52 cm for #5. Numbers of turns were 50 for shaking coils #1 and #2 and 20 for the demagnetizing coil.

![Diagram](image)

**FIG. 1.** Cross sectional view of thin multiple-structure. Spacings between shells are about 3.5 mm, unless otherwise indicated.
sists of $n$ magnetic shells. In our case, the order of the polynomial function is 4 because shells #1–#4 are subjected to magnetic shaking. The permeability of shell #5 is treated as a constant equal to 2000. When the distances between the neighboring shells are small, coefficients of higher order terms become small. Therefore, when the permeability is low, higher order terms do not affect a resulting shielding factor. In other words, a thin multiple-shell structure behaves as a single shell with the same total thickness when the permeability is low. On the other hand, when the permeability is sufficiently large, higher order terms with small coefficients become substantial, so a thin multiple-shell does work to increase shielding factor.

![Graph showing relationship between shielding factors and relative permeability.](image)

FIG. 4. Relationship between shielding factors and relative permeability.

Sasada, Yamamota, and Yamaguchi 5491
FIG. 1. Open-ended cylindrical shields employing Metglas ribbons. (a) Cylinder consisting of a helical structure of the ribbons. (b) Cylinder consisting of an axial structure of the ribbons. (c) Magnetic shaking by a toroidal coil.

Measured at the shield centers by a miniature magnetoresistive sensor of the HMC 1022 type, manufactured by Honeywell. The shielding characteristics measured (the shielding factors versus the shaking field) are shown in Fig. 3 and the ASF and TSF are shown in Table I. In order to investigate the effect of the shaking field direction on shielding enhancement, magnetic shaking by solenoidal coils was also investi-
cylindrical shields (length, outer diameter, thickness: 283 ×56×0.31 mm) consisting of helical [Fig. 1(a)] and axial [Fig. 1(b)] structures of Metglas 2705M amorphous ribbons were built for this purpose. The shielding factors were measured at the centers of these shields by a flux-gate magnetometer of the MAG-03 MC type, manufactured by Bartington, and are listed in Table I. The shaking field intensities, corresponding to maximum shaking enhancement of the shielding factors, are approximately equal to corresponding values of the same parameter obtained for miniature shields: \( \sim 50 \text{ mOe} \) for the TSF and \( \sim 320 \text{ mOe} \) for the ASF (see Fig. 3). The data in Table I shows that magnetic shaking provides an \( \sim 40 \) field increase in the TSF and \( \sim 20 \) field increase in the ASF.
A uniformly shielded area is extended toward the opening by

**FIG. 4.** Distributions of $B_x$, where the opening compensation is off in (a) and on in (b).

I. Sasada and Y. Onaka 6585

*to AIP copyright, see http://ojps.aip.org/japo/japcyrts.html.*
Update on the HV-test apparatus
Debbie Clark (Los Alamos)
EDM High Voltage Test

A. Purpose of Experiment.

B. Describe System.

C. Tests and their Significance.

D. Schedule.

E. Remaining Design Issues.

F. Questions.
EDM High Voltage Test

A. Purpose of Experiment.
   a. Learn High-voltage behavior.
   b. Liquid Helium behavior at ~1 K.
   c. Magnetic field issues.
   d. Failure points
      i. Mechanical, electrical leakage, sparks.
   e. Is 50kV possible?

B. Describe System.
   a. Vacuum shell, nitrogen shell, LHe chamber.
   b. Electrodes, actuators, bellows.

C. Tests and their Significance.
   a. Can we assemble this?
   b. Mechanical failure of components and seals.
   c. Are heat loads acceptable?
   d. Does variable capacitor work as designed?
   e. Measure dielectric constant of materials.
   f. Measure dielectric strength of LHe at 1K.
   g. Measure E Field with Kerr effect.
      i. Source, laser
   h. Effect of E Field on scintillation process.
      i. Phototube.
   i. Potentially use Squid to see Johnson effect, leakage current.

