A New Search on the Neutron Electric Dipole Moment (nEDM)

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Outline

- Introduction
- Existing measurements
- A new search for neutron EDM
- Summary

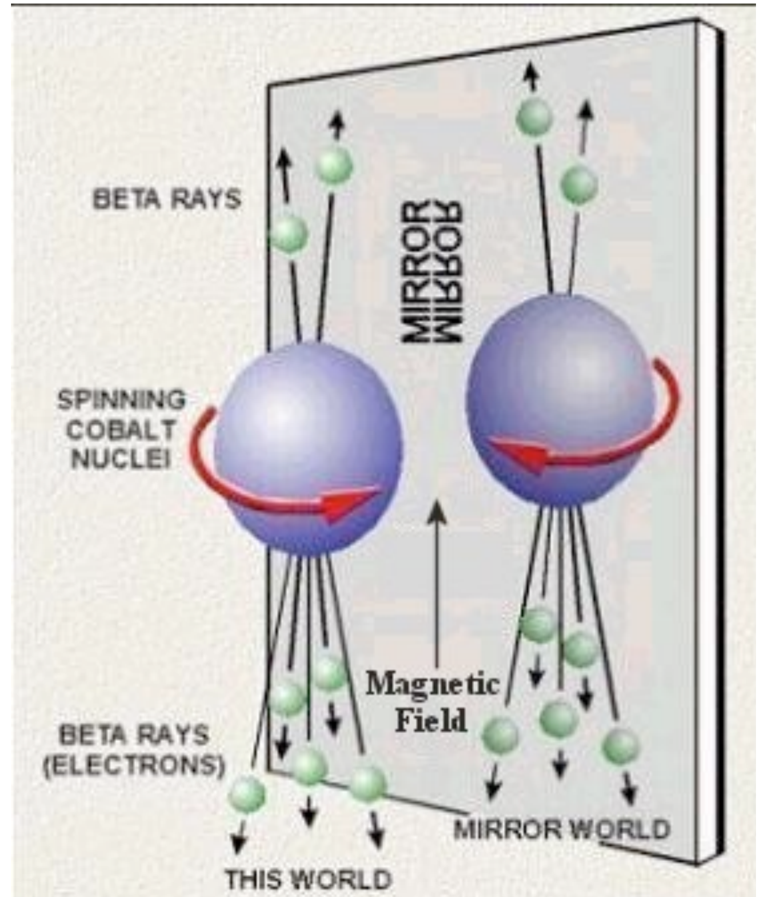
Parity-violation in weak interaction (1956)

Parity-transformation (P) : $\vec{r} \longrightarrow -\vec{r}$

T. D. Lee

C. N. Yang

October 1, 1956 issue of the Physical Review



$$^{60}\vec{C}o \rightarrow {}^{60}Ni + e^{-} + \bar{\nu}_e$$

C.S. Wu, et al.
Garwin, Lederman and Weinrich
Telegdi

C: charge conjugation symmetry: particle → anti-particle

CP Violation in weak interactions

In 1964, Christenson, Cronin, Fitch and Turlay discovered at BNL that the long-lived neutral K meson with CP=-1 could decay occasionally to $\pi^+\pi^-$ with CP=+1 about once every 500 decays

$$K^o{}_L \rightarrow \pi^+\pi^-\pi^o \qquad K^o{}_L \rightarrow \pi^+\pi^-$$

CP=-1 CP=+1 0.2%

- CP violations in nuclear systems
- More CP violations in experiments:

B meson decays, SLAC and KEK

CP violation in Standard Model

– The CKM matrix: the ***complex phase*** of CKM matrix leads to CP violation

$$\Rightarrow \begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} = \hat{V}_{CKM} \begin{pmatrix} d \\ s \\ b \end{pmatrix} \Leftarrow$$

Weak eigenstates ***Mass eigenstates***

For n generations:

n(n-1)/2	*angles*	*3*
(n-1)(n-2)/2	*phases*	*1*

Strong CP problem

- The strong CP problem in the Standard Model
  - The θ term in QCD Lagrangian

$$L_{QCD} = G_{\mu\nu}G^{\mu\nu} + \sum_k \bar{q}_k \gamma^\mu [\partial_\mu - igA_\mu^\alpha t_\alpha] q_k - \sum_k m_k \bar{q}_k q_k$$

$$L_{eff} = L_{QCD} + \frac{\theta g_s^2}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu} \qquad \tilde{G}_{\mu\nu} = \frac{1}{2}\varepsilon_{\mu\nu\kappa\lambda}G_{\kappa\lambda}$$

- Current algebra: d_n behaves like $\theta\ (m_\pi)^2 \ln\ (m_\pi)^2$

By E. Witten

d_n Neutron EDM

$$d_n \approx 1.2 \times 10^{-16} \theta\ e \bullet cm \qquad \theta < 10^{-10}$$

QCD sum rule, Pospelov and Ritz, Phys. Rev. Lett. 83, 2526 (1999)

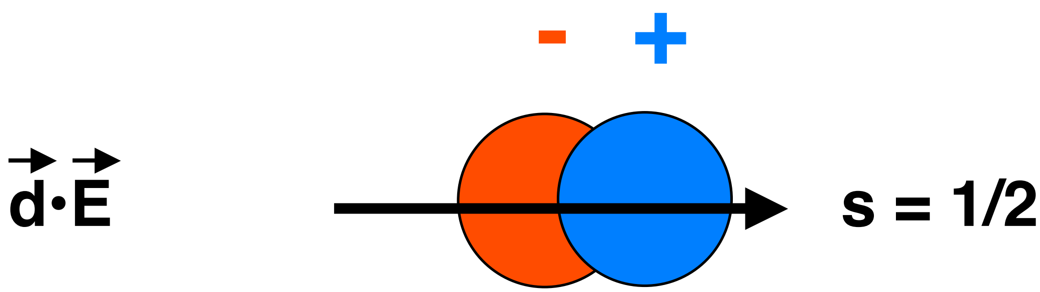
CPT Invariance

CPT is a good symmetry in a local field theory which is Lorentz invariant and has a hermitian Lagrangian

- CP violation thus implies ***time-reversal symmetry T*** violation
- Direct search for ***T violation*** is important!
  - CPLEAR: semi-leptonic decay of neutral kaons
  - KTev experiment $K_L \rightarrow \pi^+\pi^-e^+e^-$
  - Neutron electric dipole moment (nEDM)

T: time reversal symmetry: T -> -T

Neutron Electric Dipole Moment (EDM)



- If neutron possesses EDM, in an electric field, Hamiltonian $H = -d_n \vec{\sigma} \bullet \vec{E}$
  - changes sign under T (P) symmetry operation
- d_n is more sensitive to θ than it is to δ_{CKM}

Current algebra: $\theta\ (m_\pi)^2 \ln\ (m_\pi)^2$

By E. Witten

Predictions for Neutron EDM

- SM: $d_n \approx 10^{-31} e \cdot cm$
  - Renormalization of QCD vacuum parameter arising from CP violation in weak interaction (CKM)
  - Strong CP: $\theta\ (m_\pi)^2 \ln\ (m_\pi)^2$
- Left-right symmetric gauge models:

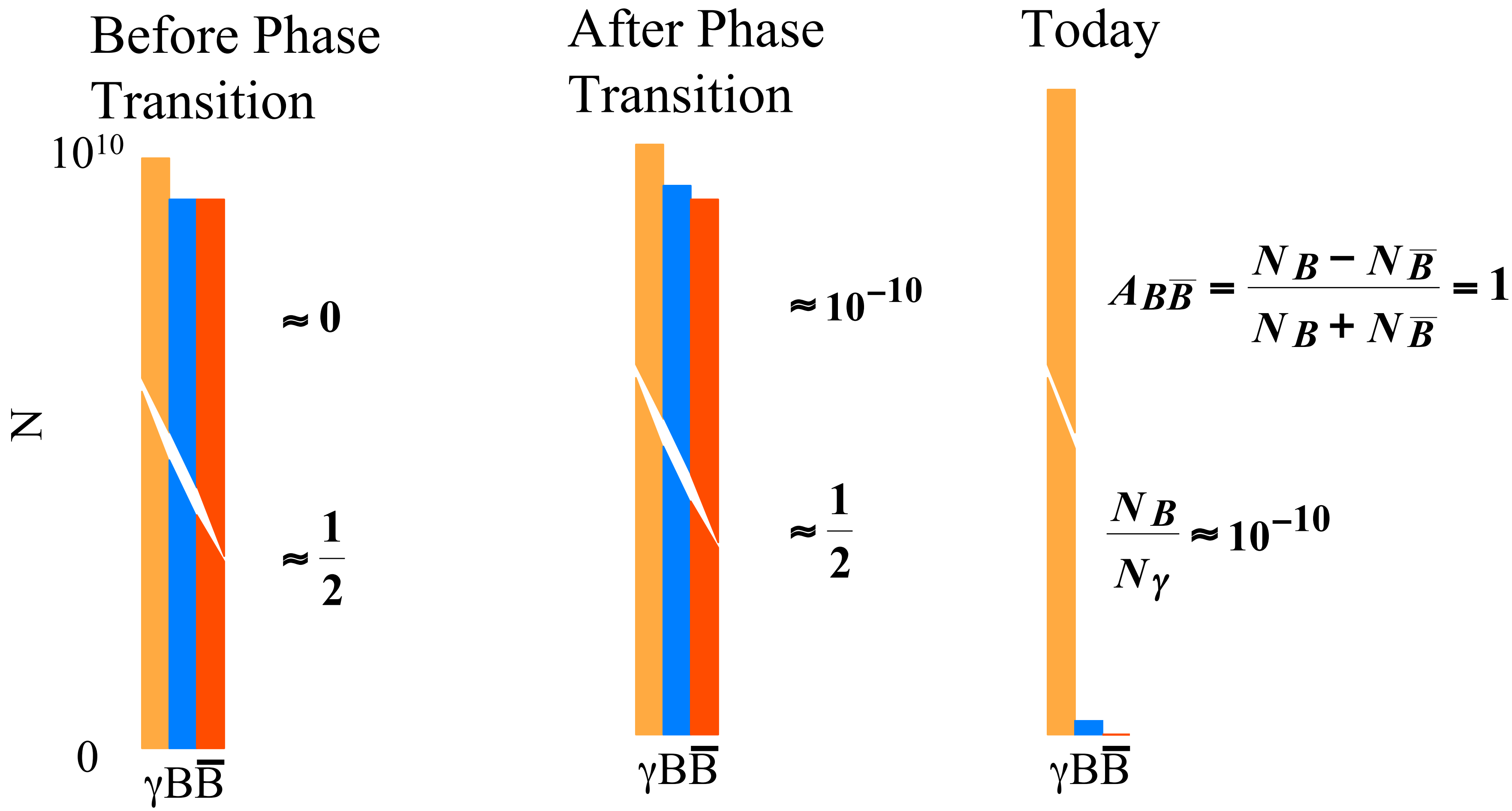
  $$d_n \approx 10^{-27} e \cdot cm$$

- Non-minimal Higgs models:
  - CP odd gluonic operators inducing:

  $$d_n \approx 10^{-27} e \cdot cm$$

- Supersymmetry (SUSY) models

$\overline{B}$-B *ASYMMETRY IN THE UNIVERSE*



CP Violation and Cosmology

- Baryon asymmetry of the universe (BAU)
- $\dfrac{\Delta n_{bar}}{n_\gamma} = \dfrac{n_{bar(today)}}{n_\gamma} = (4-7)\times 10^{-10}$
- To explain BAU, substantial New Physics in the CP violating sector is required
- Neutron EDM may play an important role in quantifying New Physics
- New source of CP beyond SM may have significant impact on our understanding of baryongenesis

