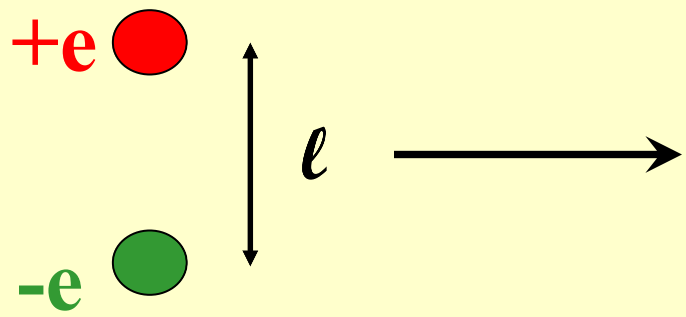
Neutron Electric Dipole Moment (EDM)

- Why is it interesting? (recall S. Gardner)
- How do we measure it?
- What is the present limit?
- How can we signifcantly improve the sensitivity (& discover neutron EDM!!)?

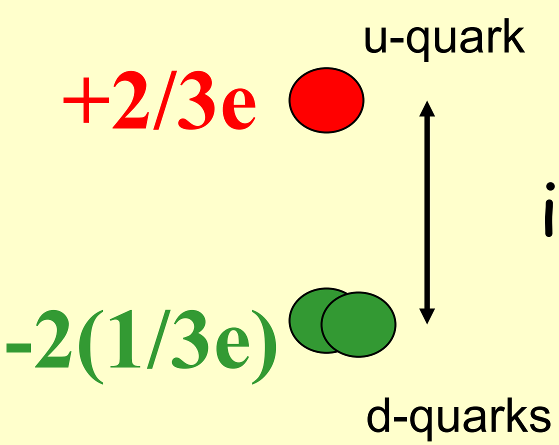
Brad Filippone
NIST Summer School
Fundamental Neutron Physics
June 26, 2009

What is an EDM?



$d = e\ell$

How big is the neutron EDM?



if $\ell \sim 0.1\ r_n$

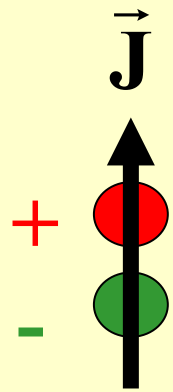
$d_n \sim 4\text{x}10^{-14}$ e-cm

Experiment says $d_n < 3\text{x}10^{-26}$ e-cm

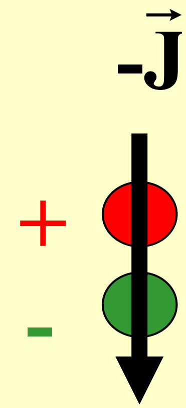
Why Look for EDMs?

- Existence of EDM implies violation of Time Reversal Invariance

Cartoon



$$\mathbf{t} \Rightarrow -\mathbf{t}$$
$$\vec{\mathbf{J}} \Rightarrow -\vec{\mathbf{J}}$$
$$\vec{\mathbf{d}} \Rightarrow \vec{\mathbf{d}}$$



- Time Reversal Violation seen in K^0–$\overline{K^0}$ system
- May also be seen in early Universe
  - Matter-Antimatter asymmetry

but the Standard Model effect is too small !

Quantum Picture – Discrete Symmetries

(08 Nobel Prize)

Charge Conjugation : $\hat{C} \bullet \psi_{n} \Rightarrow \psi_{\bar{n}}$

Parity : $\hat{P} \bullet \psi(x,y,z) \Rightarrow \psi(-x,-y,-z)$

Time Reversal : $\hat{T} \bullet \psi(t) \Rightarrow \psi(-t)$

Assume $\vec{\mu} = \mu \frac{\vec{J}}{J}$ and $\vec{d} = d \frac{\vec{J}}{J}$

Non-Relativistic Hamiltonian

$$H = \underbrace{\vec{\mu} \cdot \vec{B}}_{} + \underbrace{\vec{d} \cdot \vec{E}}_{}$$

$\vec{\mu} \cdot \vec{B}$	$\vec{d} \cdot \vec{E}$
C-even	C-even
P-even	P-odd
T-even	T-odd

	C	P	T
$\vec{\mu}$	–	+	–
$\vec{d}$	–	+	–
$\vec{E}$	–	–	+
$\vec{B}$	–	+	–
$\vec{J}$	+	+	–

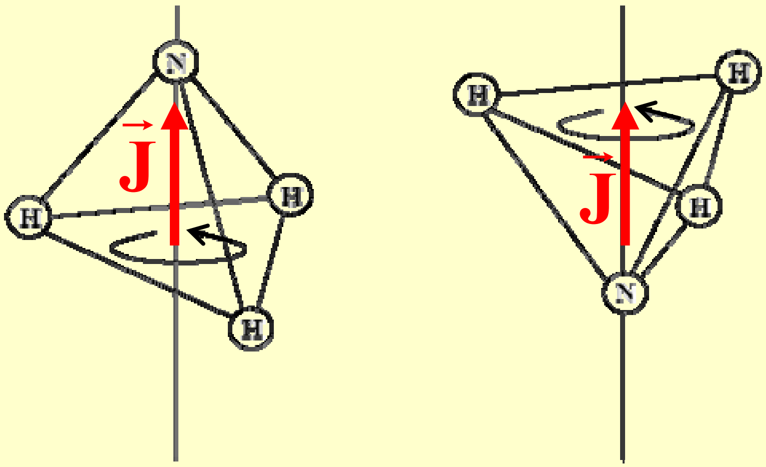
Non-zero d violates T and CP

(Field Theories generally preserve CPT)

But some molecules have HUGE EDMs!

H_2O: d = 0.4 x 10^{-8} e-cm
NaCl: d= 1.8 x 10^{-8} e-cm
NH_3: d = 0.3 x 10^{-8} e-cm

Note: n-EDM < 3 x 10^{-26} e-cm



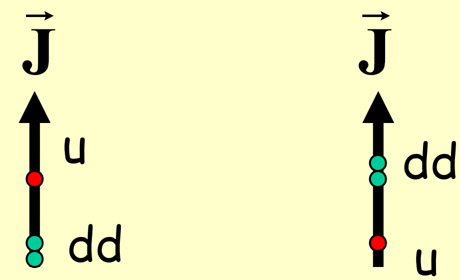
But NH_3 EDM is not T-odd or CP-odd since

$$\vec{d} \neq d\frac{\vec{J}}{J}$$

$$\left(\text{both } \vec{d} = +d\frac{\vec{J}}{J} \quad \text{and} \quad \vec{d} = -d\frac{\vec{J}}{J} \text{ exist!} \right)$$

Ground state is actually a superposition

If Neutron had degenerate state



it would not violate T or CP

Role of CP Violation in the Matter/Antimatter Asymmetry of the Universe

- **Sakharov Criteria**
  - Particle Physics can produce matter/antimatter asymmetry in the early universe *IF* there is:
    - Baryon Number Violation
    - CP & C violation
    - Departure from Thermal Equilibrium

Baryogenesis

- **Plausibility Argument**
  - Consider heavy boson - X
    - Baryon number violation:

$$\mathbf{X \to qq} \qquad \mathbf{X \to q\ell}$$
$$\mathbf{\overline{X} \to \overline{q}\,\overline{q}} \qquad \mathbf{\overline{X} \to \overline{q}\,\overline{\ell}}$$

    - C-Violation & CP-Violation

$$\Gamma_{\mathbf{X\to qq}} = (1+\Delta_q)\Gamma_q; \quad \Gamma_{\mathbf{X\to q\,\ell_L}} = (1-\Delta_\ell)\Gamma_\ell$$
$$\Gamma_{\mathbf{\overline{X}\to \overline{q}\,\overline{q}}} = (1-\Delta_q)\Gamma_q; \quad \Gamma_{\mathbf{\overline{X}\to \overline{q}\,\overline{\ell}_R}} = (1+\Delta_\ell)\Gamma_\ell$$
$$\textbf{but} \quad \Gamma_{\mathbf{X}}^{\mathbf{Tot}} = \Gamma_{\mathbf{\overline{X}}}^{\mathbf{Tot}} \ \text{(CPT conservation!!)} \ \textbf{if} \ \Delta_q\Gamma_q = \Delta_\ell\Gamma_\ell$$

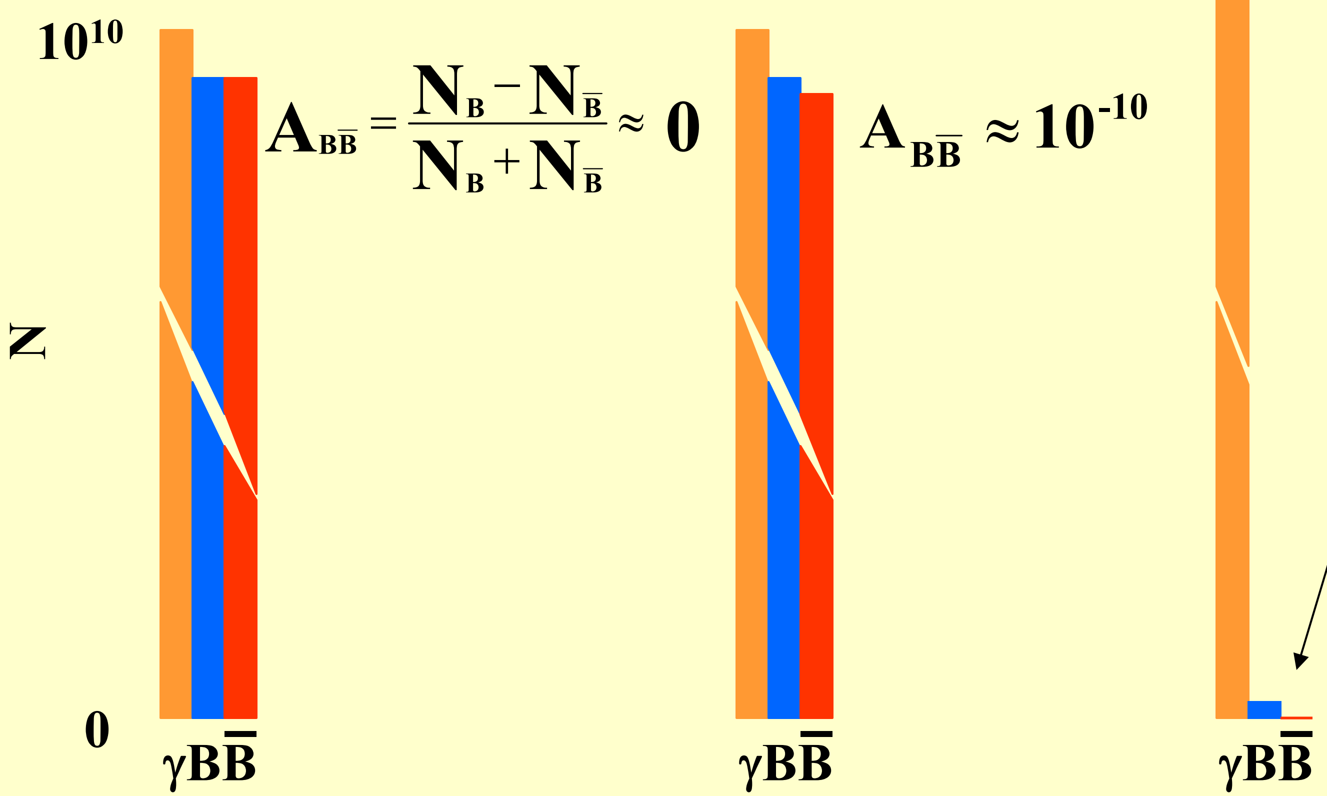
    - Out of Thermal Equilibrium

      Otherwise, in Equilibrium the reverse reactions: (e.g. $qq \to X$, $\overline{q}\,\overline{q} \to \overline{X}$) will smooth out any matter/antimatter excess