D. Schedule.

E. Remaining Design Issues.
   a. Large wire seal flanges.
   b. Cam system.

F. Questions.
# High Voltage Test Assembly

estimated June, 2002  D. Clark

<table>
<thead>
<tr>
<th>Item</th>
<th>Quantity</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hunt. Linear Actuator &amp; Cont. (2)</td>
<td></td>
<td>$7000</td>
</tr>
<tr>
<td>Outer Vac Can Assy Alum A&amp;B</td>
<td></td>
<td>16325</td>
</tr>
<tr>
<td>Nitro Shield Cu Assy A&amp;B</td>
<td></td>
<td>4850</td>
</tr>
<tr>
<td>Andonian Modification</td>
<td></td>
<td>3025</td>
</tr>
<tr>
<td>Inner He4 Copper Can A&amp;B</td>
<td></td>
<td>20500  (+$2000)</td>
</tr>
<tr>
<td>G-10 Dbl Bearing Assy (2)</td>
<td></td>
<td>725</td>
</tr>
<tr>
<td>Bellows/Flg. Weldment (4) Uses # 501</td>
<td></td>
<td>6000   (+$3000)</td>
</tr>
<tr>
<td>High Volt. End Actuator Assy (w/ 2 #500)</td>
<td></td>
<td>3685</td>
</tr>
<tr>
<td>Ground End Actuator Assy (uses 2 #500)</td>
<td></td>
<td>2325</td>
</tr>
<tr>
<td>Unistrut Stand Assy A&amp;B</td>
<td></td>
<td>2000</td>
</tr>
</tbody>
</table>

**TOTAL** $66435 (+$ 5000 spares)
Discussion of test objectives

1. Confirm viability of engineering design
   acceptable heat loads
   cold HV feedthrough survives
   flanges remain sealed
2. Validate variable capacitor design
3. Measure cryogenic properties of materials
   testbed for engineering issues
   measure dielectric constant of cell materials
4. HV properties of LHe
   determine dielectric strength
5. Develop E field measurement with Kerr effect
6. Investigate effect of E field on scintillation process
7. Study performance of SQUIDS in test environment
Measuring the Kerr effect at cryogenic temperatures
Alex Sushkov (UC-Berkeley)
Kerr Effect-based Measurement of the Electric Field

Alex Sushkov
Dima Budker
Valeriy Yashchuk
(UC Berkeley)
**Precision Measurement of Electric Fields**

- **Kerr effect:** appearance of uniaxial anisotropy in an initially isotropic medium, induced by an applied external electric field:
  \[ \Delta n = n_\parallel - n_\perp = K\lambda E^2 \]

- For input light polarized at 45° to \( E \), the induced ellipticity:
  \[ \epsilon = \pi l \Delta n / \lambda = \pi l K E^2 \]

- Circular analyzer: \( \delta \epsilon \approx 10^{-8} \text{ rad Hz}^{-1/2} \) (shot)
Kerr Effect in LHe: Electric Field Measurement Sensitivity

- **Parameters of the neutron EDM experiment:**
  - Electric field: $E = 50 \text{kV/cm}$
  - Sample length: $l = 10 \text{cm}$
  - LHe Kerr constant inferred from He gas hyperpolarizability at $T=300\text{K}$: $K = 1.7 \times 10^{-16} \text{ cm/V}^2$

- **Resulting shot-noise sensitivity:**
  - Induced ellipticity: $\epsilon \approx 10^{-5} \text{ rad}$
  - A 1s measurement gives sensitivity, $\delta E/E \approx 5 \times 10^{-4}$
Experimental Setup: Polarimeter

Diode Laser, 780nm

Aperture: diameter approx 1mm.

Polarizer

Photo-elastic modulator, 50kHz

λ/4 Analyzer

PD

To RF Lock-In
Results: Polarimeter

• Optimized performance: 
  \[ \delta \epsilon = 10^{-7} \text{ rad/Hz}^{1/2} \] 
  (lock-in input noise)

• Laser power: \( P = 0.1 \) mW, 
  corresponding to shot noise of: 
  \( 5 \times 10^{-8} \) rad/Hz\(^{1/2} \)
Experimental Setup: Kerr Effect in LN₂

Diode Laser, 780nm
Aperture: diameter approx 1mm.
Polarizer
Cryostat
Sample space filled with LN₂

High-Voltage electrodes:
- spacing 3.5mm,
- length 2.5cm,
- voltage 2.5kV.

Photo-elastic modulator, 50kHz
λ/4 Analyzer
PD
To RF Lock-In
Results: $\text{LN}_2$

- Measured Kerr constant for $\text{LN}_2$:
  $K = (7.1 \pm 1.7) \times 10^{-14} \text{ cm/V}^2$

  $K = 6.3 \times 10^{-14} \text{ cm/V}^2$
Troubleshooting

- Cryostat window birefringence, induced by stresses and temperature gradients $\implies$ large drifts in the ellipticity signal
- Find better cryostat windows!

![Graph showing ellipticity signal over time for different temperatures: 300K cold air effect, 300K steady, 77K.]
What's next?