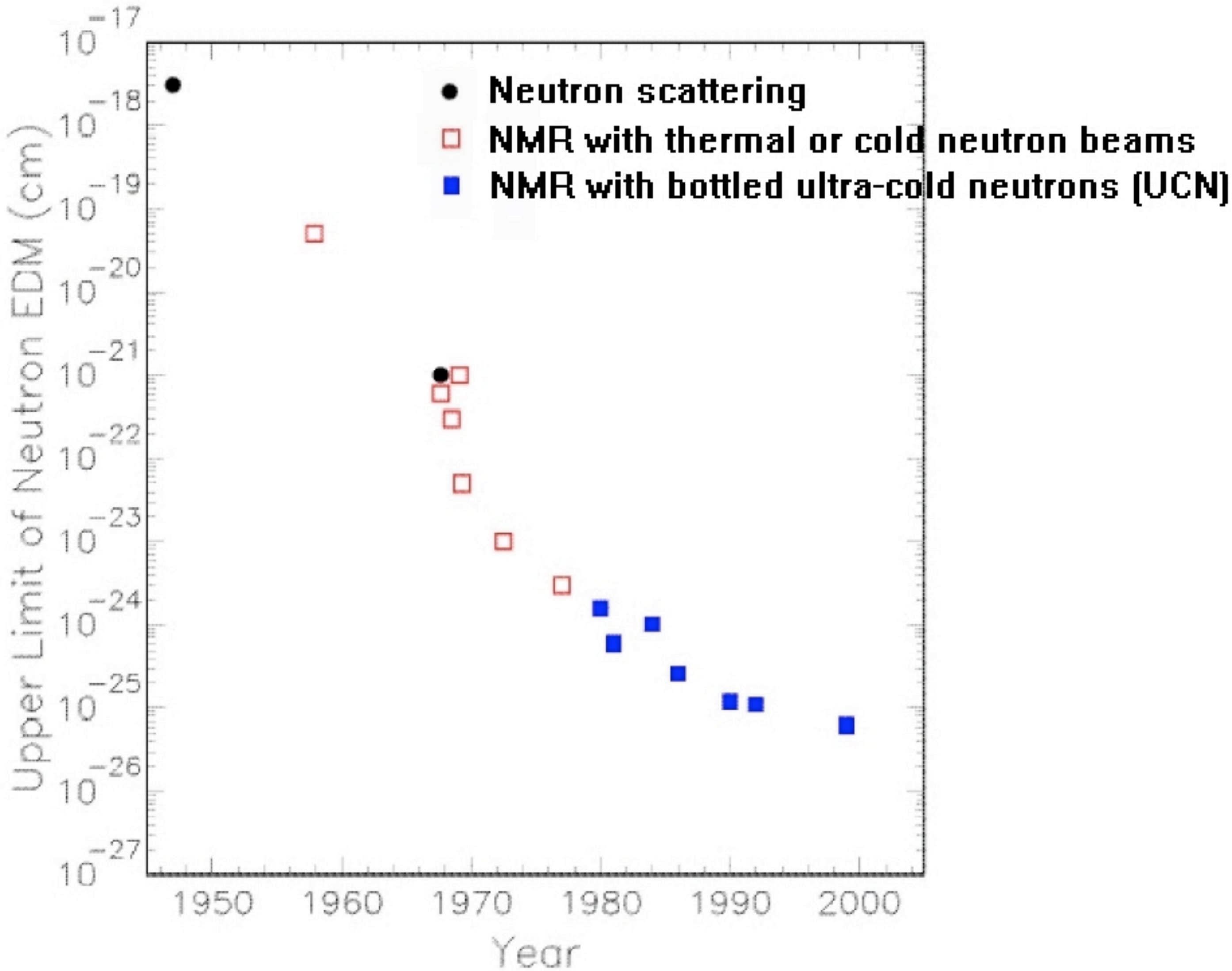
Seminar paper by A. Sakharov (1967) on calculating BAU

Existing Measurements of d_n

Experimental techniques:

- ***Neutron scattering***
  - ***Interference between neutron-nucleus and neutron-electron***
- ***Magnetic resonance technique***
  - ***thermal or cold neutron beams***
  - ***bottled ultra-cold neutrons (UCN)***

Ref: R. Golub and S. K. Lamoreaux, Phys. Report 237, 1-62 (1994)



1950, Smith, Purcell and Ramsey determined for the first time $d_n \leq 3 \times 10^{-18} e \cdot cm$

Current limit: $d_n < 3.0 \times 10^{-26} e \cdot cm$ (2006)

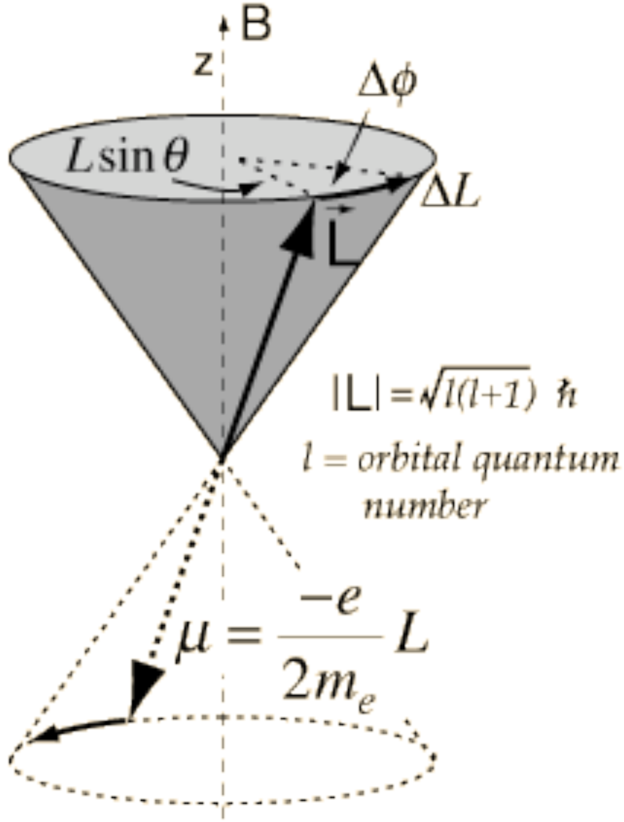
Experimental limits on the EDM of fundamental particles

Particle	Experimental EDM Value / Limit [(2)] ($e\cdot$cm)
Electron, e	$0.18 \pm 0.12 \pm 0.10 \times 10^{-26}$
Neutron, n	$< 0.63 \times 10^{-25}$ [90% C.L.]
Proton, p	$-3.7 \pm 6.3 \times 10^{-23}$
Lambda Hyperon, Λ	$< 1.5 \times 10^{-16}$ [95% C.L.]
Tau Neutrino, ν_τ	$< 5.2 \times 10^{-17}$ [95% C.L.]
Muon, μ	$3.7 \pm 3.4 \times 10^{-19}$
Tau, τ	$< 3.1 \times 10^{-16}$ [95% C.L.]

Current best limit on neutron EDM is from ILL reactor at Grenoble Hep-ex/0602020, published in Phys. Rev. Lett.

nEDM $< 3.0 \times 10^{-26}$ e•cm [90 % C.L.]

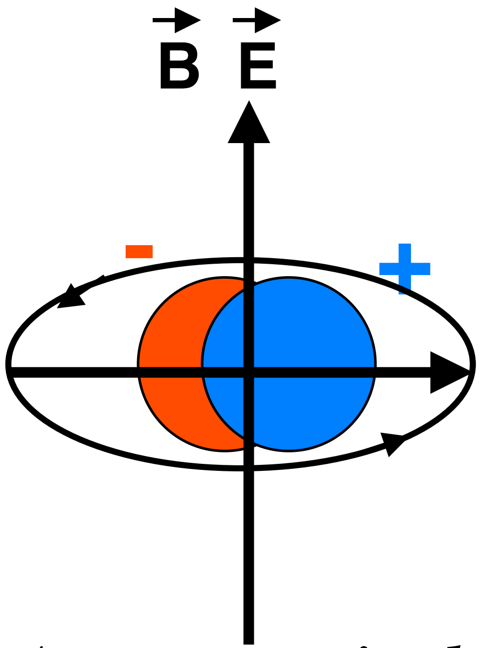
Larmor Spin Precession



$$\vec{\tau} = \vec{\mu} \times \vec{B}$$

- The torque exerted causing the magnetic moment to precess around the direction of the B field

Magnetic Resonance Technique



Look for a precession frequency ω_d

s = 1/2 dipole moment d_n

$$\nu_n = -[2\mu_n B_0 \pm 2d_n E_0]/h = \nu_0 \pm (\Delta\nu/2)$$

$$\Delta\nu = -4d_n E_0/h$$

•***A strong static electric field applied parallel (anti-parallel) to the magnetic field causes a shift in the Larmor freq.***

Frequency Measurement

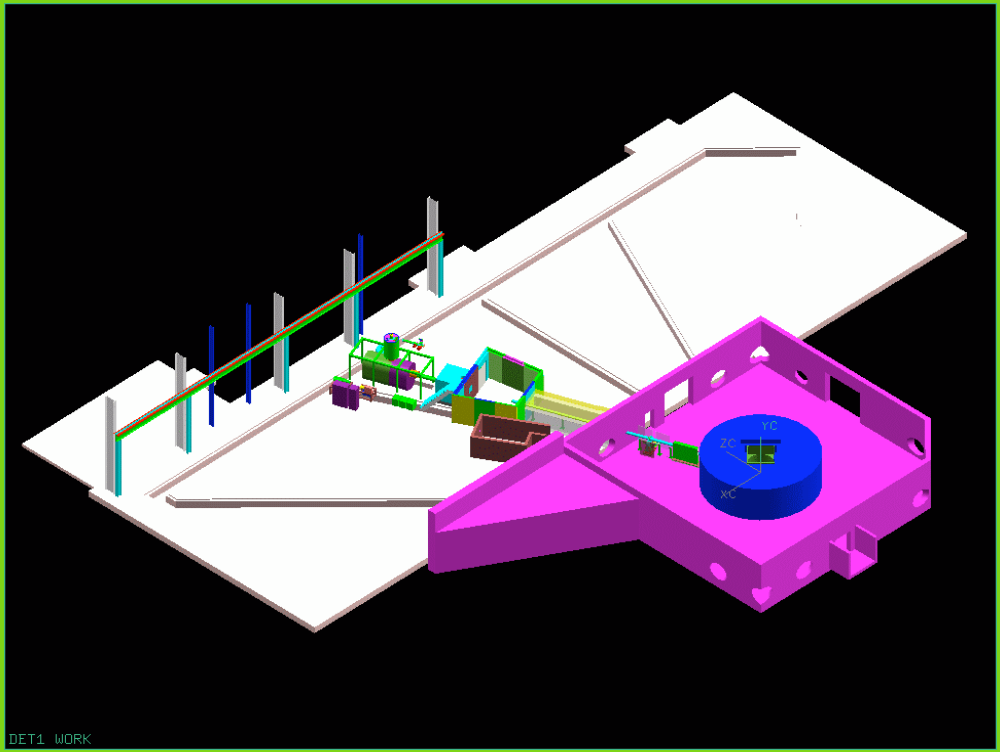
- Neutron spin aligned perpendicular to a static magnetic field
- The frequency shifts as the direction of E is reversed is ***from parallel to B to antiparallel to B***: $\Delta\nu = -4 d_n E_o / h$

$$\begin{cases} B_0 = 10mG \\ E_0 = 0 \end{cases} \rightarrow \nu_0 = 29.2Hz$$

$$\begin{cases} E_0 = 50kV/cm \\ d_n = 4\times10^{-27} e\cdot cm \end{cases} \rightarrow \Delta\nu = 0.19\mu Hz = 0.66\times10^{-8}\nu_0$$

A new nEDM Experiment

(Spokespersons: S. K. Lamoreaux, M. Cooper)