Electroweak Baryogenesis

Possible source of Matter-Antimatter Asymmetry

Before Electroweak Phase Transition — **After EW Phase Transition** — **Today**



Before Electroweak Phase Transition:

$$A_{B\bar{B}} = \frac{N_B - N_{\bar{B}}}{N_B + N_{\bar{B}}} \approx 0$$

$$\frac{N_B}{N_\gamma} \approx \frac{1}{2}$$

After EW Phase Transition:

$$A_{B\bar{B}} \approx 10^{-10}$$

$$\approx \frac{1}{2}$$

Today:

$$A_{B\bar{B}} \approx 1$$

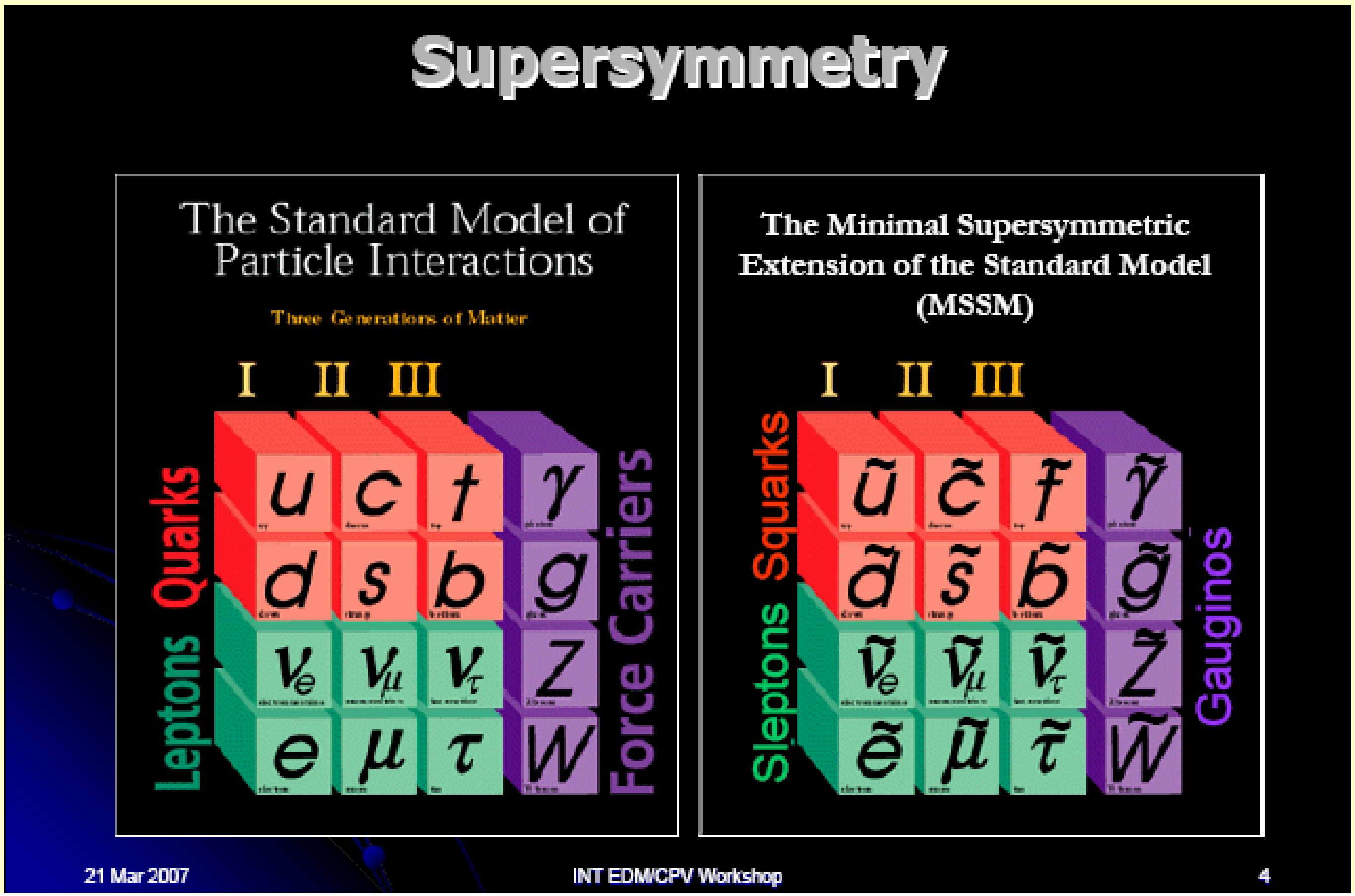
$$\approx 10^{-10}$$

But Standard Model CP violation (CKM matrix) is Insufficient

- Must search for new sources of CP
    - B-factories, Neutrinos, EDMs
- Quarks/Gluons
    - Allows production of matter-antimatter asymmetry via "Baryogenesis"
- Neutrino mixing suggests possibility of new CP violation in leptons
    - Allows production of matter anti-matter asymmetry via "Leptogenesis"

What is the possible origin of new CP-violation?

- **New physics** (e.g. SuperSymmety=SUSY)



What's in SUSY?

- Great Names:
  - Squarks, sleptons, gauginos, winos, binos, neutralinos,…
- In MSSM
  - 124 parameters - 19 from Standard Model & 105 new parameters (from SUSY and also from SUSY breaking)
    - 36 mixing angles for squarks & sleptons
    - 40 CP-violating phases for squarks & sleptons
    - 21 squark & slepton masses
    - 5 couplings and 3 phases from gauginos/higgsinos

SUSY, CP-Violation and EDMs

- New physics (e.g. SuperSymmety = SUSY) has additional CP violating phases in added couplings
  - New phases: (ϕ_{CP}) should be ~ 1 (why not?)
- Contribution to EDMs depends on masses of new particles

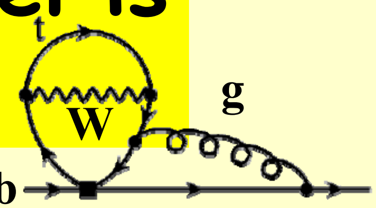
$$d_n \sim 10^{-24} \text{ e-cm} \times \sin\varphi_{CP} (200 \text{ GeV}/M_{SUSY})^2$$

Note: experimental limit: $d_n < 0.03 \times 10^{-24}$ e-cm
Standard Model Prediction: $d_n < 10^{-31}$ e-cm

Origin of EDMs

- **Standard Model EDMs are due to CP violation in the quark weak mixing matrix CKM (e.g. the K^0/B^0-system) but…**
  - e^- and quark EDM's are zero in 1st & 2nd order
  - Need at least three Feynman diagram "loops" to get EDM's (electron actually requires 4 loops!)
    - Thus EDM's are VERY small in standard model

Neutron EDM in Standard Model is ~ 10^{-32} e-cm (=10^{-19} e-fm)



Experimental neutron limit: < 3 x 10^{-26} e-cm

Electron EDM in Standard Model is < 10^{-40} e-cm

Origin of Hadronic EDMs

- Hadronic (strongly interacting particles) EDMs are from
  - θ_{QCD} (a special parameter in Quantum Chromodynamics – QCD)
  - or from the quarks themselves

θ_{QCD}

Weinberg
3-gluon term

$$\mathcal{L}^{\not{CP}}_{eff} = \frac{g_s^2}{32\pi^2}\,\bar{\theta}\, G^a_{\mu\nu}\tilde{G}^{\mu\nu,a} + \frac{1}{3} w\, f^{abc} G^a_{\mu\nu}\tilde{G}^{\nu\beta,b} G_{\beta}{}^{\mu,c}$$
$$- \frac{i}{2}\sum_{i=e,u,d,s} d_i\, \overline{\psi}_i (F\cdot\sigma)\gamma_5\psi - \frac{i}{2}\sum_{i=u,d,s} \tilde{d}_i\, \overline{\psi}_i g_s (G\cdot\sigma)\gamma_5\psi + \cdots$$

e^-,quark EDM

quark color EDM
(chromo-EDM)

EDM from θ_{QCD}

- This is the strong-CP problem in QCD

$$\mathcal{L}_{QCD} = -\theta\left(\frac{\alpha_s}{8\pi}\right)\tilde{G}_a^{\mu\nu}G^a_{\mu\nu}$$

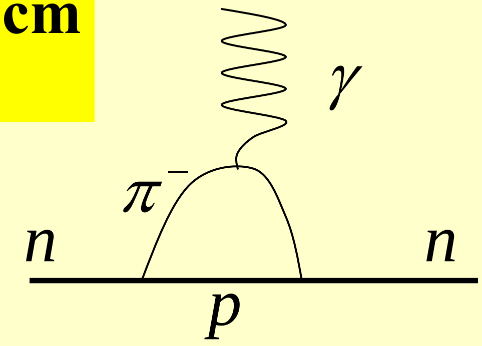
  - θ_{QCD} should be naturally about ~ 1
- This gives a neutron EDM of

$$d_n = \frac{g_{\pi NN}}{4\pi^2}\left(\frac{e}{m_p f_\pi}\right)\ln\left(\frac{m_\rho}{m_\pi}\right)\left(\frac{m_u m_d}{m_u + m_d}\right)\theta \approx (-10^{-15})\theta\ \mathrm{e\text{-}cm}$$

but $d_n^{exp} < 10^{-25}$ e-cm

$\therefore\ \theta < 10^{-10}$

Why so small??

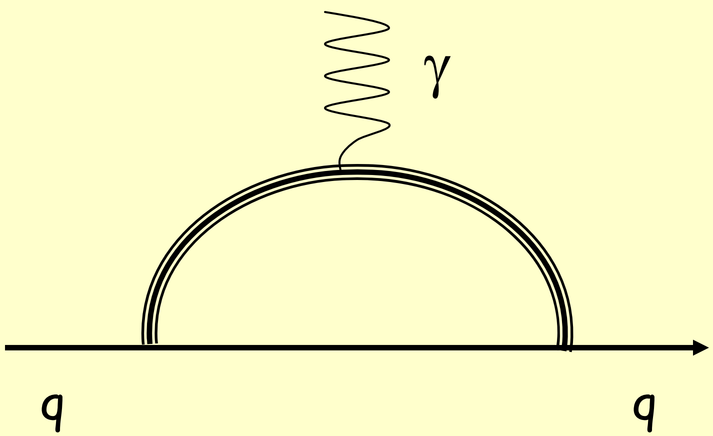


EDM from θ_{QCD}

- Small θ_{QCD} does not provide any new symmetry for $\mathcal{L}_{QCD}$
  - Popular solution is "axions" (Peccei-Quinn symmetry) – new term in $\mathcal{L}_{QCD}$
    - No Axions observed yet
  - Extra dimensions might suppress θ_{QCD}
  - Remains an unsolved theoretical "problem"