1. Sort out the cryostat windows birefringence drifts.
2. Measure the LN$_2$ Kerr constant 
3. Measure the LH$_2$ Kerr constant (UC Berkeley & LANL)
4. Evaluate the possibility of monitoring the EDM E-field using the Kerr effect.
Update on the polarized 3He source
Justin Torgerson (LANL)
\(^3\text{He polarization}\)

Requirements

- \(P_3 \approx 1\)
- \(\sim 10^{12} \text{ } ^3\text{He/cm}^3 \quad (\chi_3 \sim 10^{-10})\)
  \(\rightarrow 10^{16}\) in 8 L \quad (collect in 1000 s)

Quadrupole state selector

- \(P_3 > 0.99\) initially
- \(I_0 > 10^{14}/s\)
Experimental uncertainty

- $\delta f \propto 1/P_3 \quad P_3, P_n \approx 1$

- $\delta f \propto 1/P_3^2 \quad P_n \approx 0$

- $\delta f \propto 1/P_3^m \quad P_3, P_n \neq 1$
Our Approach

\[ \text{Exploit} \quad \vec{F} = \mu (\vec{s} \cdot \hat{r}) \vec{E} \]

Quadrupole Field

\[ \vec{F} = \pm \mu \frac{B_0}{R} \cdot \hat{r} \]

(assuming adiabatic following)
Simple Calculation of $^3$He Flux

Maximum acceptance

$$\sin(\Theta_0) \approx \sqrt{\frac{\mu B_0}{4kT}} \approx 0.9^0$$

for $B_0 = 0.75$ Tesla

$T = 0.6$ K

Maximum source pressure

$$\lambda_0 \geq \rho_s = 0.35\,\text{mm}$$

$$\rho \leq \frac{kT}{12\rho_s \sigma} \approx 10^{-4}\,\text{torr}$$

Maximum flux

$$I_0 = \frac{1}{2} \cdot 2 \cdot \sqrt{\frac{kT}{m}} \cdot \frac{P}{T} \cdot A_s \sin^2 \Theta_0 \approx 10^{15}/s$$

for $A_s = 1\,\text{cm}^2$
Numerical Analysis

\[
\begin{align*}
\vec{F}_B &= \pm \mu \frac{B_0}{R} \frac{1}{\sqrt{1 + (B_t R_e B_c c)^2}} \hat{r} \\
\vec{F}_g &= -m\left(g + \frac{L_e e^2}{R_e}\right)\left(\sin \varphi \hat{r} + \cos \varphi \hat{\varphi}\right) \\
\vec{F}_B + \vec{F}_g &= m \hat{\ddot{r}} \\
\vec{r} &= \left(\ddot{r} - r \ddot{\varphi}^2\right) \hat{r} + \left(r \dddot{\varphi} + 2 \dot{r} \dot{\varphi}\right) \hat{\varphi}
\end{align*}
\]

Furthermore,

\[
I(v) \propto v^3 e^{-\frac{mv^2}{2kT}}
\]

\[
I(\epsilon) \propto \cos \epsilon
\]
Figure 2: The light gray bars in (a) represent the velocity distribution of atoms which enter the aperture of the polarizer and the dark gray represents the subset that successfully traverses the polarizer. Panel (b) shows the same results as (a) with a different vertical scale. Panels (c-f) show the distributions of various initial conditions for atoms which successfully traverse the polarizer.

\[
\begin{align*}
\{ & t_1 = 0.53 \\
& t_2 = 0.0004 \\
& P_3 = 0.998
\end{align*}
\]
3He Polarized Source
Transport of $\uparrow^3\text{He}$

Magnetic field issues

- Gradient at quadrupole exit
- Reduce field before experimental volume
- Bent $^3\text{He}$ guide (horizontal polarizer)
- Higher $^3\text{He}$ temperatures (300 K) and field gradients

Los Alamos Physics
Gradient at quadrupole exit

\[ \left| \frac{dB}{dt} \right| \ll \mu B \]

\[ \frac{dB}{dt} = \frac{dB}{dz} v_z \]

- \( B(z) \approx B_0' \frac{R_0^4}{z^4} \)

- \( B \gg B(z) \) at \( z = \left( \frac{1}{4} \frac{\mu}{v_z} B_0' R_0^4 \right)^\frac{1}{3} \)

- \( B_0' \approx \frac{1}{30} B_0 \) (from calculation)

\[ B \gg 200 \text{ mG} \]

for \( B_0 = 0.75 \text{ T} \) and \( R_0 = 7.5 \text{ mm} \)
Bent $^3$He guide
(horizontal polarizer)