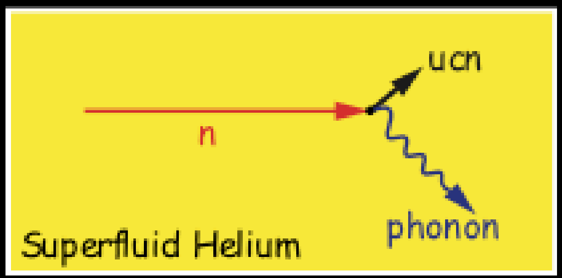
ASU, Indiana, UKY, Yale

Production of Ultracold Polarized Neutrons

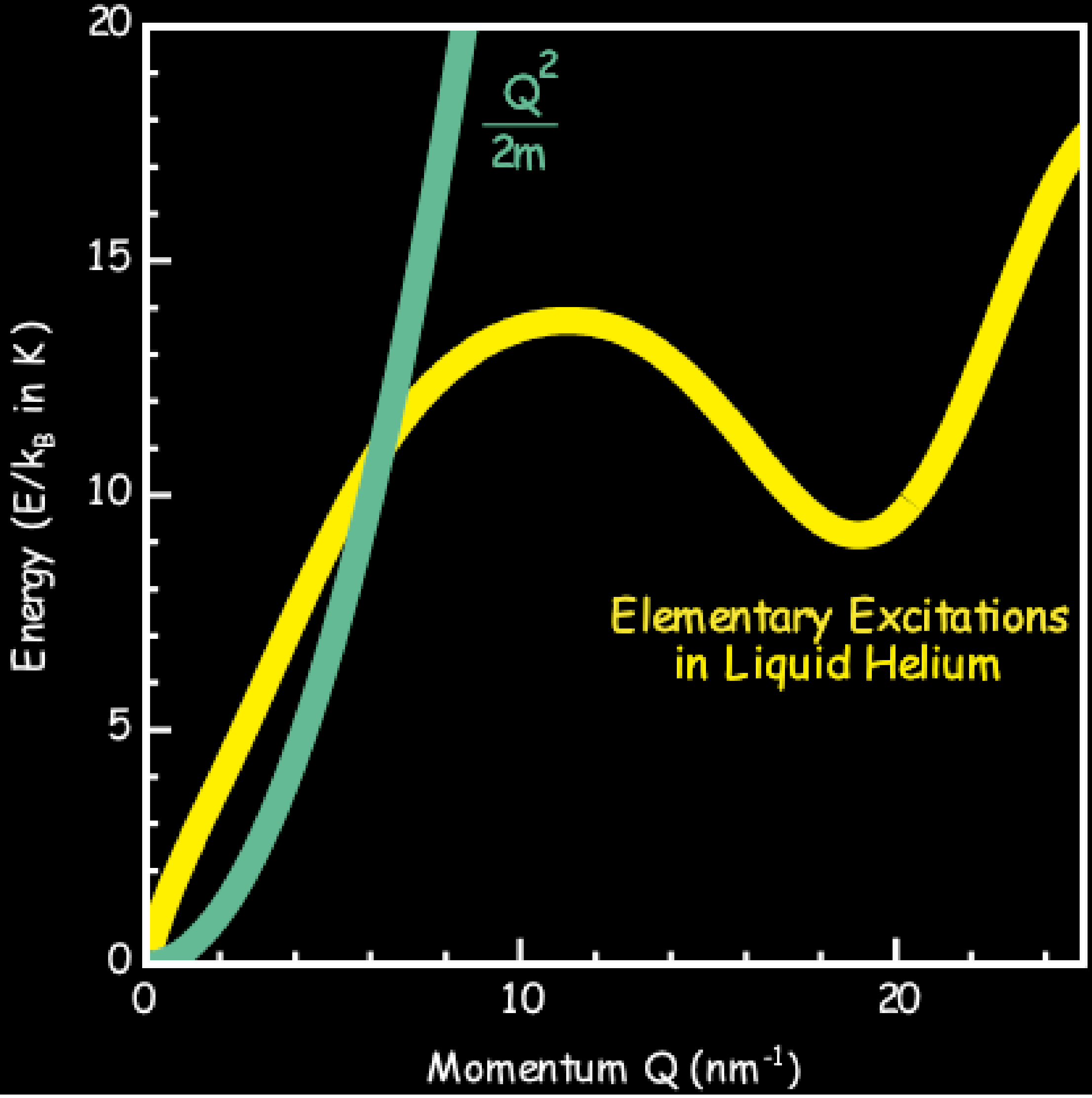
- Closed neutron trap filled with ultra-pure superfluid ^{4}He cooled to ~ 400 mK
- Placed in a beam of cold neutron (E=1 meV), polarized (~100%) using two total reflecting magnetic supermirror surfaces
- Neutrons interacting with the superfluid are downscattered to $E < 0.13 \mu eV, V < 5 m/s$ with a recoil phonon in the superfluid carrying away the missing energy and momentum ***(Golub, Pendelbury, 1975)***
- ***Technique has been demonstrated at a number of laboratories (France, Japan, US)***

UCN Production

- 0.89 nm (12 K or 0.95 meV) neutrons can scatter in liquid helium to near rest by emission of a single phonon.



- Upscattering (by absorption of a 12 K phonon)
  ~ Population of 12 K phonons
  ~ $e^{-12\ K/Tbath}$



How to measure the UCN Precession Frequency?

In the trap volume:

$$N_{UCN} = 2.5 \times 10^5,$$

$$N_{^3He} = 2 \times 10^{15}, \quad \Leftarrow ?$$

$$N_{^4He} = 2.2 \times 10^{25}$$

atoms per liter of cell volume

Measurement of the UCN Precession Frequency

- UCN precession frequency beat against the ^{3}He precession frequency
- Spin dependence of the nuclear interaction cross-section:

$$\vec{n} + {}^3\vec{H}e \rightarrow p + t + 772keV$$

- Scintillation light from nuclear reaction products (and beta decay products) (80 nm) can be wave-length shifted (440 nm) and detected

Figure of Merit for EDM Experiments ~ $E\sqrt{N\tau}$

E → 5E   τ → 5τ   N → 250 N   → 175

Compared to ILL experiment

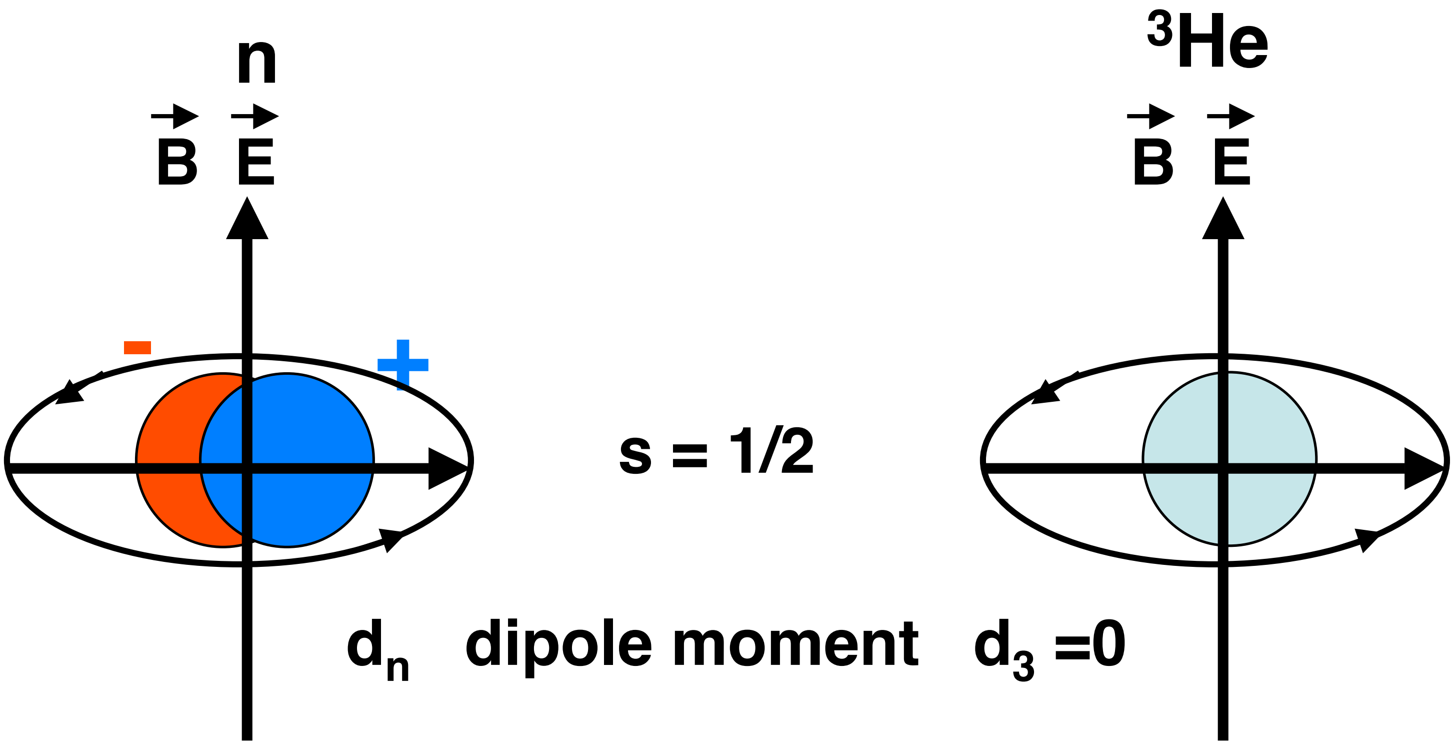
$$\vec{n} + {}^3\vec{He} \rightarrow p + t + 772keV$$

Spin State	Cross Section (barns) (v=2200 m/sec)	Cross Section (barns) (v=5 m/sec)
J=0	$\sim 1.1 \times 10^{+4}$	$\sim 4.8 \times 10^{+6}$
J=1	~ 0	~ 0

Overview of the Experiment

– A three-component fluid of neutrons, ^3He atoms in a bath of superfluid ^4He at 300 mK
– Neutron and ^3He magnetic dipoles precess in a plane perpendicular to the external magnetic field
– Precision measurement of the freq.difference in the ^3He and neutron precession frequency modified when strong E field is turned on (or reversed) --> neutron EDM

^{3}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 ω_3

UCN Precession Frequency

The time dependent, velocity independent loss rate

$$\Phi(t) = \frac{N_o}{\boldsymbol{\tau}_{abs}}[1 - \vec{P}_3 \bullet \vec{P}_n]e^{-\lambda t}$$

$$= \frac{N_o}{\boldsymbol{\tau}_{abs}}\{1 - p_3 p_n \cos[(\gamma_{^3he} - \gamma_n)Bt + 2d_n Et]\}e^{-\lambda t}$$

Polarized ^3He

Two purposes:

- Serve as a co-magnetometer (SQUID)

  Precise knowledge of B field is crucial

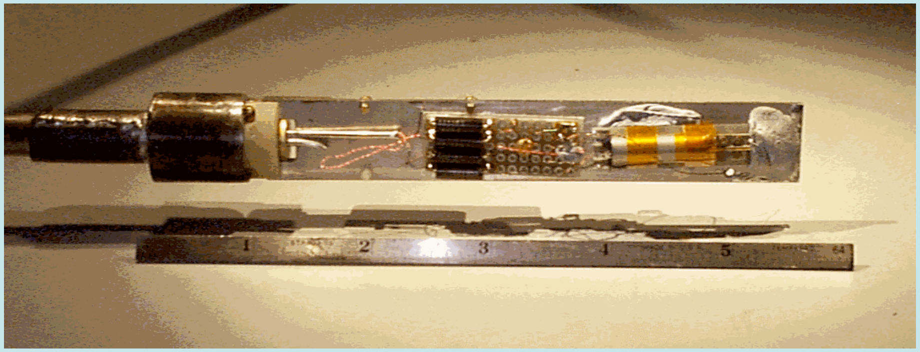
  The B field must be stable and uniform to better than 1 part in 1000 ($B_o = 10\text{mG}$)