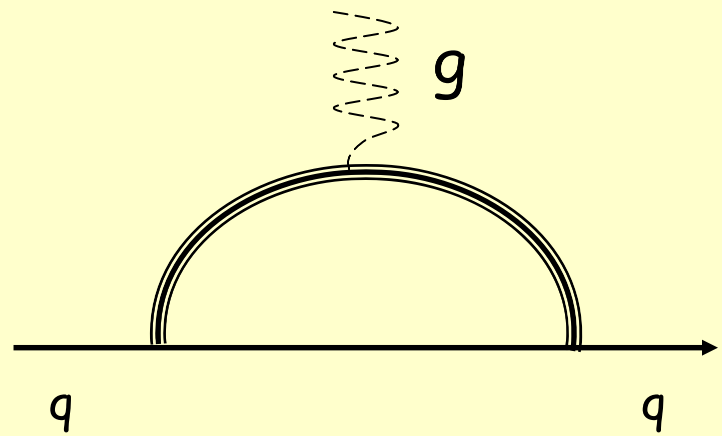
Hadronic EDM from Quarks

- Quark EDM contributes via



d_q

Quark EDM



$\tilde{d}_q$

Quark ChromoEDM

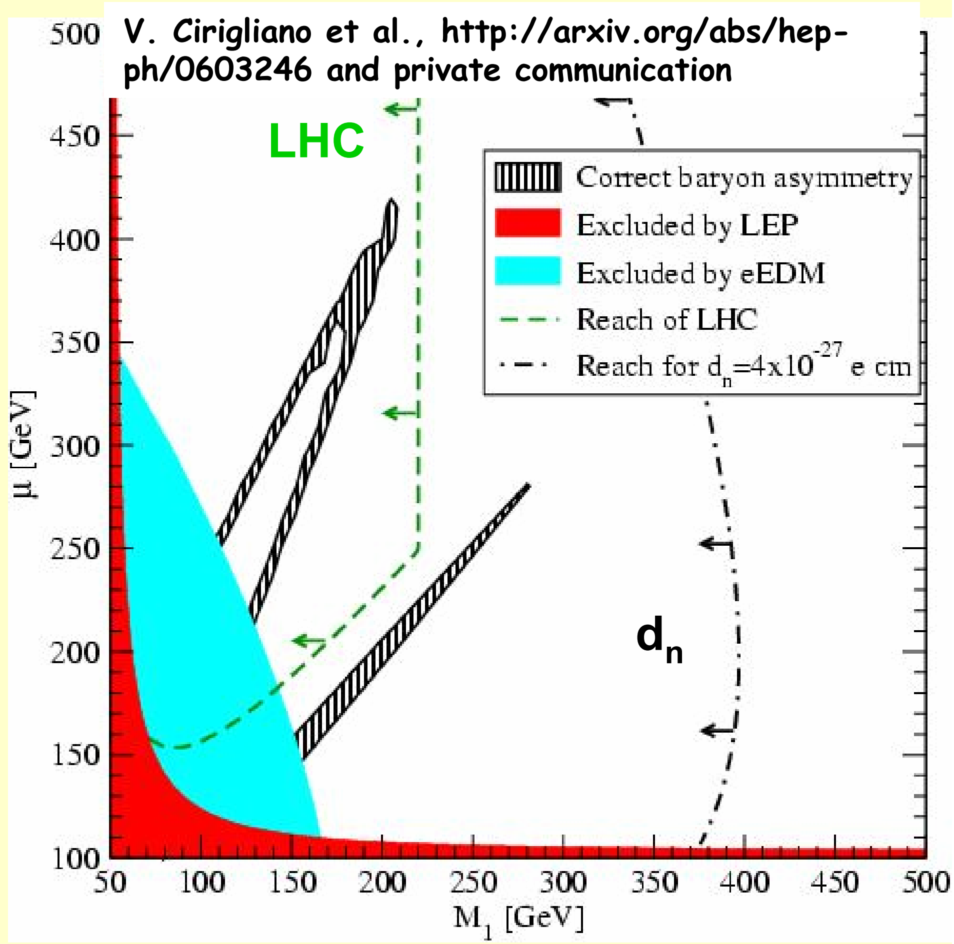
Relative EDM Sensitivities

System	Dependence	Present Limit (e-cm)	Future (e-cm)
n	$d_n \sim (3\times10^{-16})\theta_{QCD}$ + $0.7(d_d - \frac{1}{4}d_u) + 0.6e(\tilde{d}_d + \frac{1}{2}\tilde{d}_u)$	$<3\times10^{-26}$	10^{-28}
d	$d_d \sim (-1\times10^{-16})\theta_{QCD}$ + $6e(\tilde{d}_d - \tilde{d}_u)$	?	10^{-27}(?)
^{199}Hg	$d_{Hg} \sim (0.007\times10^{-16})\theta_{QCD}$ - $0.007e(\tilde{d}_d - \tilde{d}_u)$	$<7\times10^{-29}$	10^{-29}(?)

Possible impacts of non-zero EDM

- Must be new Physics
- Sharply constrains models beyond the Standard Model (especially *with* LHC data)

Large Hadron Collider



~ Higgs superpartner mass

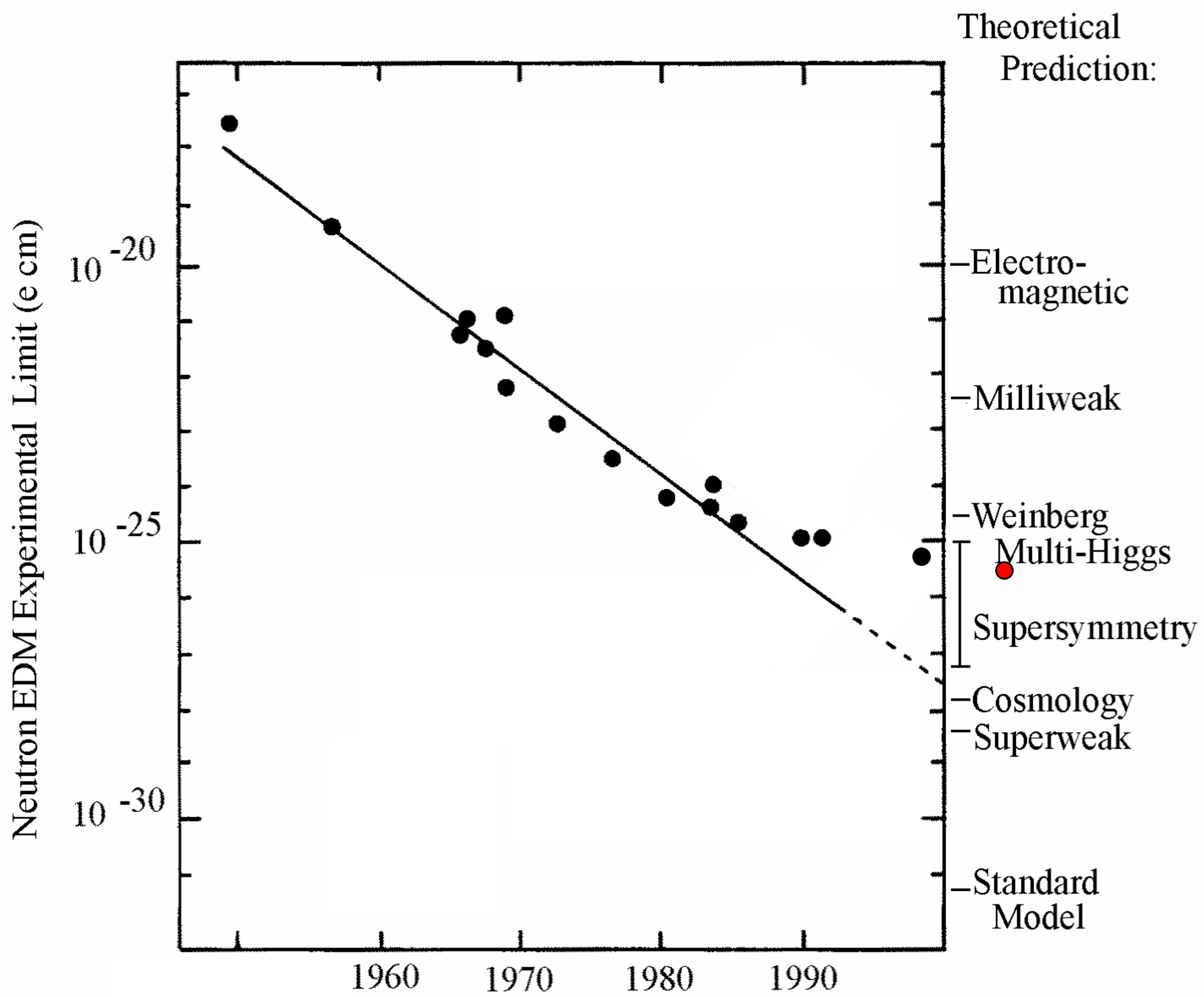
gauge boson superpartner mass

- May account for matter-antimatter asymmetry of the universe

First result for neutron EDM


- E.M. Purcell and N.F. Ramsey, *Phys. Rev.* **78**, 807 (1950)
  - Neutron Scattering
  - Searching for Parity Violation
  - Pioneered Neutron Beam Magnetic Resonance

n-EDM vs Time


Theoretical
Prediction:
Neutron EDM Experimental Limit (e cm)
10^{-20}
10^{-25}
10^{-30}
1960
1970
1980
1990
Electro-
magnetic
Milliweak
Weinberg
Multi-Higgs
Supersymmetry
Cosmology
Superweak
Standard
Model

How to measure an EDM?

Recall magnetic moment in B field:

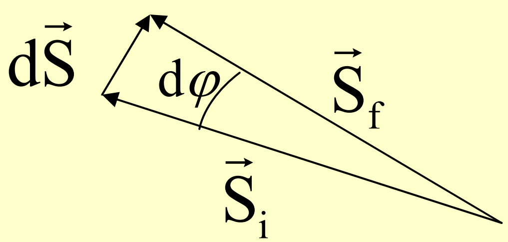
$$\hat{H} = \vec{\mu}\cdot\vec{B}; \qquad \vec{\mu} = 2\left(\frac{\mu_N}{\hbar}\right)\vec{S} \quad ;\text{for spin } \frac{1}{2}$$

$$\vec{\tau} = \frac{d\vec{S}}{dt} = \vec{\mu}\times\vec{B} \Rightarrow 2\left(\frac{\mu_N}{\hbar}\right)\left|\vec{S}\right|\left|\vec{B}\right|; \quad \text{if } \vec{S}\perp\vec{B}$$

Classical Picture:

- If the spin is not aligned with B there will be a precession due to the torque
- Precession frequency ω given by

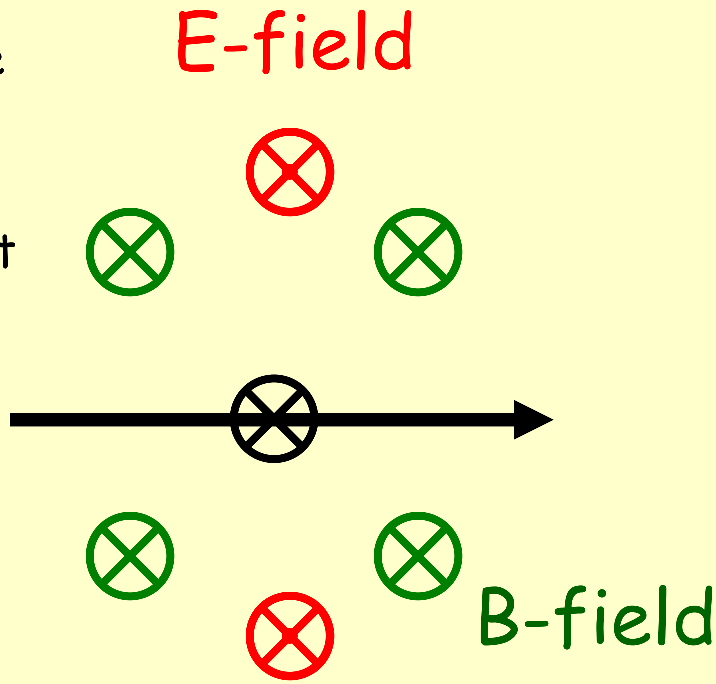
$$\omega = \frac{d\varphi}{dt} = \frac{1}{S}\frac{dS}{dt}$$



$$= \frac{2\mu_N B}{\hbar} \;;\quad \text{or} \quad \frac{2d_N E}{\hbar} \quad \text{for a } \vec{d}_N \text{ in } \vec{E}$$

Simplified Measurement of EDM

1. Inject polarized particle
2. Rotate spin by $\pi/2$
3. Flip E-field direction
4. Measure frequency shift



$$\nu = \frac{2\vec{\mu}\cdot\vec{B} \pm 2\vec{d}\cdot\vec{E}}{h}$$

Must know B very well

What is the precision in EDM measurement?

$$\mathcal{E} = \hbar\omega = \vec{\mathbf{d}} \cdot \vec{\mathbf{E}}$$

Using Uncertainty Principle:

$$\Delta\mathcal{E}\Delta \mathbf{t} \sim \hbar$$

Precise energy measurement requires long measurement time, giving

$$\sigma_{\mathbf{d}} \sim \frac{\hbar}{|\vec{\mathbf{E}}|\mathbf{T}_{\mathbf{m}}}$$

But must include counting statistics $\propto \frac{1}{\sqrt{\mathbf{N}}}$

Sensitivity: $$\sigma_{\mathbf{d}} \cong \frac{\hbar}{|\vec{\mathbf{E}}|\mathbf{T}_{\mathbf{m}}\sqrt{\mathbf{mN}}}$$