- $B_z = B_0 \cos(\theta)$ and $v_z = v \cos(\theta)$

- $|\frac{dB}{dz}| = B_0 \frac{z}{R^2}/\cos(\theta)$

- assuming $|B| = B_0$ everywhere

$$B_0 \gg \frac{z}{R^2} \frac{v}{\mu} \gg \frac{v}{R\mu}$$

$$B_0 \cdot R \gg 100 \text{ mG} \cdot \text{m at } 300 \text{ K}$$

$$B_0 \cdot R \gg 3 \text{ mG} \cdot \text{m at } 0.6 \text{ K}$$
Reducing B field before experiment

- \( \frac{dB}{dz} \ll \frac{\mu}{v_z} B^2 \)

(max) \( \frac{dB}{dz} \ll 100 \text{ mG/m} \)

for 300 K and \( B = 100 \text{ mG} \)

\( B \rightarrow 10 \text{ mG} \) is very difficult at 300 K
Experiences with hexapole state selectors
Janos Fuzi (Budapest)
Experiences with hexapole state selectors

Füzi János

Hungarian Academy of Sciences
Research Institute for Solid State Physics and Optics
Particles with magnetic moment in inhomogeneous magnetic field

\[ s = \gamma L \]

\[ F = \left( s \cdot \nabla \right) B ; \quad T = s \times B \]

\[ F = m \frac{d^2 r}{dt^2} ; \quad T = \frac{dL}{dt} = w \times L \]

\[ \Psi = C r^n \cos n \varphi \]

\[ B = \mu_0 C n r^{n-1} \left( -\cos n \varphi e_r + \sin n \varphi e_\varphi \right) \]

\[ F = s_r \frac{\partial B}{\partial r} + s_\varphi \frac{1}{r} \frac{\partial B}{\partial \varphi} \]

\[ F = \nabla (s \cdot B) = \pm s \nabla |B| \]
Quadrupole versus hexapole field configurations
Hexapole neutron lens electromagnet

Definition of pole geometry
Boundary conditions:
\[ b < \frac{a}{\sqrt{3}} \]
\[ \alpha < 30^\circ. \]
Magnetic field computation

Division of iron core cross-section

\[
H_f = -\frac{1}{2\pi} \iint_{A_s} \left( M_x \nabla_f \frac{x_f - x_s}{r^2} + M_y \nabla_f \frac{y_f - y_s}{r^2} \right) dA
\]

\[
H_f = (C_{xx} M_x + C_{xy} M_y) \hat{i} + (C_{yx} M_x + C_{yy} M_y) \hat{j}
\]

\[
C_{xx} = \frac{1}{2\pi} \iint_{A_s} \frac{2(x_f - x_s)^2 - r^2}{r^4} dA
\]

\[
C_{xy} = C_{yx} = \frac{1}{2\pi} \iint_{A_s} \frac{(x_f - x_s)(y_f - y_s)}{r^4} dA
\]

\[
C_{yy} = \frac{1}{2\pi} \iint_{A_s} \frac{2(y_f - y_s)^2 - r^2}{r^4} dA
\]
**Singularity exclusion**

\[
\begin{align*}
\nabla_x \times \left( \frac{y_f - y_s}{2r^2} i + \frac{x_f - x_s}{2r^2} j \right) &= \frac{2(x_f - x_s)^2 - r^2}{r^4} k \\
\nabla_x \times \left( -\frac{x_f - x_s}{2r^2} i + \frac{y_f - y_s}{2r^2} j \right) &= \frac{2(x_f - x_s)(y_f - y_s)}{r^4} k \\
\nabla_x \times \left( -\frac{y_f - y_s}{2r^2} i - \frac{x_f - x_s}{2r^2} j \right) &= \frac{2(y_f - y_s)^2 - r^2}{r^4} k
\end{align*}
\]

\[
\begin{align*}
\iiint_{A_0} 2\left(\frac{x_f - x_s}{r^2}\right)^2 - r^2 \, dA &= 0 \\
\iiint_{A_0} \left(\frac{x_f - x_s}{r^4}\right)(y_f - y_s) \, dA &= 0 \\
\iiint_{A_0} 2\left(\frac{y_f - y_s}{r^2}\right)^2 - r^2 \, dA &= 0
\end{align*}
\]

\[
C_{xx} = \frac{1}{2\pi} \iiint_{A_s} \frac{2(x_f - x_s)^2 - r^2}{r^4} \, dA = \\
\frac{1}{2\pi} \iiint_{A_s - A_0} \frac{2(x_f - x_s)^2 - r^2}{r^4} \, dA + \frac{1}{2\pi} \iiint_{A_0} \frac{2(x_f - x_s)^2 - r^2}{r^4} \, dA = \\
\frac{1}{4\pi} \oint_{r_s} (y_f - y_s)i + (x_f - x_s)j \, dl - \frac{1}{4\pi} \oint_{r_0} (y_f - y_s)i + (x_f - x_s)j \, dl = \\
\frac{1}{4\pi} \oint_{r_c} (y_f - y_s)i + (x_f - x_s)j \, dl - \frac{1}{2}
\]
Magnetic field computation