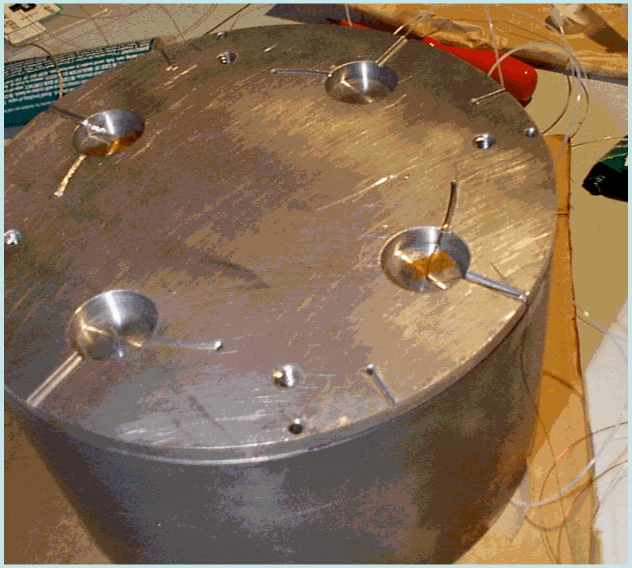
- Nuclear reaction used for measuring the neutron precession frequency relative to ^{3}He

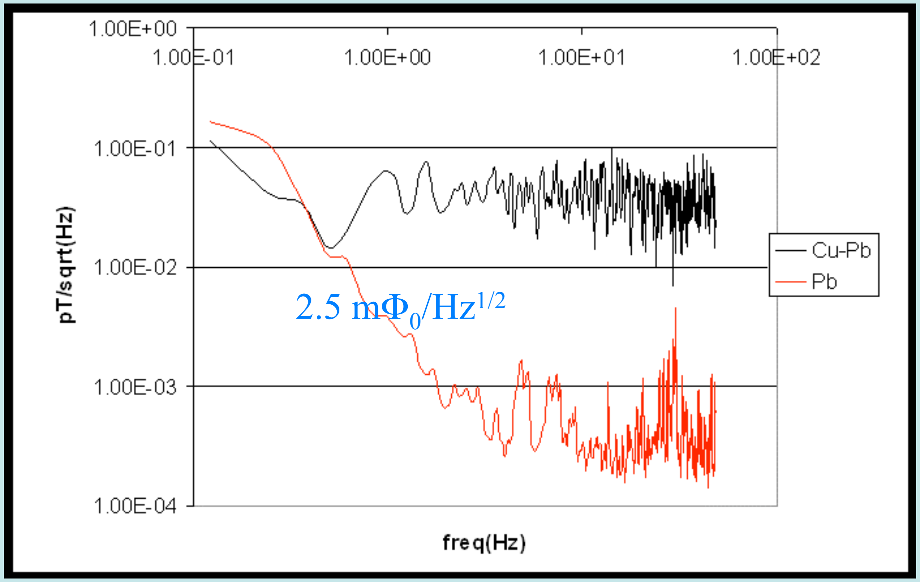
SQUIDs M. Espy, A. Matlachov

~100 cm^2 superconducting pickup coil

Flux = $2 \times 10^{-16}\ Tm^2 = 0.1\ \Phi_0$ Noise = $4\ m\Phi_0/Hz^{1/2}$ at 10 Hz ~ $T^{1/2}$

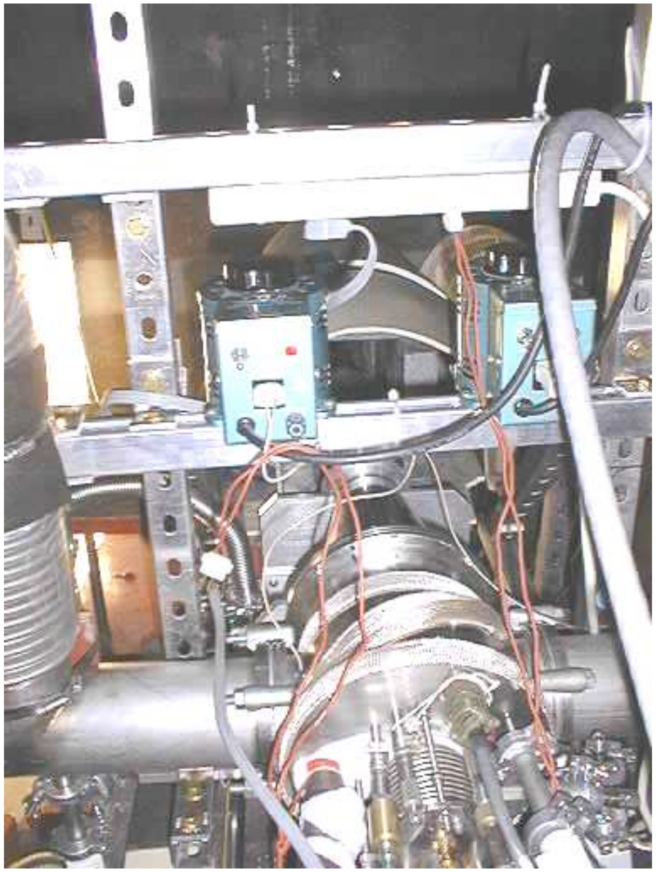


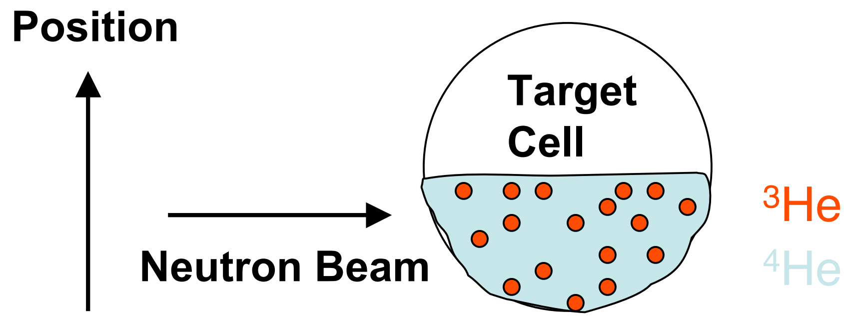


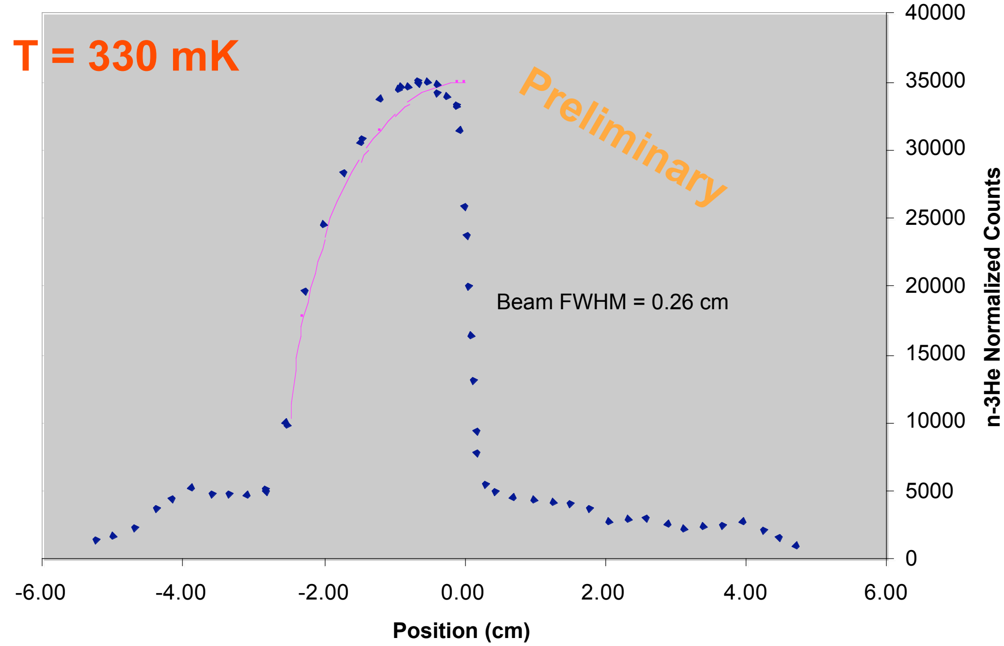


^{3}He Distributions in Superfluid ^{4}He

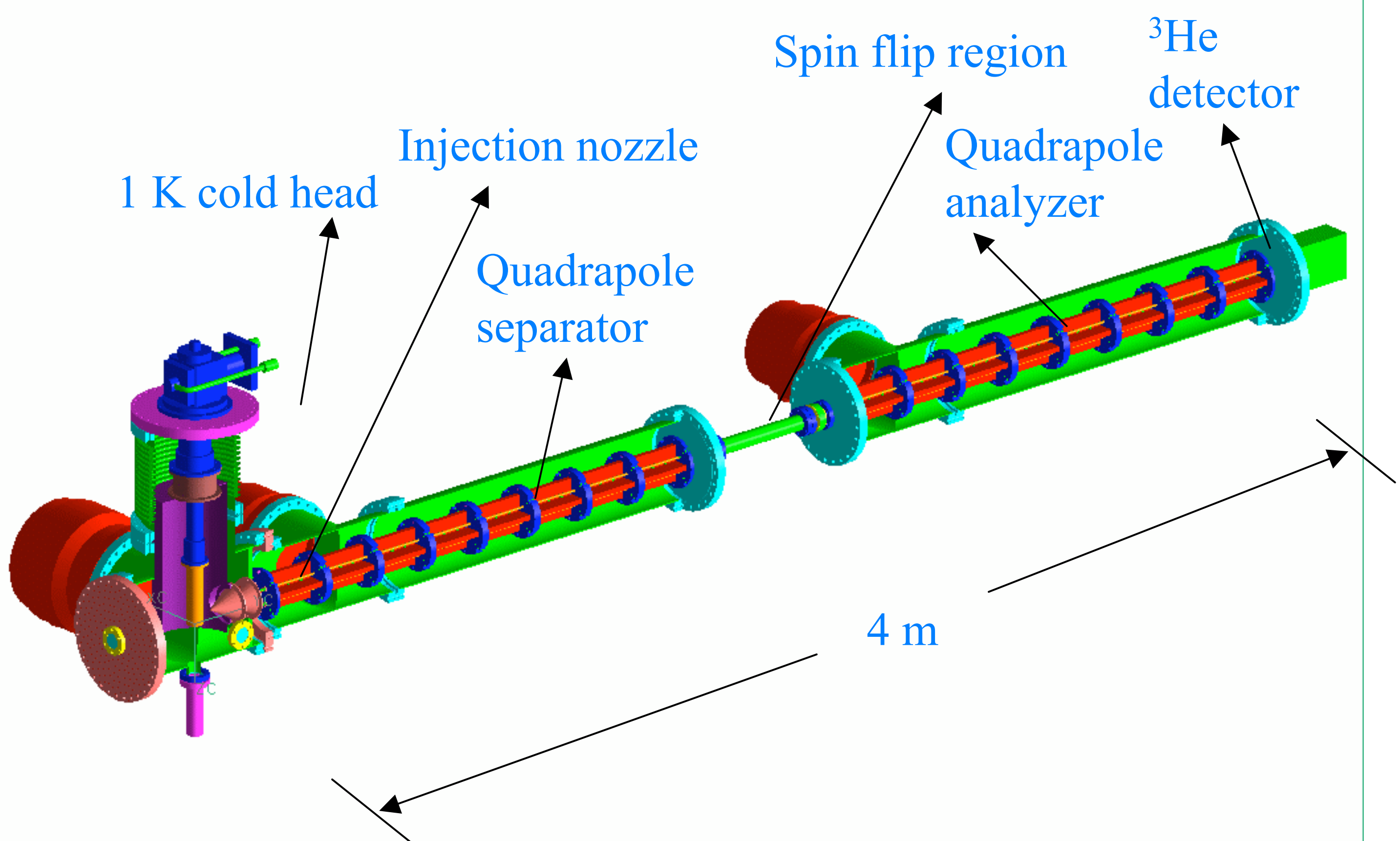
Dilution Refrigerator at LANSCE Flight Path 11a