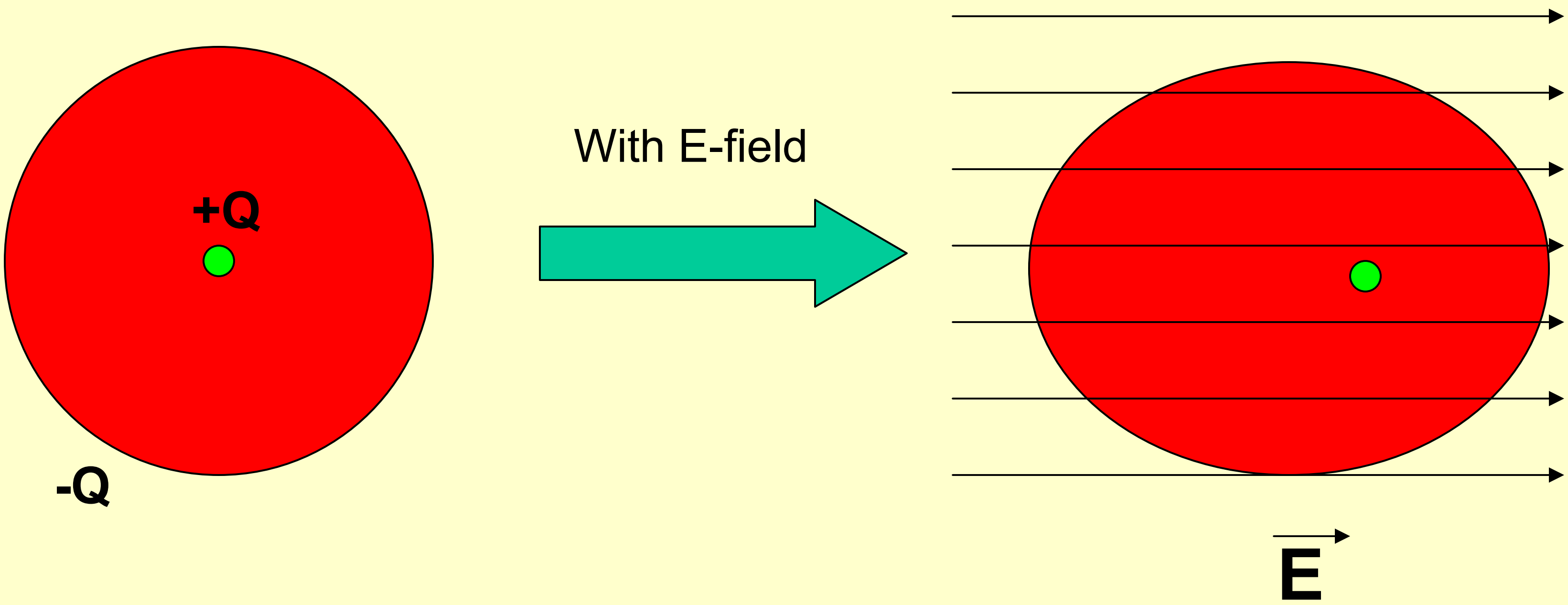
E – Electric Field
T_m – Time for measurement
m – total # of measurements
N – Total # of counts/meas.

What particles can be measured?

- Charged particle is difficult
  - Electric field accelerates
  - May work for storage ring
- Neutral particle is easier
  - Atoms (for electron EDM)
    - Also can work for quark EDM
  - Free Neutrons (for quark EDM)

Atomic EDMs

- Schiff Theorem
  - Neutral atomic system of point particles in Electric field readjusts itself to give zero E field at all charges



But …

- Magnetic effects and finite size of nucleus can break the symmetry (relativistic effects can also enhance)
  - Enhancement for d_e in paramagnetic atoms (unpaired electrons)

    (magnetic effect with mixing of opposite parity atomic states)

    Thus $d_{Tl} \sim -585\, d_e$ & $|d_e| < 1.5 \times 10^{-27}$ e-cm

  - Suppression for hadronic EDMs in Diamagnetic atoms (paired electrons) – but Schiff Moment is non-zero

    (due to finite size of nucleus and nuclear force)

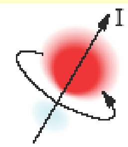
$$\text{Naively expect } d_A \sim \left(\frac{R_{Nucleus}}{r_{Atom}}\right)^2 d_{n,p} \sim \left(\frac{A^{1/3}R_0}{a/Z}\right)^2 d_{n,p} \sim 10^{-4} d_{n,p}$$

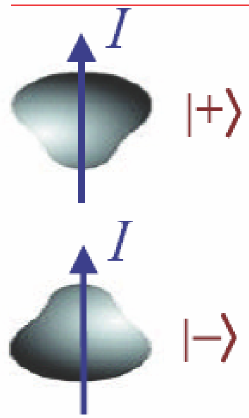
for ^{199}Hg

But, but, ...

Can enhance heavy atom EDMs via nuclear deformation

Octupole deformations





ΔE: $\Psi^+ = (|+\rangle + |-\rangle)/\sqrt{2}$, $\Psi^- = (|+\rangle - |-\rangle)/\sqrt{2}$

~~P~~, ~~T~~ ⇒

$\Psi^+ = ((1+\alpha)|+\rangle + (1-\alpha)|-\rangle)/\sqrt{2}$

$\Psi^- = ((1-\alpha)|+\rangle + (1+\alpha)|-\rangle)/\sqrt{2}$

$$\alpha = \frac{\langle \Psi^- | V^{PT} | \Psi^+ \rangle}{\Delta E} \sim \frac{\beta_3 A^{-1/3}}{\Delta E}$$

$S_{intr} \sim eZA\beta_2\beta_3$ $\quad S_{lab} \sim e\, Z\, A^{2/3}\, \beta_2\, \beta_3^2/\Delta E$ $\quad \beta_2, \beta_3 \sim 0.1$

Haxton & Henley; Auerbach, Flambaum & Spevak; Hayes, Friar & Engel

	^{223}Rn	^{223}Ra	^{225}Ra	^{223}Fr	^{225}Ac	^{229}Pa	^{199}Hg	^{129}Xe
$t_{1/2}$	23.2 m	11.4 d	14.9 d	22 m	10.0 d	1.5 d		
I	7/2	3/2	1/2	3/2	3/2	5/2	1/2	1/2
Δe_{th} (keV)	37	170	47	75	49	5		
ΔE_{exp} (keV)	--	50.2	55.2	160.5	40.1	0.22		
10^5 S ($e$fm^3)	1000	400	300	500	900	12000	-1.4	1.75
10^{28} d_A (e cm)	**2000**	**2700**	**2100**	**2800**			-5.6	0.8

Experimental EDMs

- Present best limits come from atomic systems and the free neutron
  - Paramagnetic like ^{205}Tl are primarily sensitive to d_e
  - Diamagnetic atoms (e.g. ^{199}Hg) and the free neutron are primarily sensitive to $\theta_{QCD}, d_q, \tilde{d}_q$

- Future best limits may come from
  - Molecules (ThO, YbF)
  - Liquids (^{129}Xe)
  - Solid State systems (high density)
  - Storage Rings (Muons, Deuteron)
  - Radioactive Atoms (^{225}Ra, ^{223}Rn)
  - New Technology for Free Neutrons (PSI, ILL, SNS)

Present and Future EDMs

particle	Present Limit (90% CL) (e-cm)	Laboratory	Possible Sensitivity (e-cm)	Standard Model (e-cm)
e^- (Tl) e^- (PbO) e^- (YbF) e^- (GGG)	1.6×10^{-27}	Berkeley Yale Sussex Yale/Indiana	 10^{-29} 10^{-29} 10^{-30}	 $<10^{-40}$
μ μ	9.3×10^{-19}	CERN BNL	 $<10^{-24}$	$<10^{-36}$
n n n n	3×10^{-26}	ILL ILL PSI SNS	1.5×10^{-26} $\sim 2 \times 10^{-28}$ $\sim 7 \times 10^{-28}$ $< 1 \times 10^{-28}$	 $\sim 10^{-32}$
^{199}Hg ^{129}Xe ^{225}Ra ^{223}Rn d	3×10^{-29} (if interpreted as $d_n < 6 \times 10^{-26}$)	Seattle Princeton Argonne TRIUMF BNL/JPARC?	1×10^{-29} 10^{-31} 10^{-28} 1×10^{-28} $<10^{-27}$	$\sim 10^{-33}$ $\sim 10^{-34}$

Non-neutron EDMs

- Atomic EDMs for electron EDM
- Atomic EDMs for quark chromo-EDM
- Possible storage ring experiments:
  - In particle rest frame see an electric field

$$\vec{\mathbf{E}} = \frac{\vec{\mathbf{v}} \times \vec{\mathbf{B}}}{\mathbf{c}}$$

(Can be large if $\beta \sim 1$)

Rotates a longitudinally polarized particle into the vertical direction

^{205}Tl EDM

Phys. Rev. Lett. 88, 071805 (2002)
B. C. Regan, E. D. Commins,
C. J. Schmidt , & D. DeMille