\[ C_{xx} = \begin{cases} \frac{-1}{2} + \frac{1}{4\pi} \oint_{r_s} \frac{(y_f - y_s)\mathbf{i} + (x_f - x_s)\mathbf{j}}{r^2} \, dl & \text{if } (x_f, y_f) \in A_s \\ \frac{1}{4\pi} \oint_{r_s} \frac{(y_f - y_s)\mathbf{i} + (x_f - x_s)\mathbf{j}}{r^2} \, dl & \text{if } (x_f, y_f) \notin A_s \end{cases} \]

\[ C_{xy} = C_{yx} = \frac{1}{4\pi} \oint_{r_s} \frac{-(x_f - x_s)\mathbf{i} + (y_f - y_s)\mathbf{j}}{r^2} \, dl \]

\[ C_{yy} = \begin{cases} -1 - C_{xx} & \text{if } (x_f, y_f) \in A_s \\ -C_{xx} & \text{if } (x_f, y_f) \notin A_s \end{cases} \]
Magnetic field computation

\[ H_k = H_0(i) + \sum_{l=1}^{N} [C_{kl}] M_l \quad k = 1, \ldots, N \]

\[ \mu_0 \tilde{M} = \frac{H}{H} \sum_{k=1}^{n} m_k \tan^{-1}(a_k H) \]

Error minimization

\[ \varepsilon = \sum_{k=1}^{N} |M_k - \tilde{M}_k|^2 \rightarrow \min \]

Contraction iteration

\[ M_{k}^{i+1} = \tau M_{k}^{i} + (1-\tau)\tilde{M}_{k}^{i} \quad ; \quad 0 < \tau \ll 1 \]

Magnetization vectors of surface elements
Results of the magnetic field computation

Magnetization vectors of surface elements in the vicinity of the aperture

Magnetic flux density vectors in the aperture
Measurement results
Measurement results

\[ B = \left[ C_1 \cos(\varphi - \varphi_1) - C_3 r^2 \cos 3(\varphi - \varphi_3) \right] e_r \\
+ \left[ -C_1 \sin(\varphi - \varphi_1) + C_3 r^2 \sin 3(\varphi - \varphi_3) \right] e_\varphi \]

\[ C_1 = B_1 = 5.8 \text{ mT} \quad \varphi_1 = 120^\circ \]
\[ C_3 = B_3 / r_p^2 = 34810 \text{ T/m}^2 \quad \varphi_3 = 0 \]
\[ r_p = 5.5 \text{ mm} \]

Contour plot of magnetic flux density magnitude in the aperture (parabolic scale, 5 mm radius plotted).
Neutron optical simulation
Permanent magnet neutron lens
Permanent magnet neutron lens
Beam divergence: 15'
Wavelength: 6 Å
Magnet length: 900 mm
Hexapole field constant: 40 000 T/m²
Dipole field: 20 mT (same orientation in each segment)
Beam divergence: 15’
Wavelength: 6 Å
Magnet length: 900 mm
Hexapole field constant: 40 000 T/m²
Dipole field: 20 mT (different orientation in different segments)
First beam experiment

one lens two lenses
330 cm from magnet end

one lens two lenses
120 cm from magnet end
Permanent magnet $^3$He spin state separators
Conclusions

Hexapole magnets are efficient tools both for neutron beam focusing and $^3$He spin state separation. From all possible inaccuracies, the most disturbing is the presence of a dipole component (it affects the neutron optical characteristics and causes spin flips and reduces the efficiency of spin state separators).

Hexapole $^3$He spin state separators can be more efficient than quadrupole ones. The performance of the latter can be significantly improved by the use of a thin axial rod which hinders the crossing of the low field area where spin flips occur.

Since the very low temperature is given, it would be worth considering the use of superconducting hexapole electromagnets.

Issues to be adressed:
- permanent magnet characteristics at very low temperature;
- optimal permanent magnet hexapole design to allow exit of atoms in the wrong spin state;
- measures to minimize the dipolar field component to avoid unwanted spin flips.
Thank you for your attention
Experiments relevant to transporting 3He into the superfluid He and the 3He polarization lifetime
Mike Hayden (Simon-Fraser)
Issues relevant to getting the $^3$He into the liquid, moving it about, and keeping it polarized ...