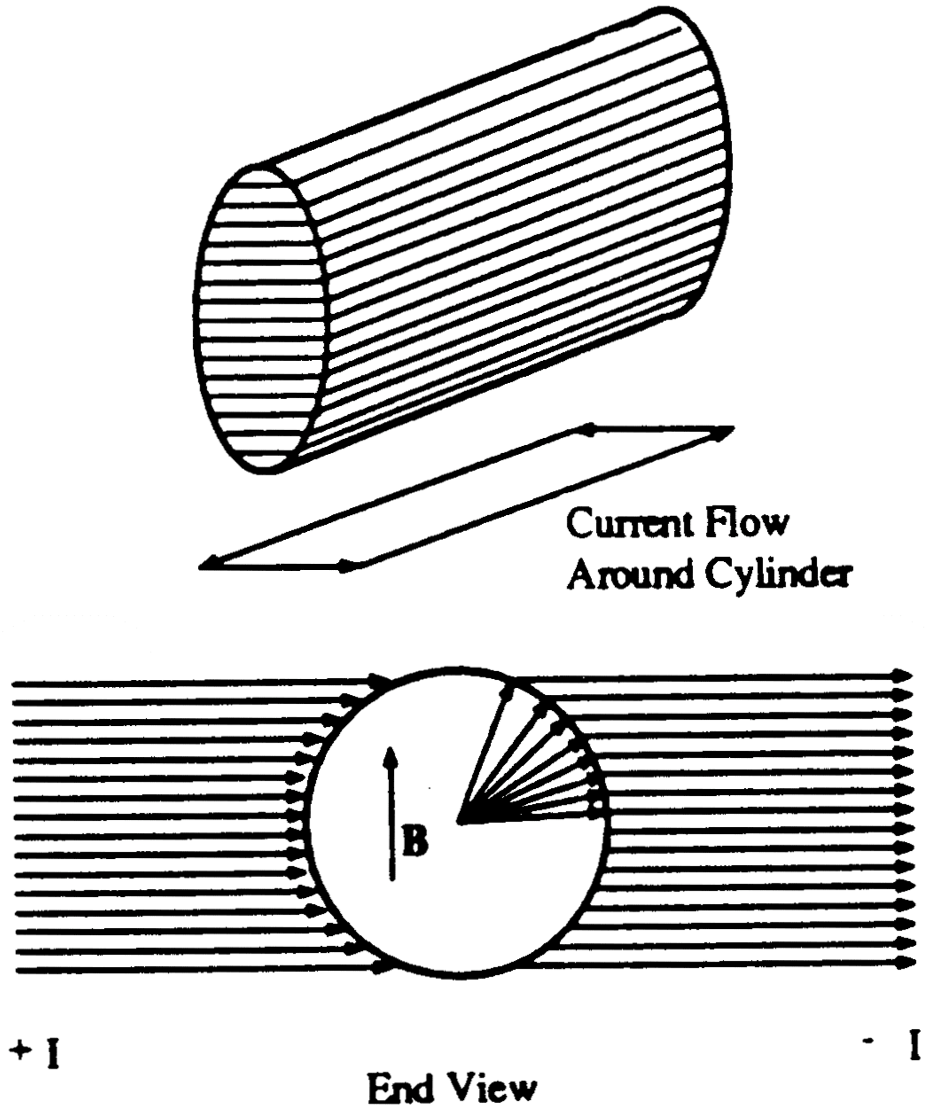
POLARIZED ^{3}He SOURCE



Achieved ~100% polarization,
10^{14} /sec flux

LANL

COSθ COIL

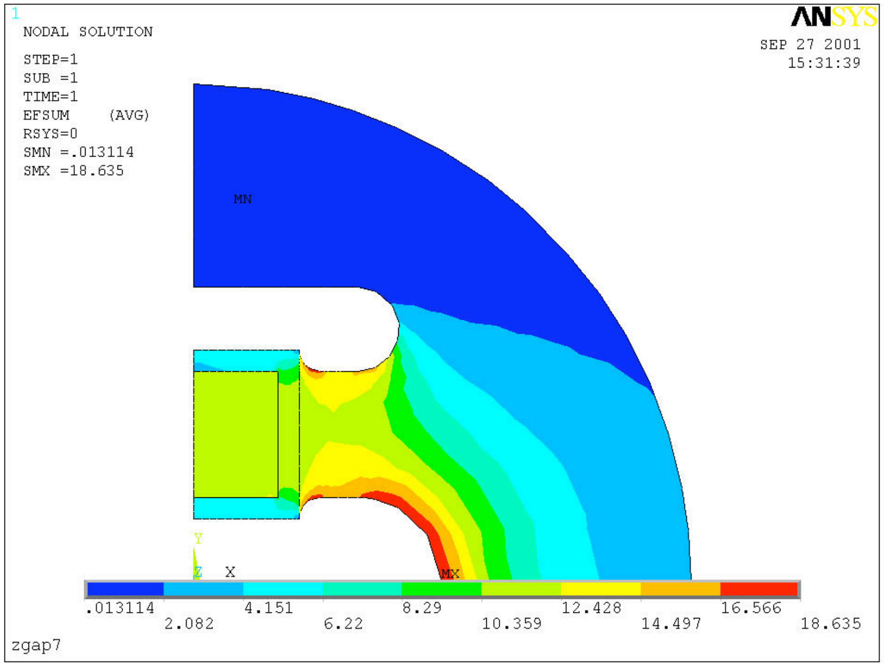


Caltech and others

ELECTRIC FIELD

Ground plate	25 x 75 x 5 cm
HV plate	30 x 80 x 10 cm
Ground shell coil	30 cm radius

design goal of 50 kV/cm

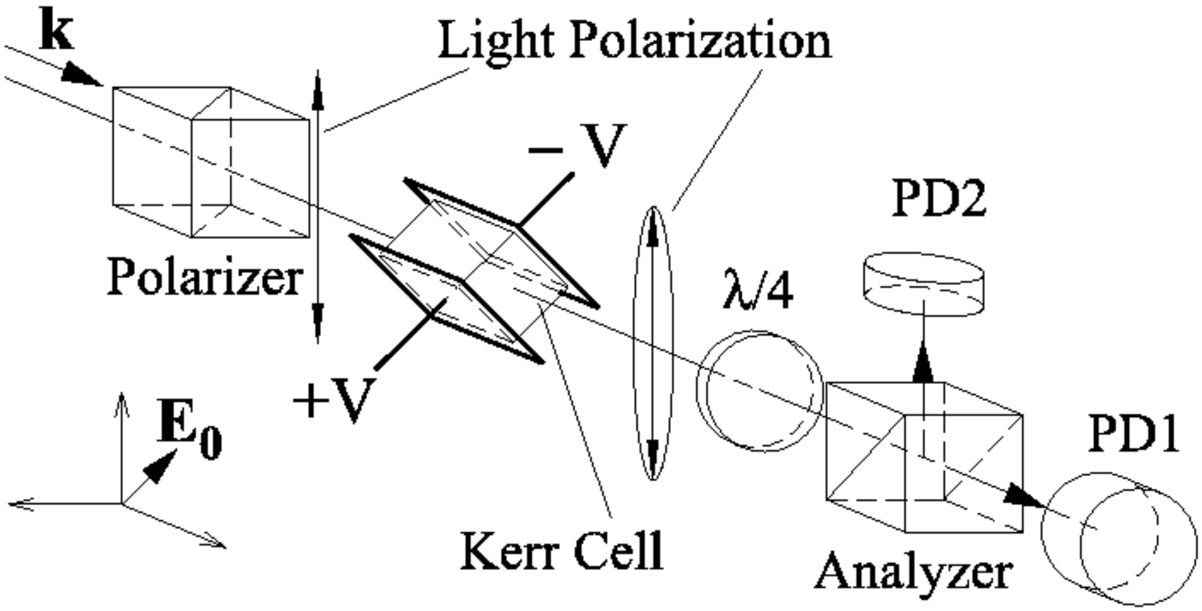


- Uniformity in cell:
  - 0.1% without side walls
  - 1% with recess
- Peak E field is ~1.5 of value in cell
- Next step - 3D model
- Cell 7.5 x 10 x 50 cm and 1.3 cm walls