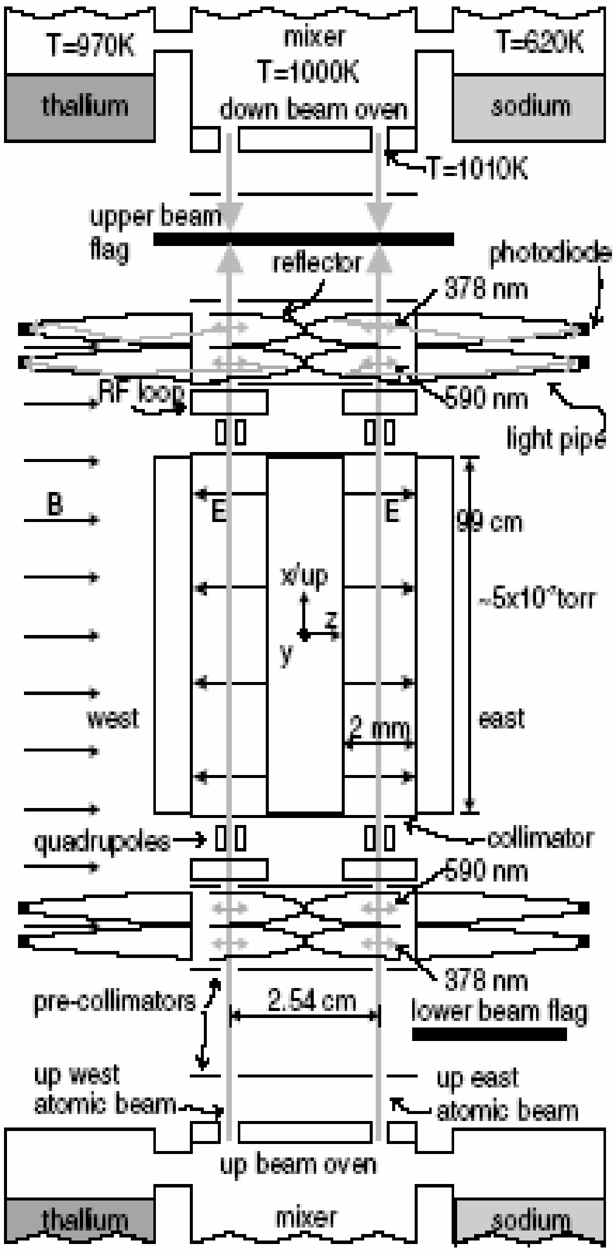
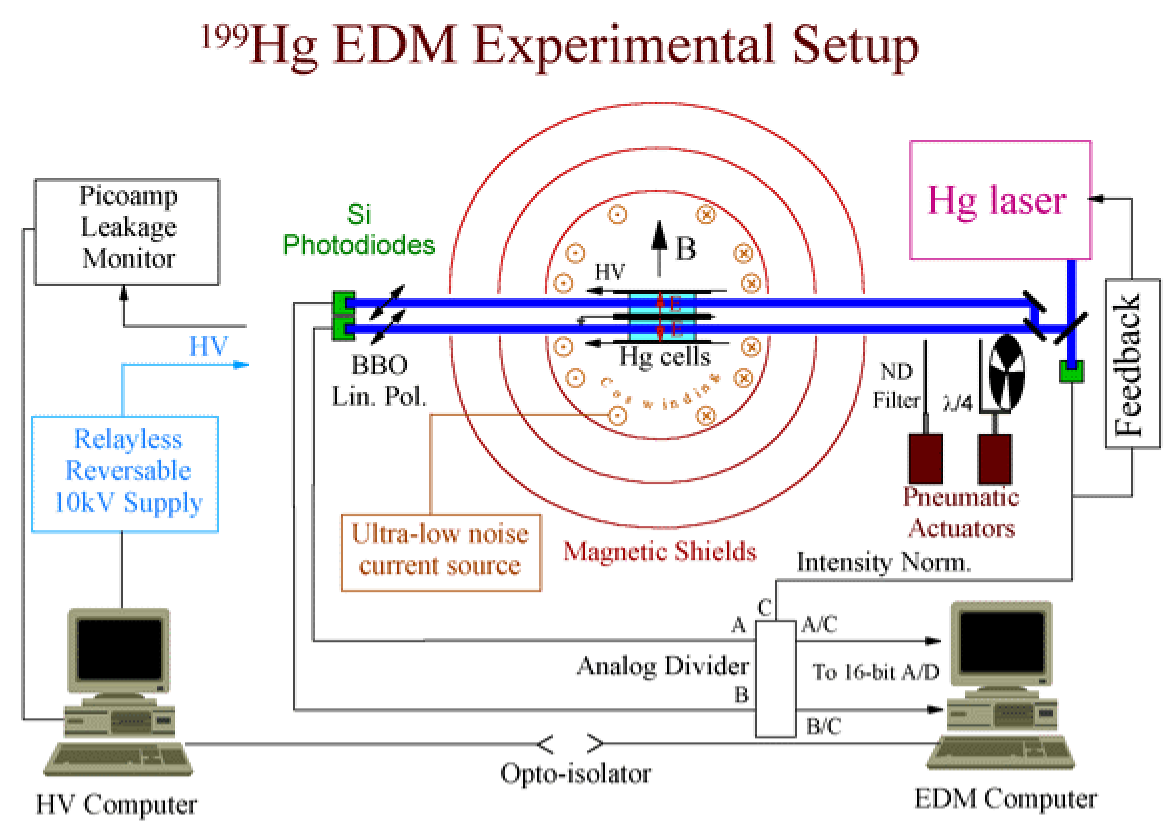
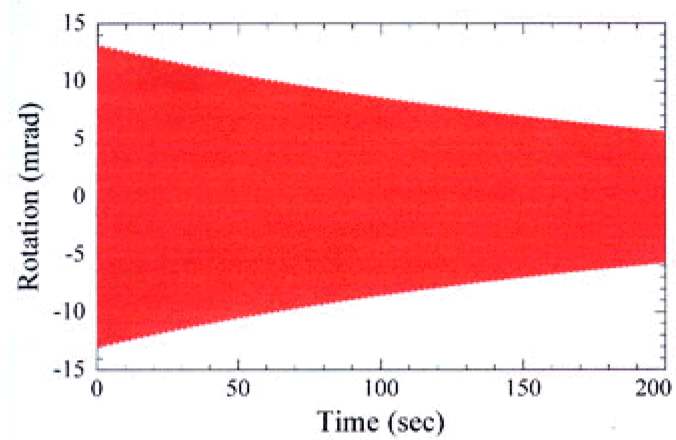


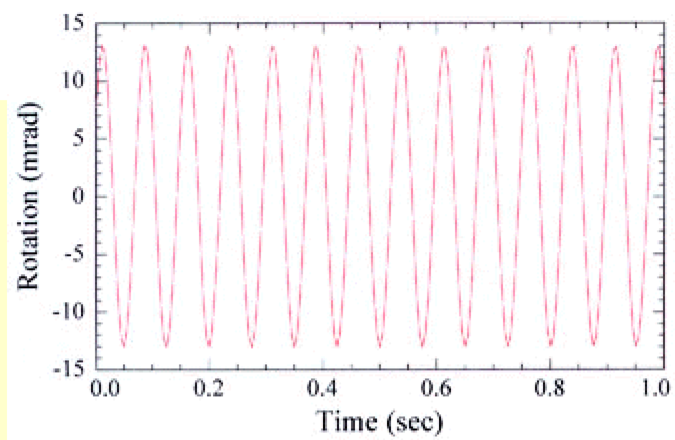
FIG. 1. Schematic diagram of the experiment; not to scale.

^{199}Hg EDM



Phys. Rev. Lett. **102**, 101601 (2009)
W. C. Griffith, M. D. Swallows, T. H. Loftus,
M. V. Romalis, B. R. Heckel, and E. N. Fortson



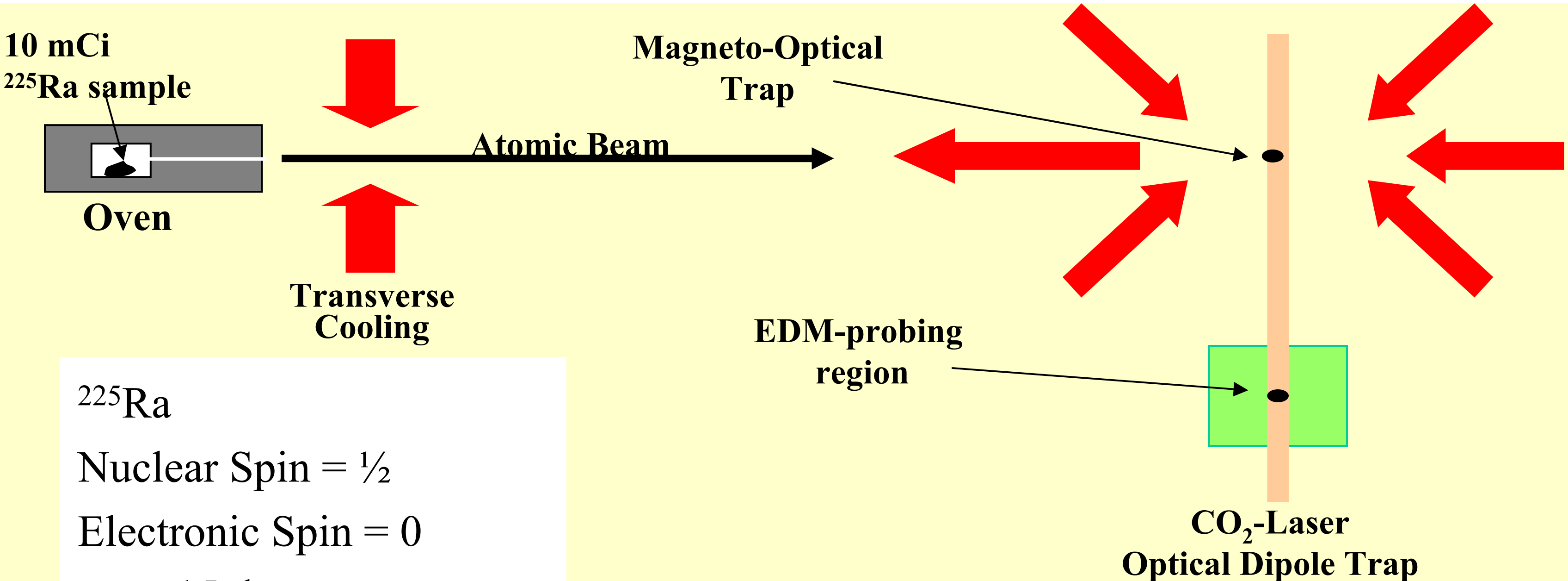


EDM with Trapped Radium Atoms

Irshad Ahmad, Roy J. Holt, Zheng-Tian Lu, Elaine C. Schulte, Physics Division, Argonne National Laboratory

Advantages of an EDM measurement on ^{225}Ra atoms in a trap

- In ^{225}Ra the EDM effect is enhanced by two orders of magnitude due to nuclear quadrupole and octupole deformation.
- Trap allows a long coherence time (~ 300 s).
- Cold atoms result in a negligible "v x E" systematic effect.
- Trap allows the efficient use of the rare and radioactive ^{225}Ra atoms.
- Small sample in an UHV allows a high electric field (> 100 kV/cm).



^{225}Ra

Nuclear Spin = ½

Electronic Spin = 0

$t_{1/2}$ = 15 days

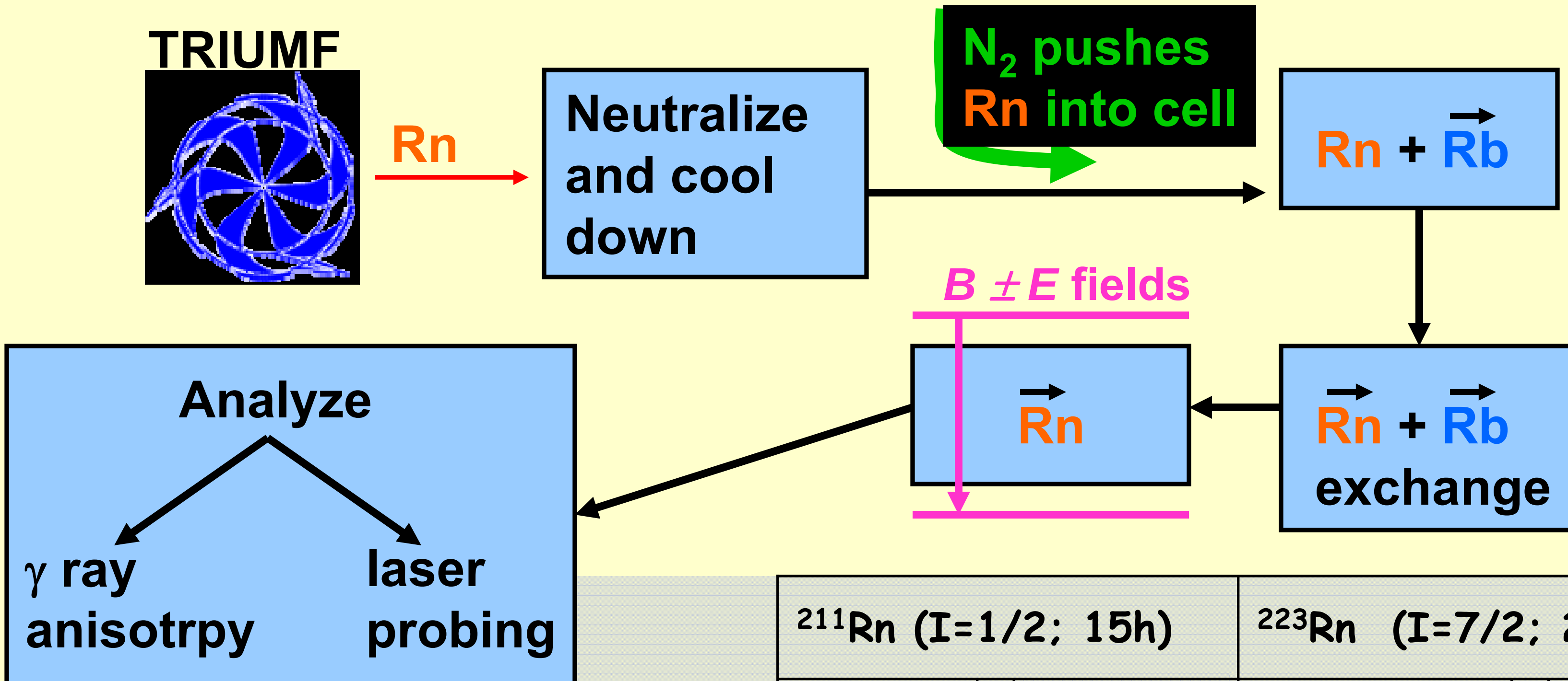
EDM in Rn

Spokesmen: Timothy Chupp[2] and Carl Svensson[1]

Sarah Nuss-Warren[2], Eric Tardiff[2], Kevin Coulter[2], Wolfgang Lorenzon[2], Timothy Chupp[2]

John Behr[4], Matt Pearson[4], Peter Jackson[4], Mike Hayden[3], Carl Svensson[1]