Mike Hayden
Simon Fraser University

Outline:
- source of polarized $^3$He?
- liquid-vapour exchange
- motion of $^3$He within the liquid
- wall relaxation
- experiments
Polarized Atomic Beam Source

Hexapole (focusing)

flow impedance

Cs annulus

$^3\text{He} \text{ ABS}$

differential pumping line.

$^4\text{He} \text{ surface}$
Apparatus for Production of High Nuclear Polarization in Liquid $^3$He-$^4$He Mixtures


- Optical pumping volume: $T \sim 295$ K
- Direction of vapour flow
- Heater
- Cesium ring: inhibits HEVAC
- $T_{\text{evap}} \sim T_{\text{cond}} + 50$ mK
- $T_0 \sim 200$ mK
HEVAC Effect

(Helium Vapour Compression)

JLTP 27 417, 1994
Physica B 194-6 677, 1994

net evaporation of $^4\text{He}$ creates pressure gradient

Superfluid $^4\text{He}$ film climbs to warmer parts of the cell

Refluxing $^4\text{He}$ vapour entrains $^3\text{He}$
$^{3}\text{He Evaporation Rate}$

\[ \Lambda = \sqrt{\frac{2\pi h^2}{mkT}} \]

\[ \dot{n}^* = -\frac{A\phi_{lv}}{V} \]

\[ \phi_{lv} = \frac{1}{4} n^* \sqrt{\frac{m}{m^*}} \alpha_{lv} \]

\[ \phi_{lv} = \frac{1}{4} n \bar{v} \alpha_{vl} \]

\[
\begin{align*}
\phi_{lv} &= \phi_{vl} \\
\mu &\quad \phi_{lv} \quad \phi_{vl} \\
E &\quad \text{liquid} \\
&\quad n^* \\
&\quad \text{vapour} \\
&\quad n
\end{align*}
\]

\[
\begin{align*}
\text{require} & \quad \phi_{lv} = \phi_{vl} \\
&\quad kT\ln[n\Lambda^3] = kT \ln \left[ n^* \left( \frac{m}{m^*} \right)^{\frac{3}{2}} \Lambda^3 \right] - E
\end{align*}
\]

\[
\begin{align*}
\alpha_{lv} &= \alpha_{vl} \frac{m}{m^*} \exp \left( \frac{-E}{kT} \right) \\
n &= n^* \left( \frac{m^*}{m} \right)^{\frac{3}{2}} \exp \left( \frac{-E}{kT} \right)
\end{align*}
\]

\[
\tau = \frac{4V}{A\bar{v} \alpha_{vl}} \left( \frac{m^*}{m} \right)^{\frac{3}{2}} \exp \left( \frac{E}{kT} \right)
\]
For $^3\text{He}$:

$$\Lambda \sim \frac{1 \text{ nm} \cdot \text{K}^{1/2}}{T^{1/2}}$$

$$k \cos \theta \sim (0.6 \, \text{Å/K}^{1/2}) \, T^{1/2}$$

Saturated Vapour Pressure of $l^{-4}\text{He}$

e.g. Rusby and Durieux, Cryogenics 24, 363 (1984)

![Graph showing the saturated vapour pressure of $l^{-4}\text{He}$ as a function of temperature (T in Kelvin), with a design goal for pressure in the magnet region of ABS.]
\[ \tau = \frac{4V}{A\bar{v}\alpha_{vl}} \left( \frac{m^*}{m} \right)^\frac{3}{2} \exp\left( \frac{E}{kT} \right) \]

\[ E_s \sim 2.8 \text{ K} \]
\[ \frac{m_3^*}{m_3} \sim 2.4 \]
\[ \alpha_{vl} \sim 1 \]
\[ \bar{v}_3 = (83.8 \text{ m/s}) \sqrt{\frac{T}{1K}} \]

(internal diffusion fast)

a 1cm \( \phi \) hole gives \( \tau \sim 2 \text{ h} \) at 0.5K

...but a 30cm \( \phi \) free surface gives an exchange time \( \tau \sim 10 \text{ s}! \)
$T_1$ Relaxation: Influence of Diffusion


$^3$He atoms see a fluctuating magnetic field as they undergo Brownian motion in the presence of a field gradient.