LANL, IUCF

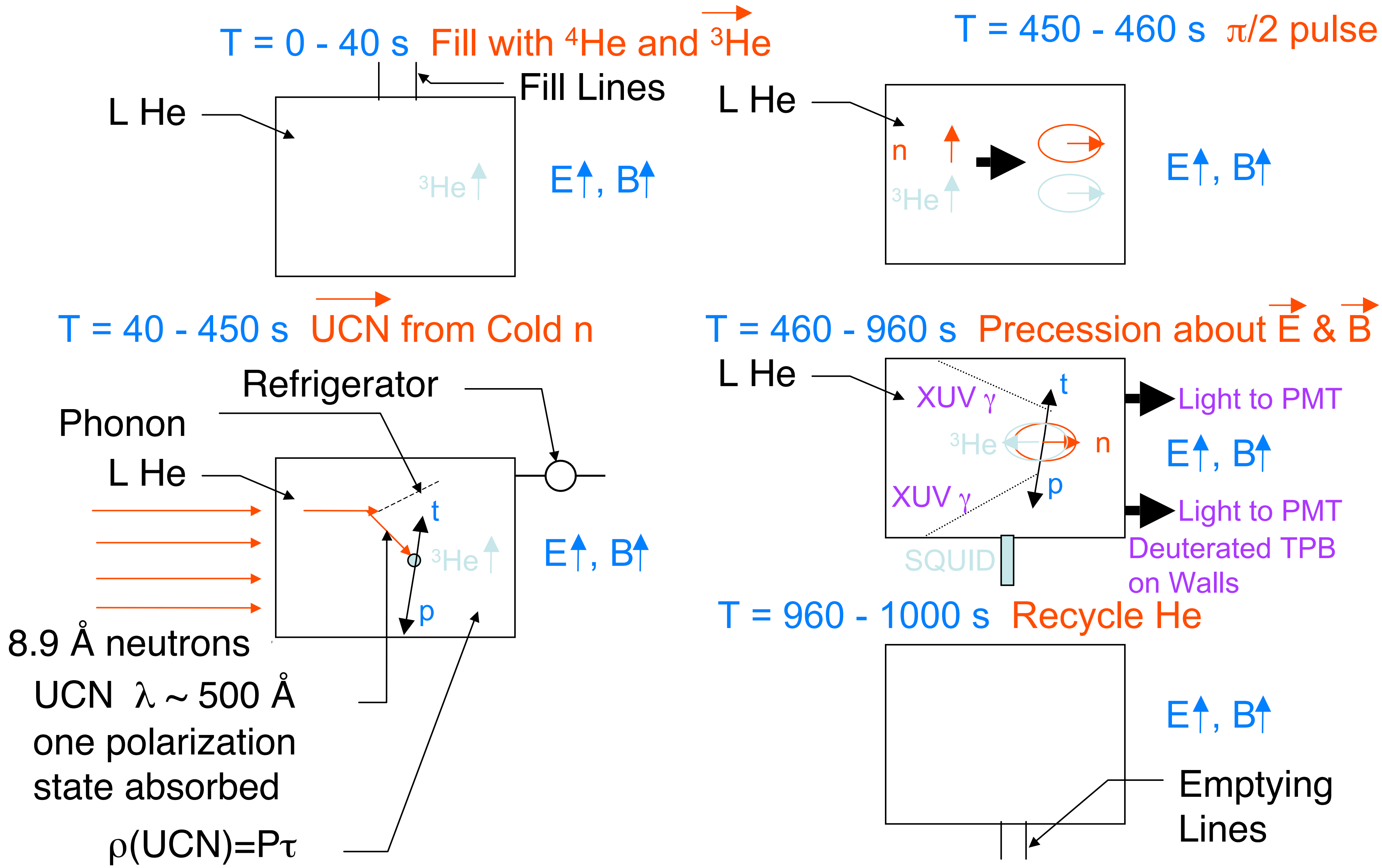
ELECTRIC FIELD MEASUREMENT

Kerr Effect $\varepsilon = \pi K l E_0^2$ ellipticity of Transmitted light

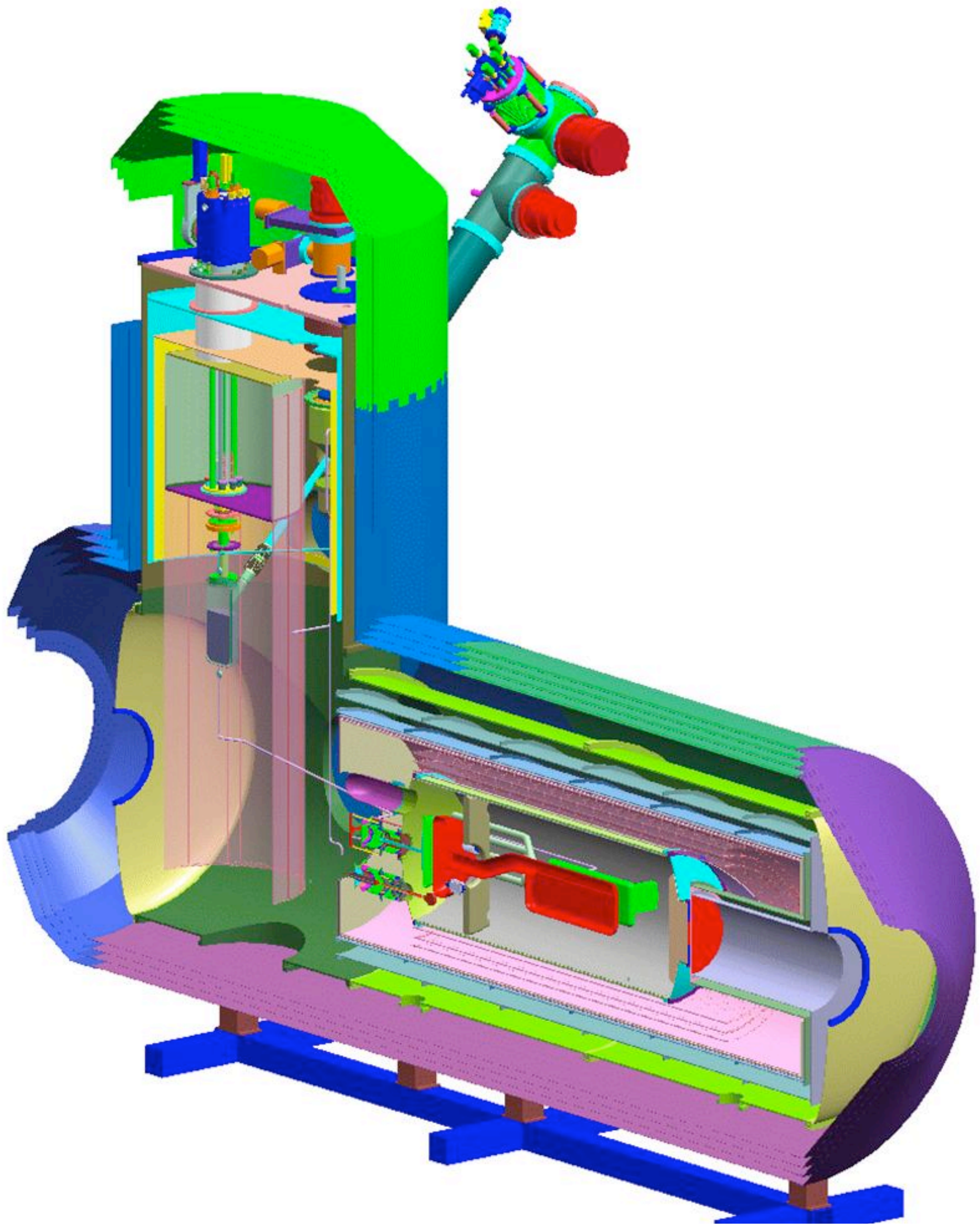


UC Berkeley and others

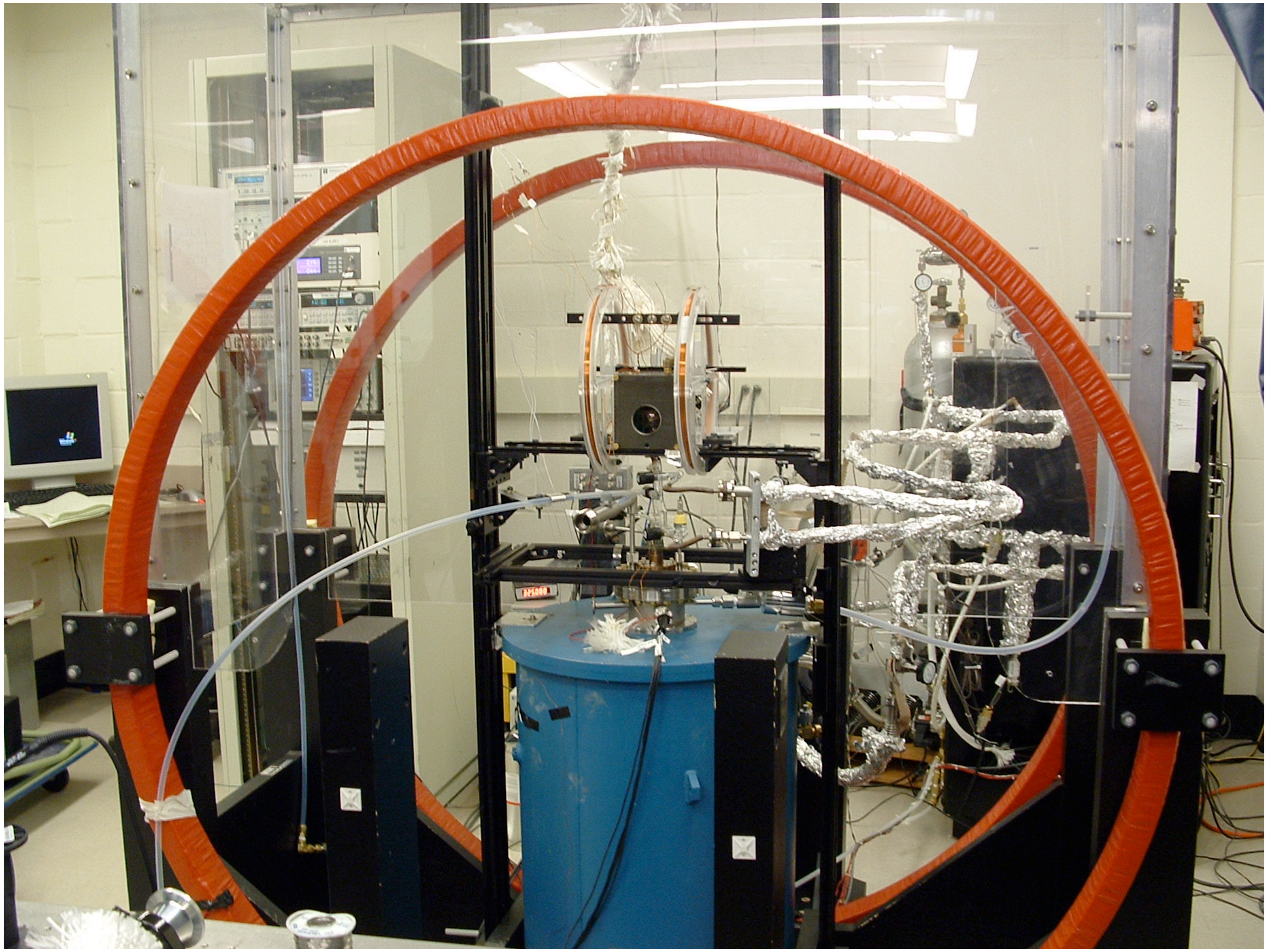
EXPERIMENT CYCLE



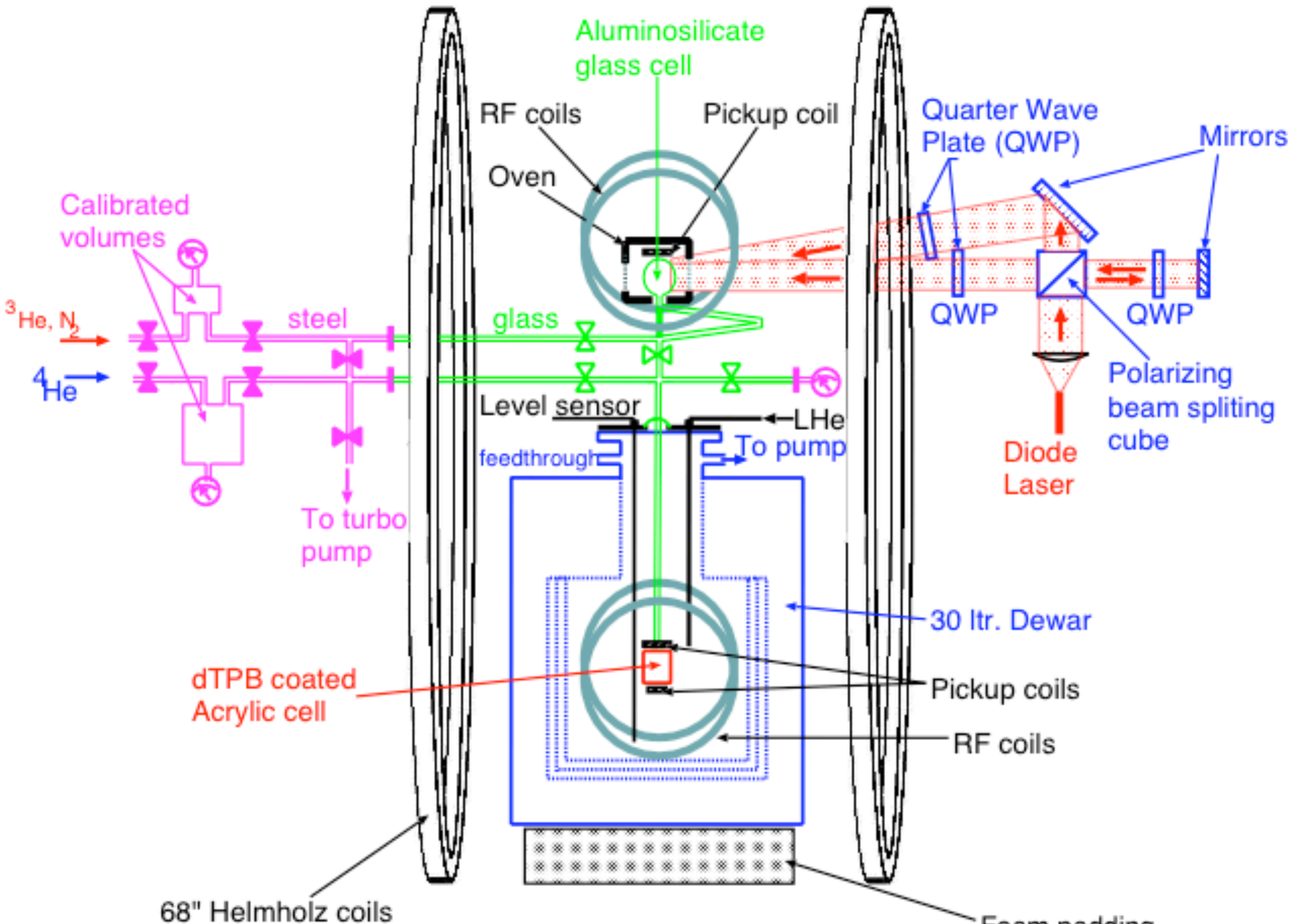
Schematic of the experiment



^{3}He Relaxation Study at Duke University

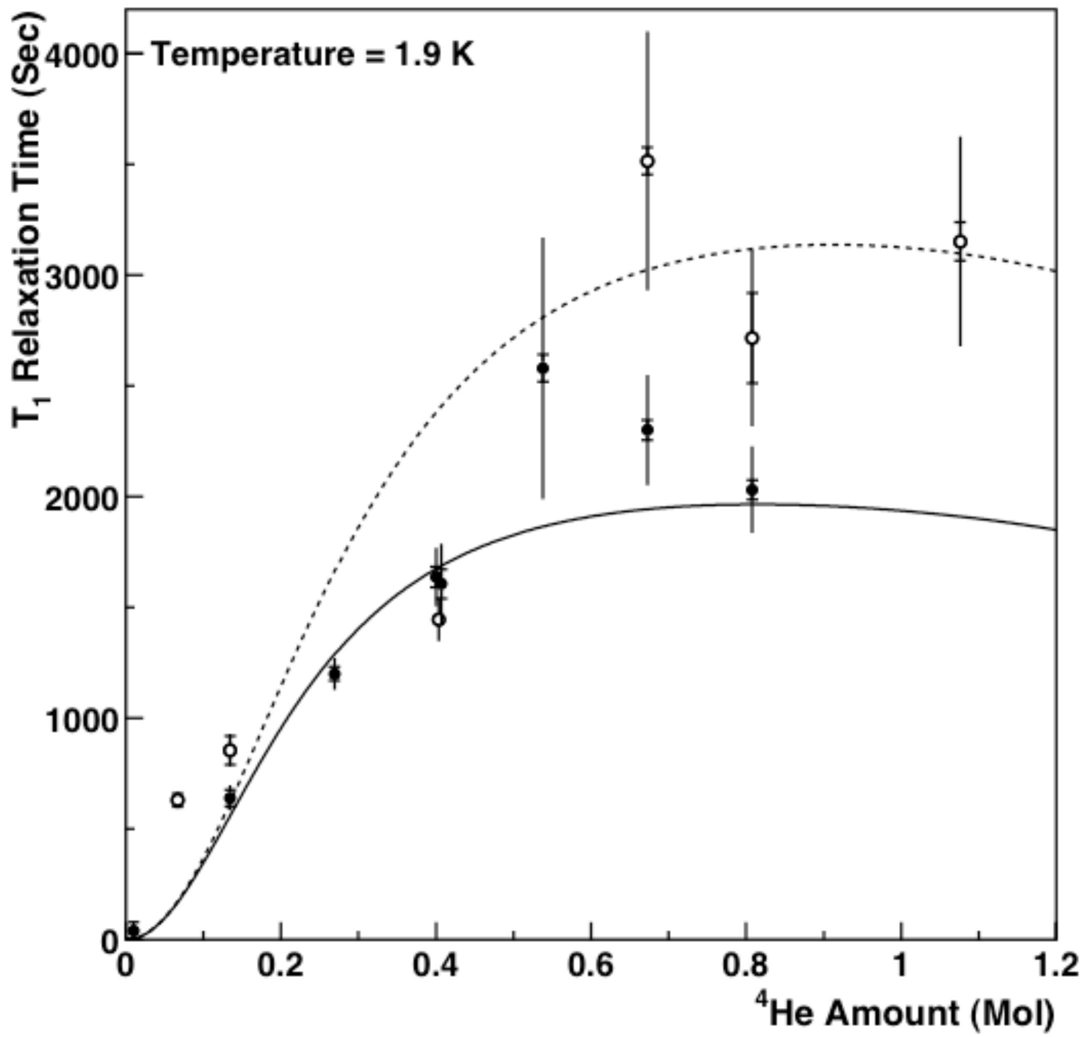


Collaborators from Caltech and NC state



Aluminosilicate
glass cell
RF coils
Pickup coil
Oven
Quarter Wave
Plate (QWP)
Mirrors
Calibrated
volumes