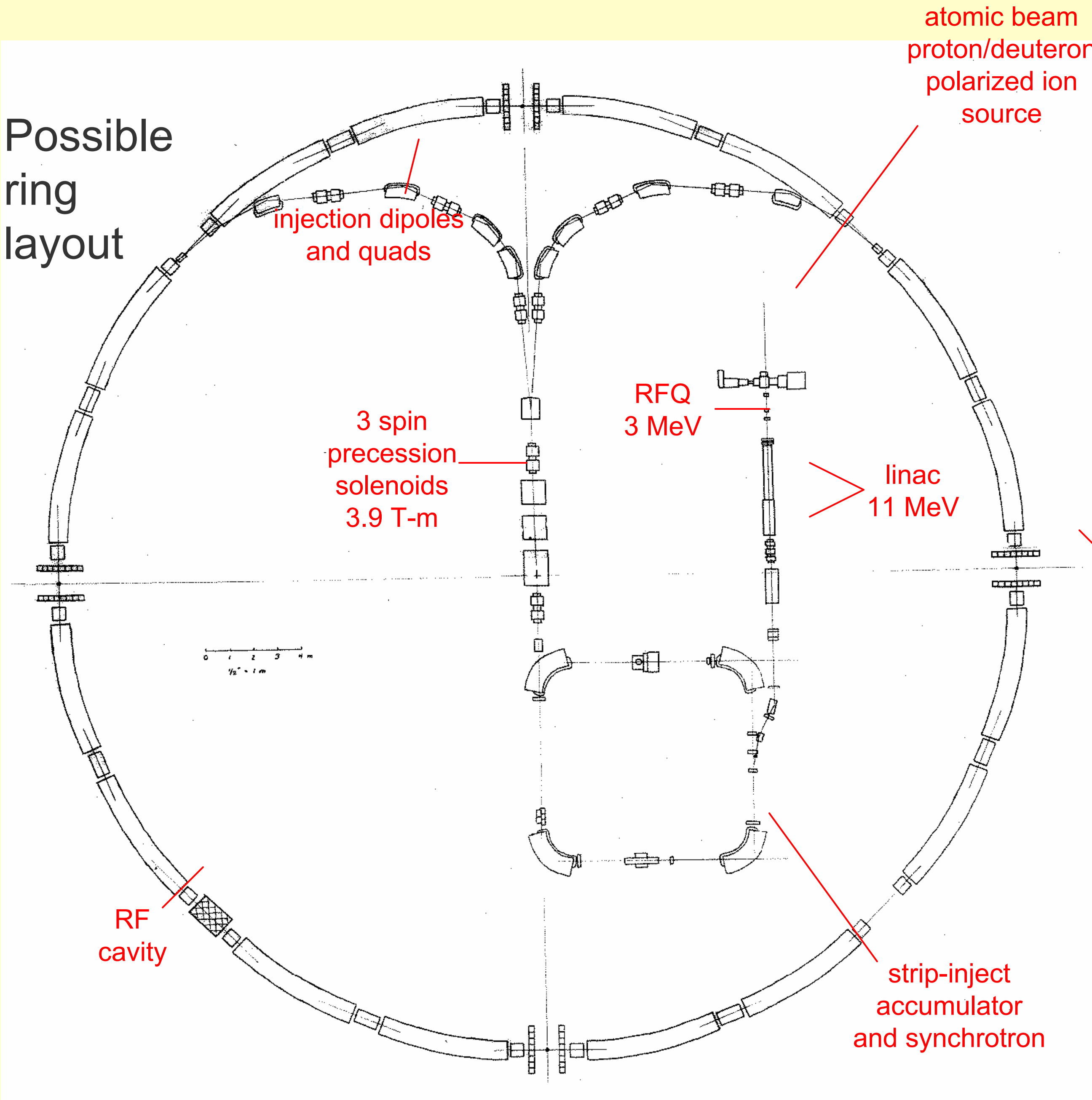
University of Guelph[1], University of Michigan[2], Simon Fraser University[3], TRIUMF[4]



	^{211}Rn (I=1/2; 15h)			^{223}Rn (I=7/2; 23 m)		
	Rate		σ_d (√day)	Rate		σ_d (√day)
TRIUMF	2×10^{9}		6×10^{-29}	1×10^{7}		2×10^{-27}
RIA	1×10^{10}	1	3×10^{-29}	5×10^{8}		1×10^{-28}

Deuteron (and Muon) EDM in Storage Ring

BNL, BU, Cornell, Illinois, Indiana, Massachusetts, Oklahoma & Foreign Institutions



Example for ring:

1. polarized ion source
2. pre-accelerator
3. accumulator
4. accelerator
5. spin preparation
6. injection
7. EDM ring

Ring Properties:

E = 3.5 MV/m
B = 2.1 kG
T(d) = 126 MeV
p = 0.7 GeV/c
β = 0.35
γ = 1.07
dipole radius = 13.3 m

Neutron EDM Experiments

- Most recent published result
  - (from ILL)
  - Experiment limited by new systematic effect "discovered" during measurement
- Future experiments
  - 3xILL, PSI, SNS, TRIUMF(?), NIST(?)

ILL-Grenoble neutron EDM Experiment

Harris et al. Phys. Rev. Lett. 82, 904 (1999)

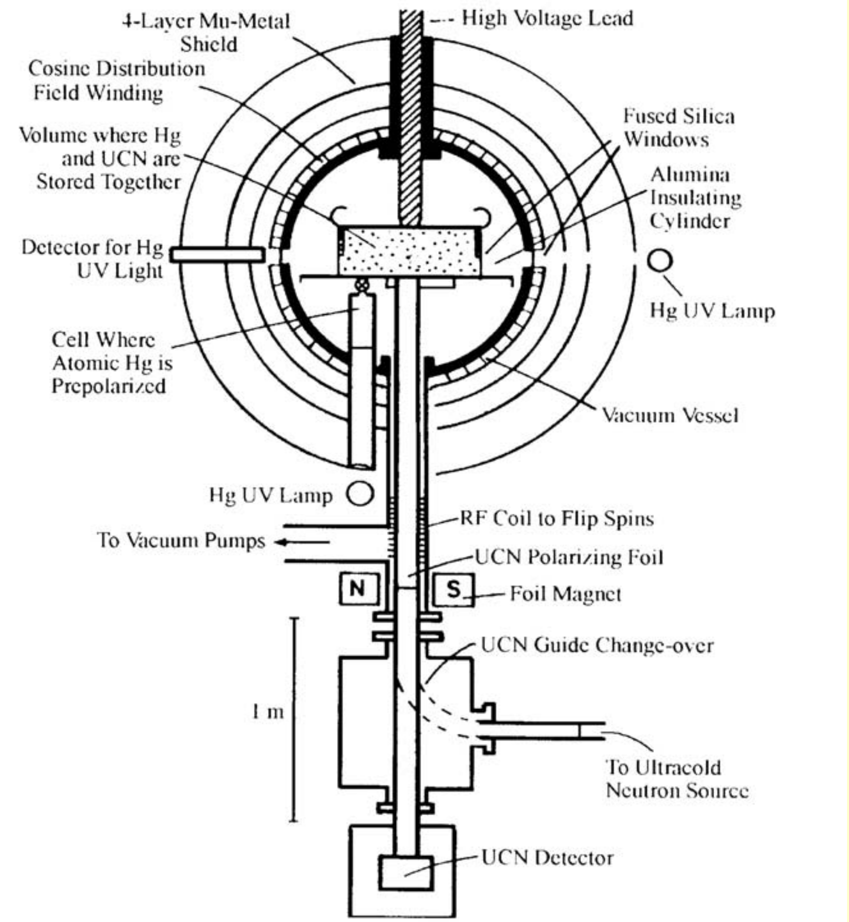
Baker et al. Phys. Rev. Lett. 97, 131801 (2006)