As long as their mfp $\ll$ container dimensions ...

$$\frac{1}{T_1} = \frac{2}{3} \left( \frac{G}{B} \right)^2 \left\langle v^2 \right\rangle \frac{\tau_c}{1 + \omega_0^2 \tau_c^2}$$

or

$$\frac{1}{T_1} = 2D \left( \frac{G}{B} \right)^2 \left[ 1 + \left( \frac{3\gamma BD}{\left\langle v^2 \right\rangle} \right)^2 \right]^{-1}$$

... $T_1$ depends on the *relative* field gradient.
Diffusion Coefficients


Vapour: $D_{34} = 1.463 \times 10^{-3} \frac{T^{1.65}}{P}$ (MKS units)
- see JLTP 97, 417 (1994).
Expect maximum sensitivity to \textit{relative} fluctuations in \textbf{B} near $T=0.6$ K

Absolute field gradients become important when $\text{mfp} > \text{container dimensions}$

$$\frac{1}{T_1} \sim \frac{1}{2} \frac{\gamma G^2 L^3}{<v>} \left( \frac{\gamma BL}{2 <v>} \right)^4$$


This regime is not as well understood ...  
... rough estimate gives $G_{\text{max}} \sim 1 \mu \text{G/cm}$ 
for $T_1 \sim 10^5$ s and $T \sim 0.4$ K
Maximum Permissible Gradients in \( B \) are limited by relaxation rate \( 1/T_2 \)

**Longitudinal Gradient**
(50 cm long cell)

\[
\frac{1}{T_2} = \frac{\gamma^2 J_0^2 (x_c) G^2 L^4}{120D}
\]

Data and extrapolations are derived from recent measurements of D

**Transverse Gradient**
(10 cm high cell)
Wall Relaxation

- Liquid $^4$He
- Surface coating
- Substrate
- $^3$He
- Magnetic impurity

Cs on Pyrex: very long $T_w$
- Not compatible with neutrons
- Useful in accumulation cell and "plumbing"

H$_2$ on Pyrex and Styecast 1266: long $T_w$
- Not compatible with neutrons, but D$_2$ continues to work
$^3\text{He}$ Mean Free Path

![Graph showing the mean free path of $^3\text{He}$ compared to temperature (T in Kelvin). The graph includes data points for both the vapour and liquid phases.]
"Cesiated" Glass Substrates

Room temp


- relaxation occurs in bulk Cs and underlying substrate

Low temp

pore $^3$He Tastevin JLTP 89 669 (1992)

- relaxation due to dipolar interactions in bulk liquid

$^3$He - $^4$He mixtures PRL 73 2587 (1994)

T ~ 1K

$T_i > 5000\ s$

$A/n \sim 66\ cm^{-1}$

Implies $T_i \sim 180h$

for EDM expt.

Closed Circulation Loop

T ~ 200 mK

Benefit: gettering action of Cs tends to passivate paramagnetic $O_2$

Issues: Compatibility with substrates other than pyrex unknown

Risk of contamination in an "open" geometry
H$_2$-coated Substrates

- Evidence that T improves out to ~10 layers of H$_2$

Experimental with unsaturated l-$_4$He films

Pyrex: "Clean"-baked at 470°C (10^-6 Torr) + r.f. discharge cleaning

For T ~ 0.5 K

Sussex Lusher et al. JLTP 72, 71 (1988)

T$_1$ ~ 10$^{-4}$s at 2.5 KG


T$_1$ ~ 10$^{-3}$s at 14 K

Postulate difference due spectral densities of correlation function for perturbation

$\frac{1}{T_1} \sim \frac{1}{1 + \omega^2 T_c^2}$
Fig. 2. Longitudinal relaxation time $T_1$ (logarithmic scale) versus the inverse temperature between 4.2 K and 0.5 K for a particular cell. Lower temperatures are on the right part of the figure.

Fig. 4. Values of $T_1$ measured at 7.7 MHz in sealed Pyrex cells containing $^3$He-$^4$He-$\text{H}_2$ mixtures. (■) $n_3 = 3.3 \times 10^{23} \text{ m}^{-3}$, $^3\text{He}:^4\text{He} = 5:1$; (□) $n_3 = 9.8 \times 10^{21} \text{ m}^{-3}$, $^3\text{He}:^4\text{He} = 100:1$.
Estimate $\tau_c \sim 6 \times 10^{-8}$ s ... long!

$\tau_c \gg$ transit time through film

\sim exchange time in solid $^3$He ??

(suggests relaxation near $^3$He-$^4$He border)

II Experiments with bulk liquid $^3$He-$^4$He mixtures

UBC PRL 67 839 (1991)

\rightarrow Condenser of $^3$He-$^4$He distillation column for producing polarized $^3$He

$T_1 \sim 1$ min at $47$ K on bare Stycast

\sim $4000$ s at $47$ K on $^3$He-coated Stycast.
Relevance to EDM Expt.

What happens to $T_1$ as the bulb is filled by adding $^3$He? ??