3He, N2
4He
steel
glass
QWP
QWP
Polarizing
beam spliting
cube
Level sensor
LHe
To pump
feedthrough
Diode
Laser
To turbo
pump
30 ltr. Dewar
dTPB coated
Acrylic cell
Pickup coils
RF coils
68" Helmholz coils
Foam padding

3He relaxation time at 1.9 K from dTPB coated acrylic cell



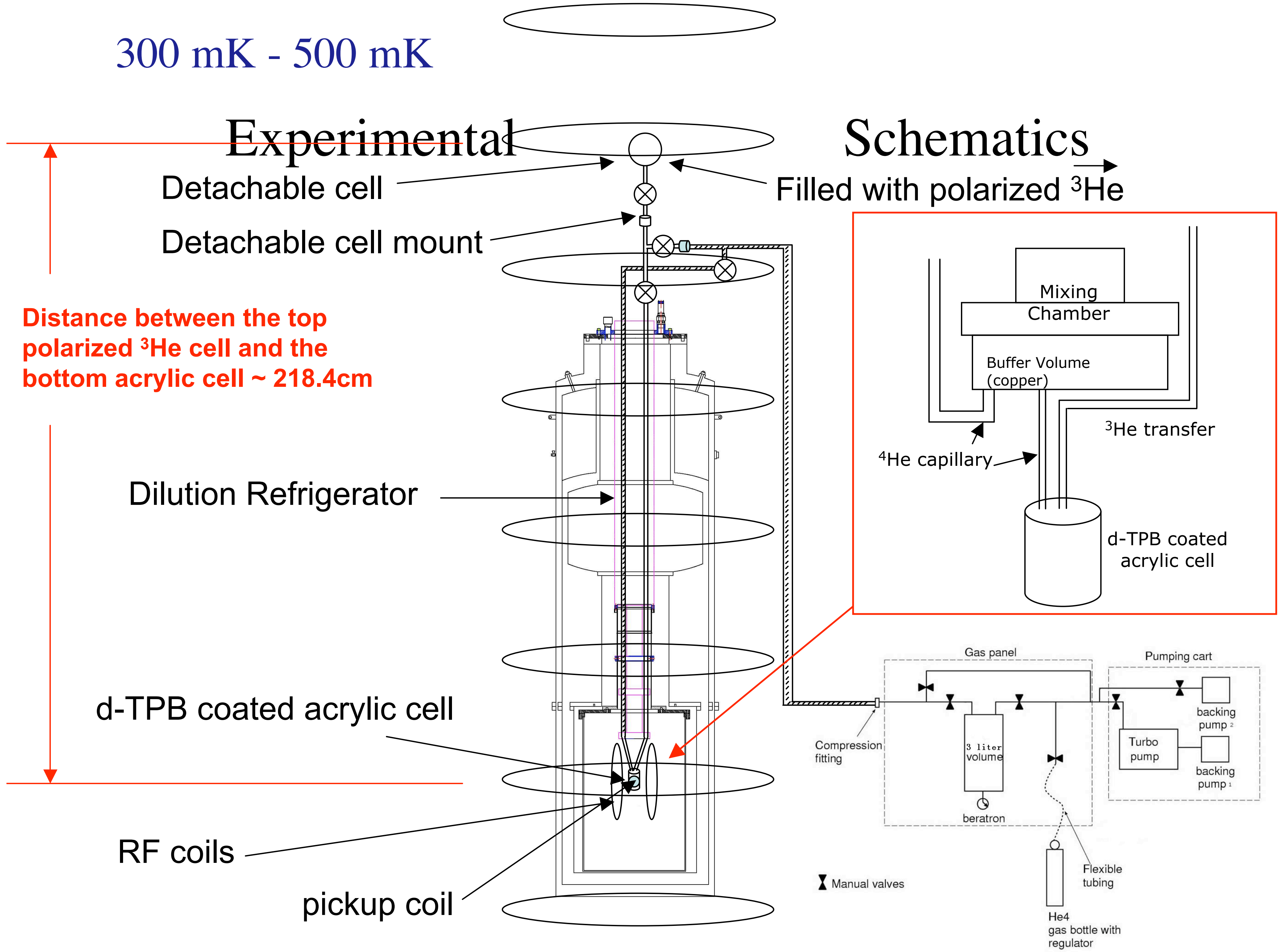
Extracted wall-relaxation coefficient from dTPB coated acrylic surface at 1.9 K in cm/sec

$$(2.0 \pm 0.12)E-04$$

Q. Ye et al., physics/0603176

300 mK - 500 mK

Experimental Schematics



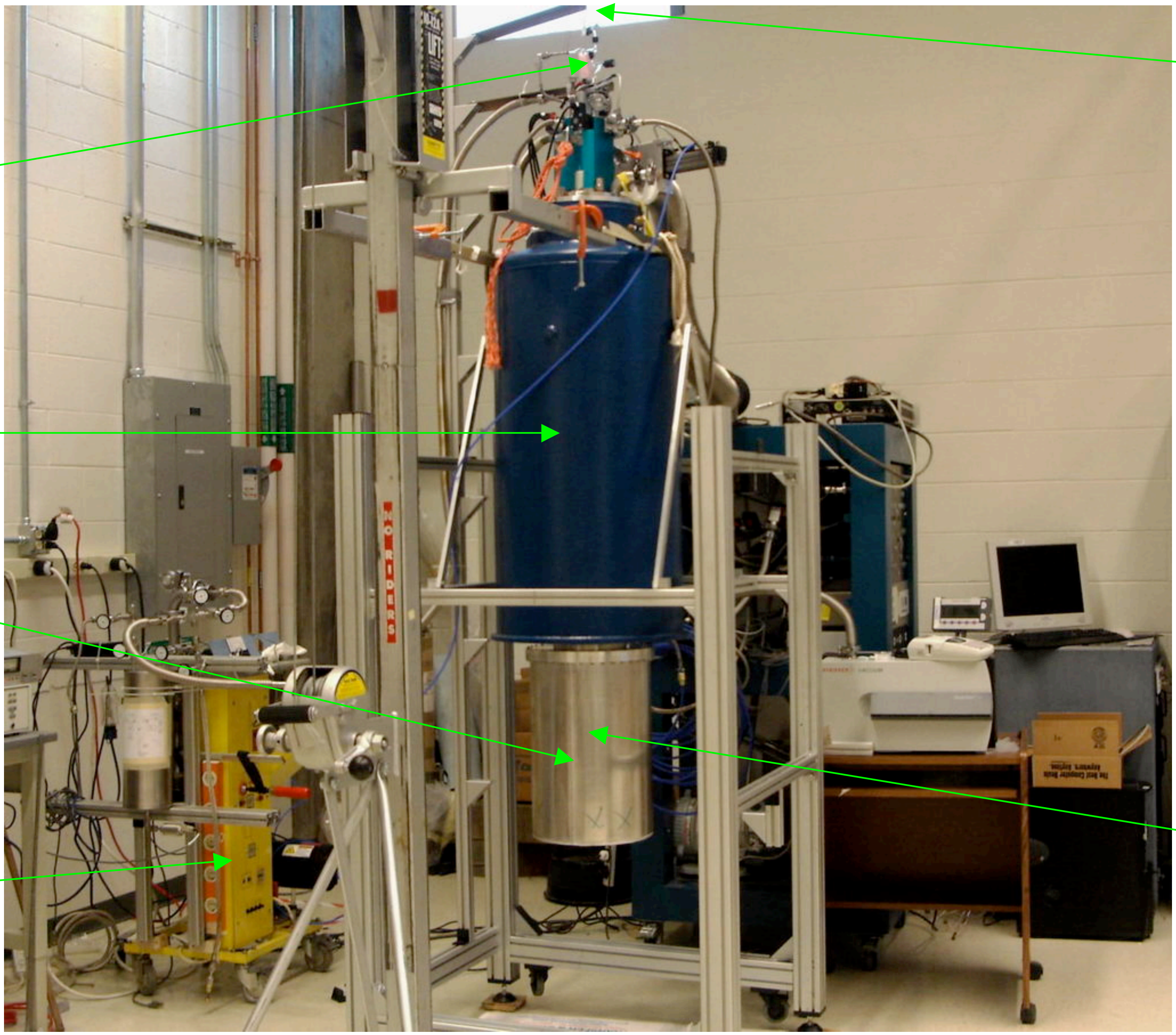
Experimental setup in French Science Building