Trapped Ultra-Cold Neutrons (UCN) with N_{UCN} = 0.5 UCN/cc

|E| = 5 - 10 kV/cm

100 sec storage time

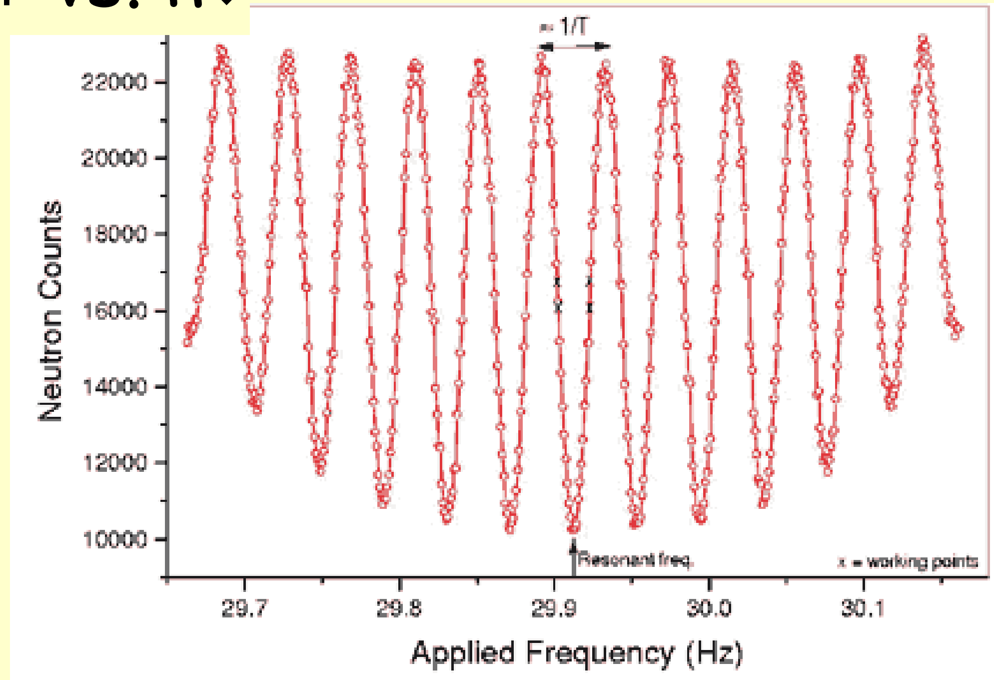
$\sigma_d = 3 \times 10^{-26}$ e cm



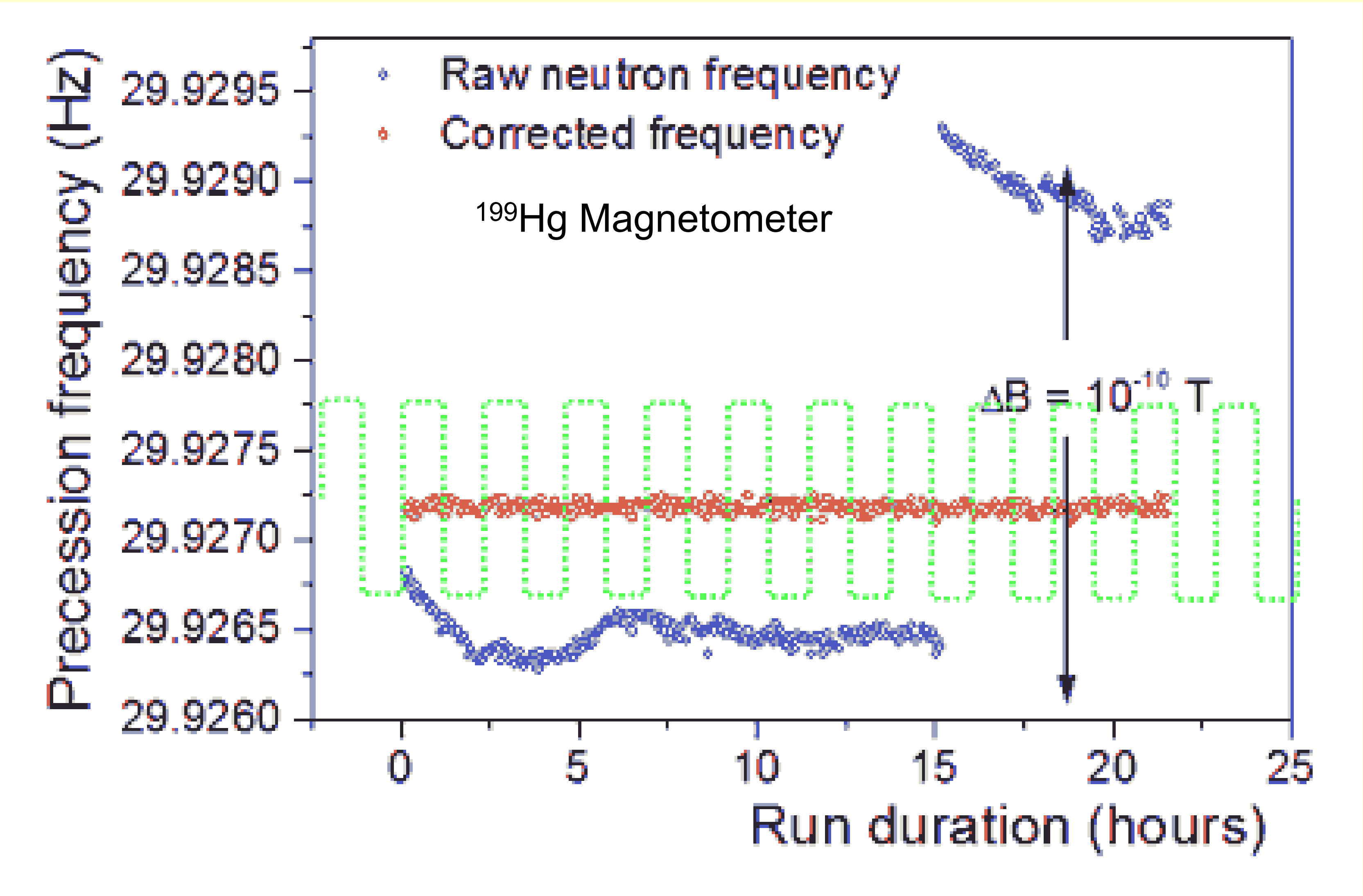
Schematic of the ILL UCN EDM experiment incorporating a ^{199}Hg comagnetometer

Measurement of frequency difference

- ILL uses Ramsey separated-oscillatory field technique
  - Inject n
  - Rotate and precess for Δt
  - Spin rotates by $\Delta\omega\Delta t$ (assuming << 1)
  - Measure how many n↑ vs. n↓



Careful magnetometry is essential !

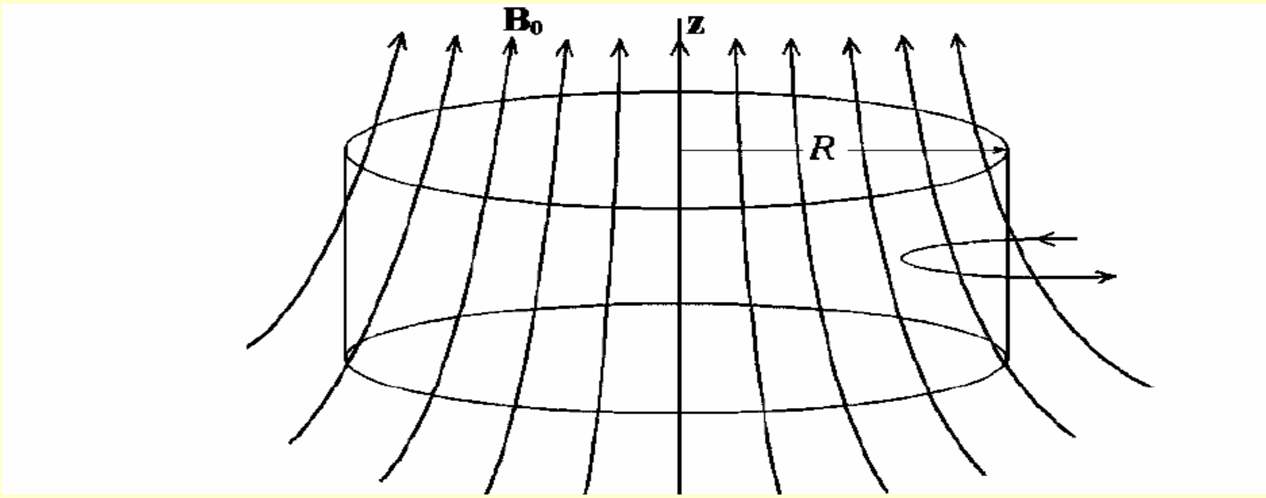


Experiment limited by systematic effect "Geometric Phase"

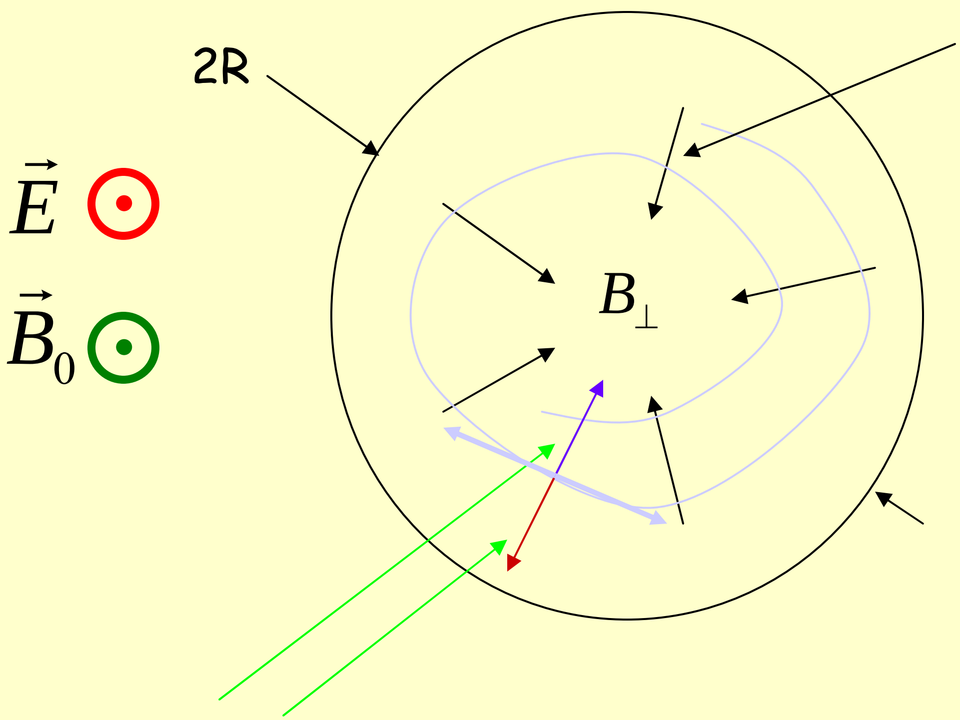
- For slow particles:
  - Path-dependent phase
  - E.g. Parallel transport of vector on sphere
  - In Quantum Mechanics often called Berry's phase
  - Actually a *relativistic* effect!

False EDM from Geometric phase

- Commins Am J Phys 59, 1077 (91)
- Pendlebury et al PRA 70 032102 (04)
- Lamoreaux and Golub PRA 71 032104 (05)
- Motional (vxE) B-fields can add to radial B fields perpendicular to B_0 **(These result e.g. from dB_0/dz) giving a false EDM**



Geometric phase with $B_E = v \times E$ field



Radial B-field due to gradient

v x E field
changes sign with
neutron direction

- **Motion in B – field shifts the precession frequency - ω_0 :**

$$\Delta\omega \cong \frac{\omega_\perp^2\left[1 \pm (2\vec{v}_n \times \vec{E})/cB_\perp\right]}{2\left(\omega_0 \mp v_n/R\right)}$$

- **$\pm,\mp$ due to different trajectories**
- **Does NOT average to 0**
- **Is proportional to $\vec{E}$**

$\therefore$

- **Gives :**

$$d_n \approx \frac{v_\perp^2\left|\frac{\partial B}{\partial z}\right|}{B_0^2}$$

Observed in ILL Experiment

ω depends on E-field
For neutrons and
magnetomers

ILL exp. oriented vertically!!

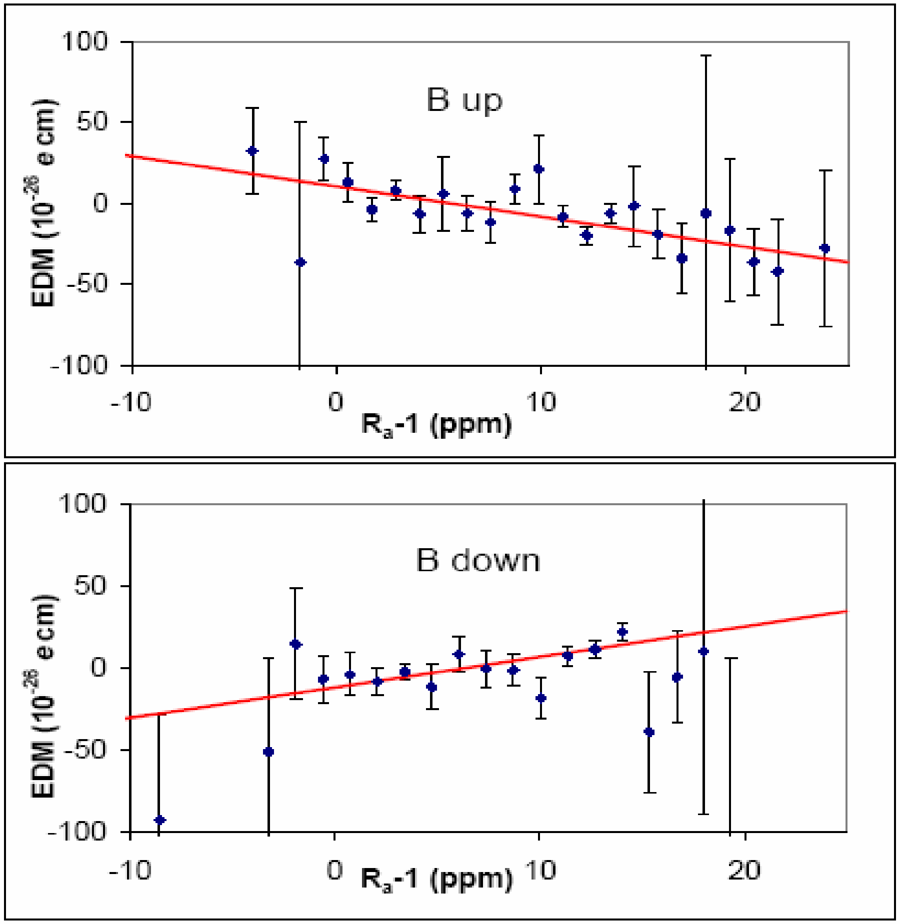


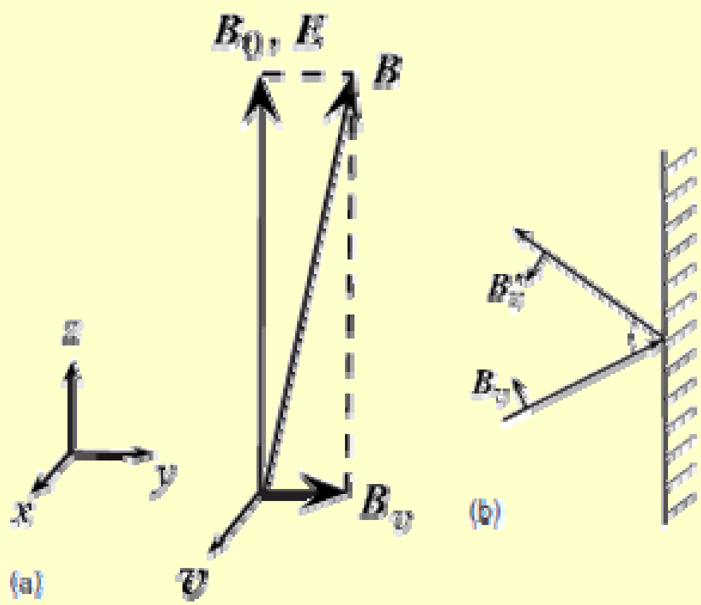
FIG. 2: (Color online) Measured EDM as a function of the relative frequency shift of neutrons and mercury. For clarity, data are binned.