$s.f. \ l^4\text{He film}$  
$(x \sim 2\% \ at \ 0.5K)$  
$T_1 \sim 10^3$ s  
(ENS Expt)

$^3\text{He vapour}$

$^3\text{He in s.f. } l^4\text{He}$

$H_2$-coating on Pyrex substrate

$T_1 \sim ?$ ..

Pessimistic viewpoint: \[ \frac{1}{T_1} \sim \frac{A}{V} \]

\[
\text{ENS expt } A/V \sim 3 \text{cm}^{-1} \\
\text{ EDM expt } A/V \sim 0.5 \text{cm}^{-1}
\]

factor 6 to be gained

(Overly) optimistic viewpoint: concentration of $^3\text{He}$ near wall is also diluted by a factor

\[
\frac{A^*}{n} = (\frac{m^*}{m})^{3/2} \exp(\frac{E_s}{kT}) \sim 10^3 \ at \ 0.5K
\]

Reality: Not enough experimental data!
Experiments

H₂/D₂ coatings is crucial to demonstrate Ti adequate for EDM experiment “open geometry” will be a challenge.

No data on D₂.

Cs coatings & Pyrex works as a substrate but nothing else has been tried!

Durability of coating will be an issue for “open geometries” accum. + meas. cell can’t communicate at room Ti.

ABS of pol. ³He: delicate balance between mfp, orifice diameter, differential pumping rate, temp. gradients. LyHe level may be required to keep ³He in liquid – demonstration needed!

Field Gradients is tightly linked to design*, but the long mfp regime is not as well understood as short mfp regime.

- analogy to H masers ... well shift if stacking times on D₂ are Basic Science long?

↓ Simultaneous measurement of mass and spin diffusion coefficients?

ABS may be a great tool for studies of R(6, 3)

* refine design criteria to reflect \( \frac{1}{t_1}, \frac{1}{t_2} \sim G^2 \)?
Determining the projects to be undertaken at each institution
moderated by Steve Lamoreaux (Los Alamos)
To Do - Prioritized List

1. $T_1, T_2$, $^3$He in realistic cells
   A. Polarized $^3$He production
   
   B. Transport - theory, apparatus
   
   C. Test Cells - Room temp, superfluid helium filled, etc.

Experiment #1

source

\[ \text{Quad 1 spin flip Quad 2 RGA} \]

Bulb, 20 cm diameter

\[ \text{20 cm} \]
\[ \text{1 cm} \]

\[ \nu = 10^5 \text{cm/s} \quad 300K \]

\[ \frac{A}{4R} \quad \nu = 5 \text{sec}^{-1} \]

\[ \delta = 10^{14} \text{/sec} = 2 \times 10^{13} \]

\[ \approx 10^{-7} \text{ torr} \quad (5 \times 10^9 / \text{cc}) \]
2. High Voltage tests UCRL/LANL
   A. Background light
   B. Capacitive multiplier
   C. Damage
   D. Kerr effect for in situ measurements UCRL

   E. Review LANL design

3. Couple 1 & 2
   HV effects on lifetime

4. Field Modelling

5. Light collection tests & Modeling
   Maryland... NIST, UIUC
   Fibers LANL...
Heat pulse due to RF spin reorientation pulse

If dressing is used, penetration not in optimal region for static or RF field.

Need 3-d calculations with eddy currents

Measurements of low temp properties of Metglas, cryoperm.
6. Materials selection

A. Johnson noise theory

\( u_{CB} \approx E \rho_f \sqrt{f} \)

B. Ferromagnetic Shielding

a. Shaking
b. Dressing

Need hysteresis loops to get power dissipation

HMI Metglas, Cryoporin, Acrylic

Plastic cryostat?

B/H Curves, conductivity

C. Eddy currents from

dressing, shaking

HMI Barkhausen noise

b. need \( 10^{-3} \) homogeneity of dressing field

Skin depth \( \delta \) thickness \( t/\delta = 10^{-3} \)

Super ferro \( \Phi = 0.01 \mu \text{m} \)

\( f = 1 \text{kHz} \)

\( \Phi = \sim 0.01 \mu \text{m} \)
8. Monte Carlo Studies
   A. Activation
   B. Polarizer
   C. Light Collection

9. UCN Test - NIST
   HMI / NIST
   LANL

10. Proposal
    Peter Barnes
Future telephone conference calls moderated by Martin Cooper (Los Alamos)
Development of a financial strategy
moderated by Martin Cooper (Los Alamos)
DEVELOPMENT OF A FINANCIAL STRATEGY

Funding for equipment to carry out the R&D plan
Funding for people to carry out the R&D plan
Final experiment funding from non-DOE Nuclear Physics
Breaking the experiment into distinct pieces