Long piece of glass going thru dewar

Dewar

Inner Vacuum Chamber (IVC)

Pumping station



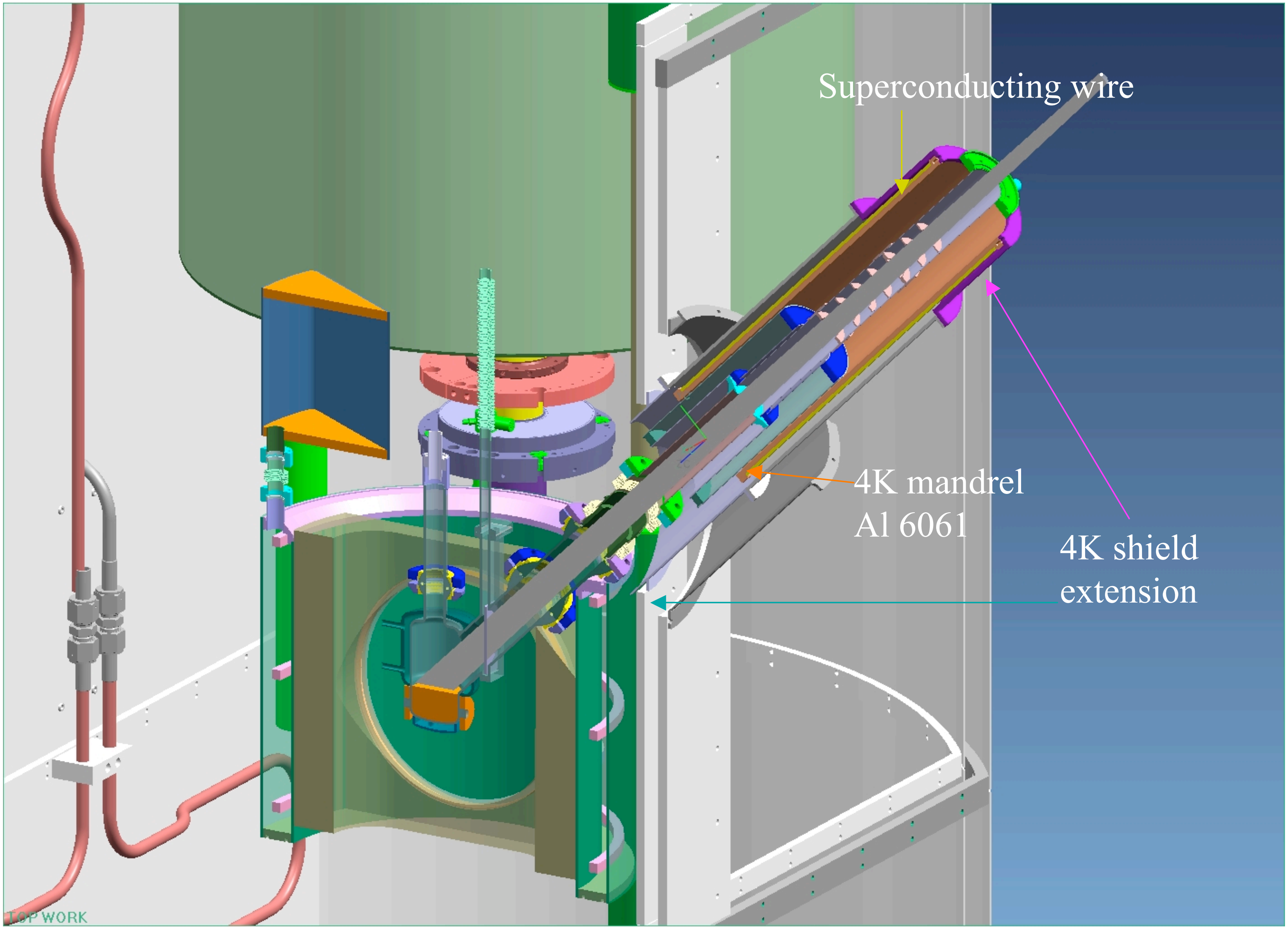
Polarized ^{3}He cell

8 coils will be set up around the dewar

d-TPB coated acrylic cell inside

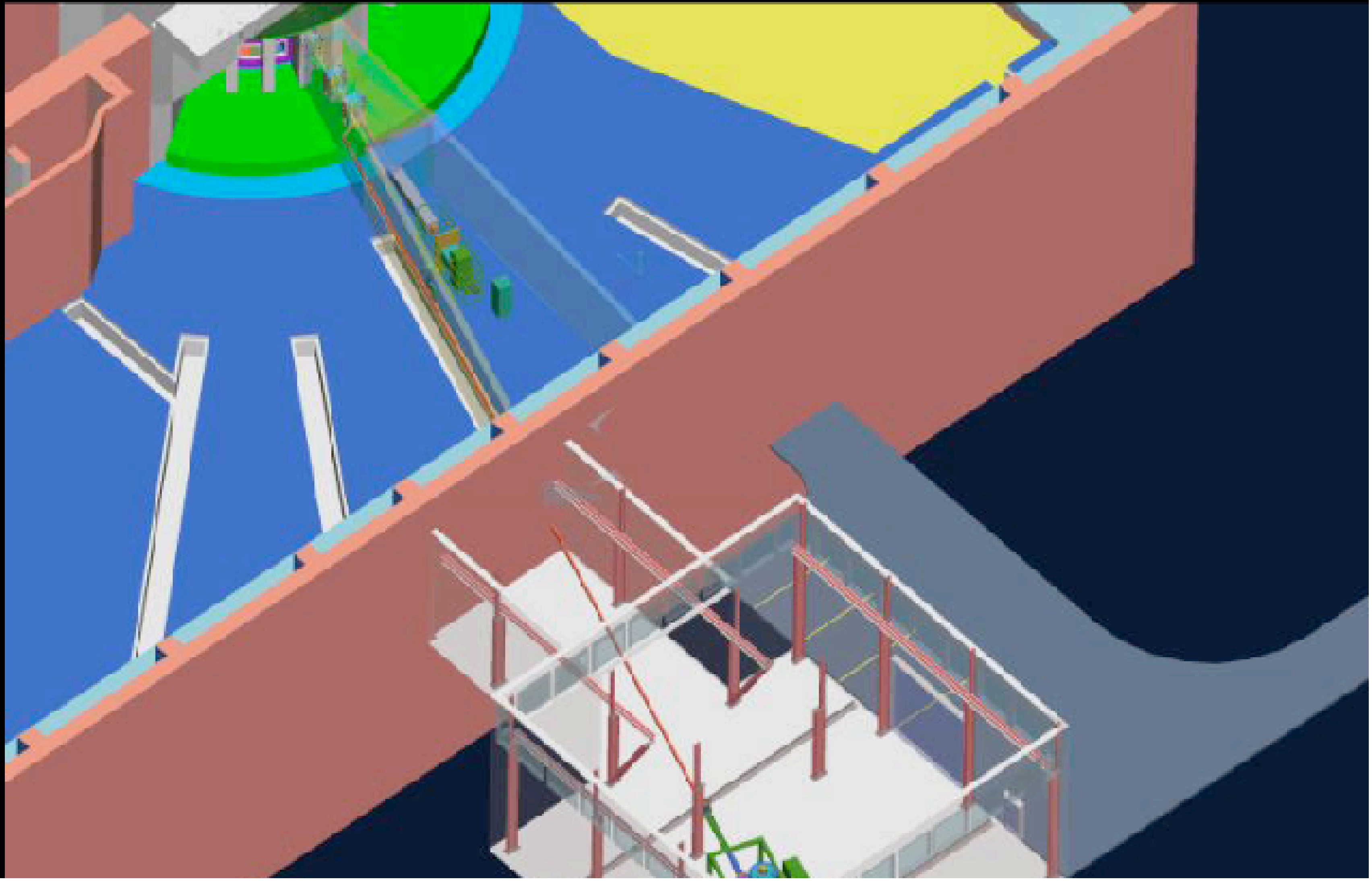
3He injection and collection test

Duke, Caltech, Arizona, MIT



Spallation Neutron Source

Fundamental Physics Facili



nEDM Collaboration List

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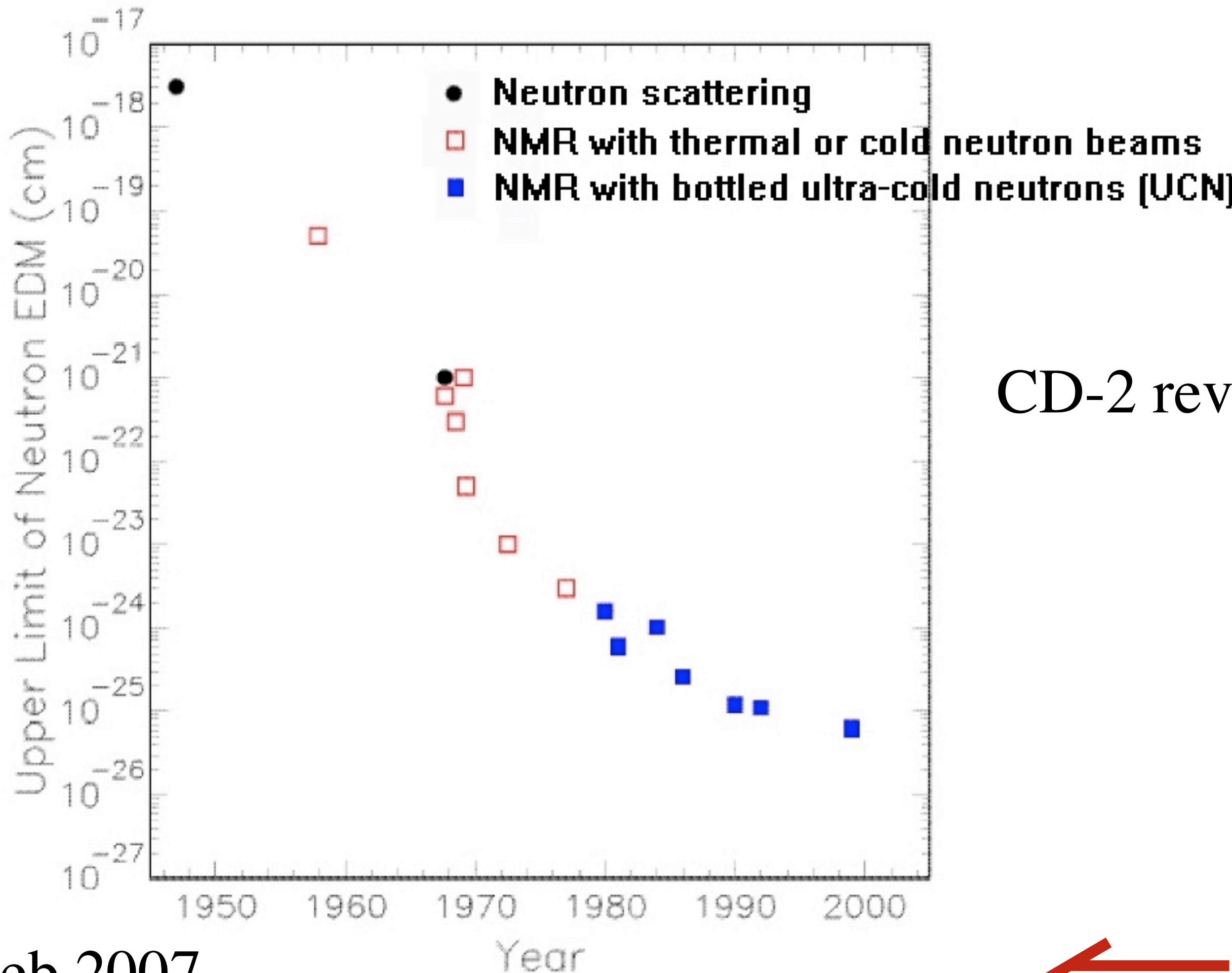
Summary



CD-2 review 08

CD-1 Feb 2007

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