Related Relativistic Issue

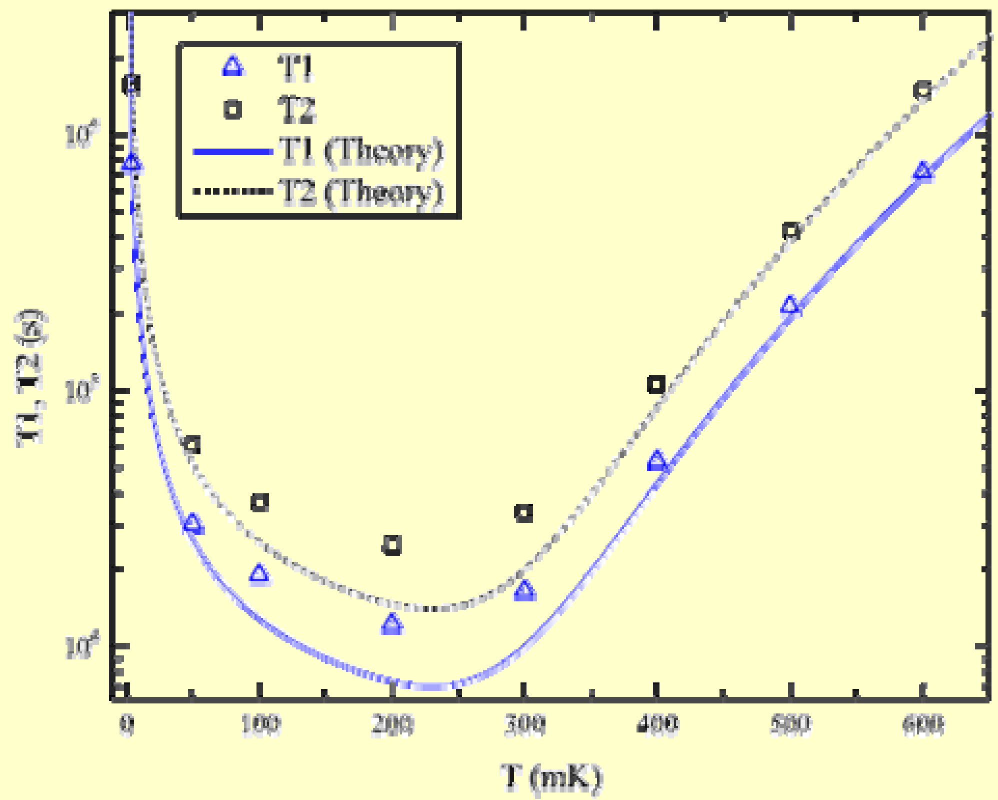
PHYSICAL REVIEW A 78, 023401 (2008)

Motional spin relaxation in large electric fields

Riccardo Schmid, B. Plaster, and B. W. Filippone
California Institute of Technology, Pasadena, California 91125, USA
(Received 16 May 2008; published 1 August 2008)



For Polarized ^{3}He



To further improve search for neutron EDM, need new techniques

- Enhance number of stored neutrons
- Increase Electric field
- Minimize key systematic effects

Active worldwide effort to improve neutron EDM sensitivity

- ILL – Grenoble
  - CryoEDM at ILL (superfluid ^4He)
  - Multiple cell
  - Crystal diffraction of neutron beam
- Paul-Scherrer Institute (PSI) – Switzerland
  - Large Solid D_2 UCN source
- TRIUMF (possible continuation at JPARC
  - Superfluid ^4He source
- Spallation Neutron Source (SNS) @ Oak Ridge National Lab
  - Superfluid ^4He

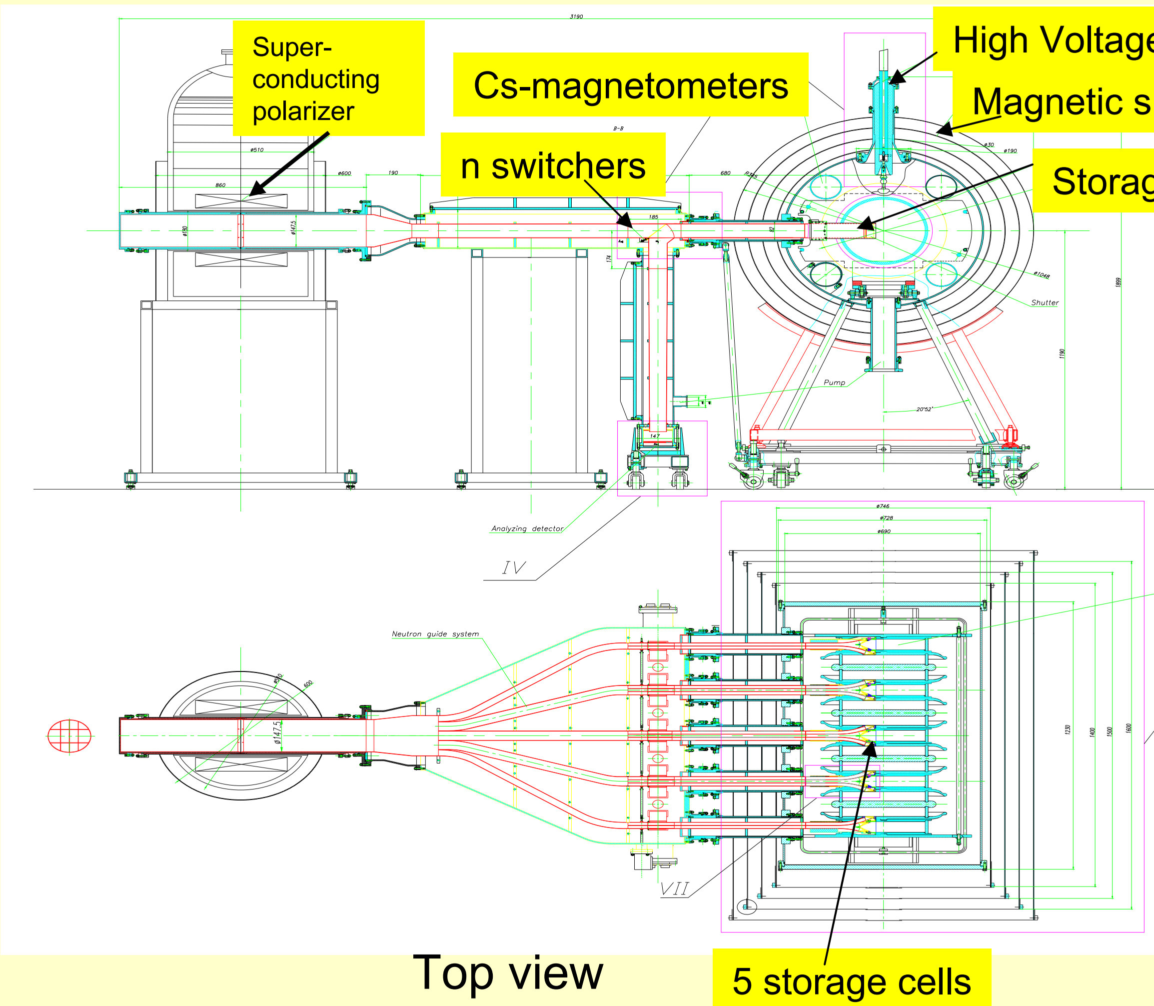
Example of future Neutron EDM Sensitivity

	EDM @ ILL	EDM @ SNS
N_{UCN}	1.3×10^4	4×10^5
$\lvert\vec{E}\rvert$	10 kV/cm	50 kV/cm
T_m	130 s	500 s
m (cycles/day)	270	30
σ_d (e-cm)/day	3×10^{-25}	8×10^{-27}

$$\sigma_d \cong \frac{\hbar}{\lvert\vec{E}\rvert T_m \sqrt{m N_{UCN}}}$$

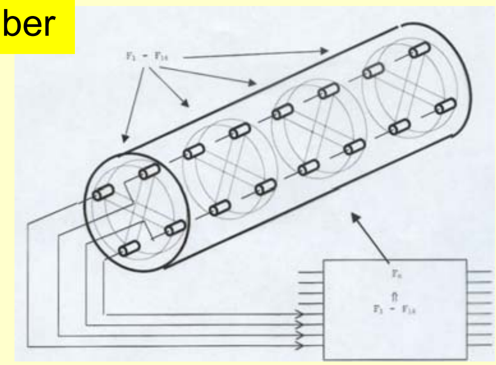
Scheme of PNPI-ILL multi-chamber EDM spectrometer

Side view



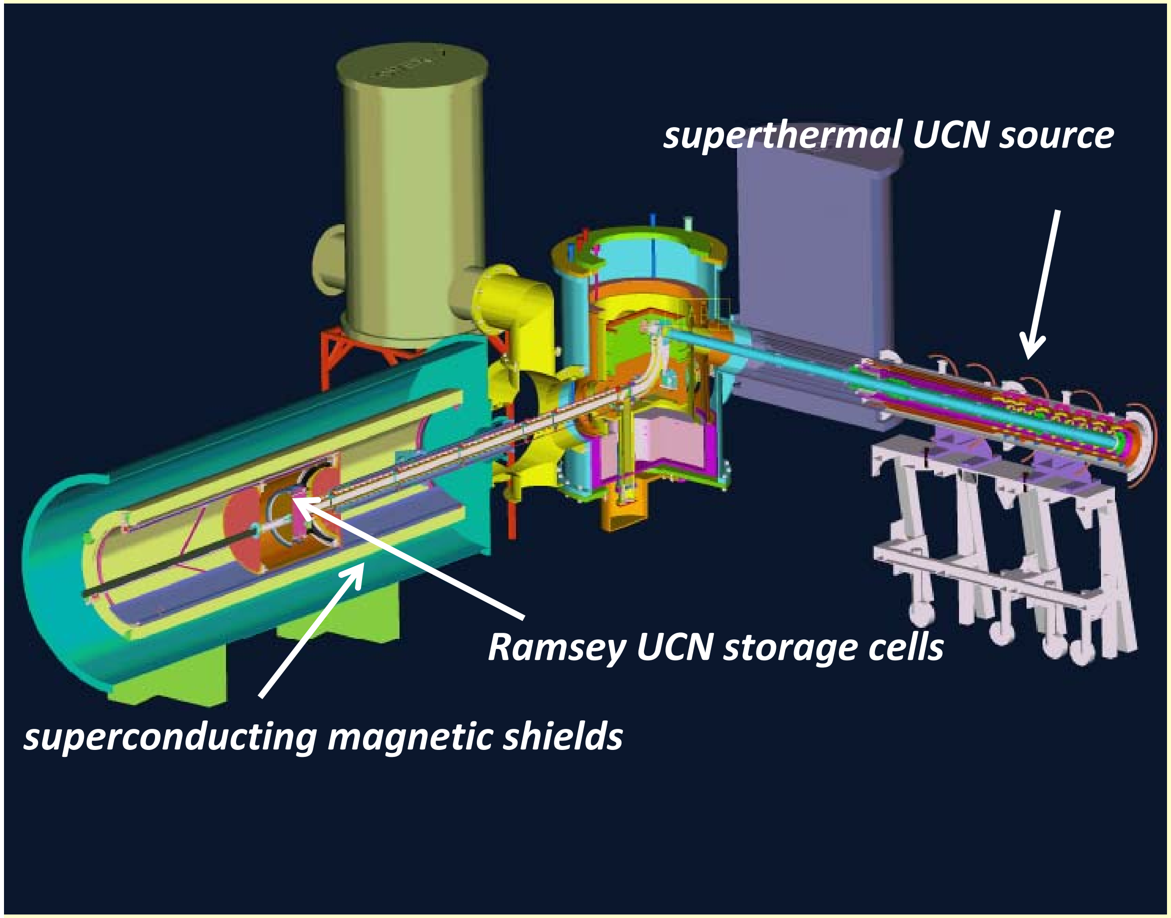
Top view

System of 16 Cs-magnetometers



Could move experiment to Solid D_2 UCN source at PNPI

CryoEDM @ ILL

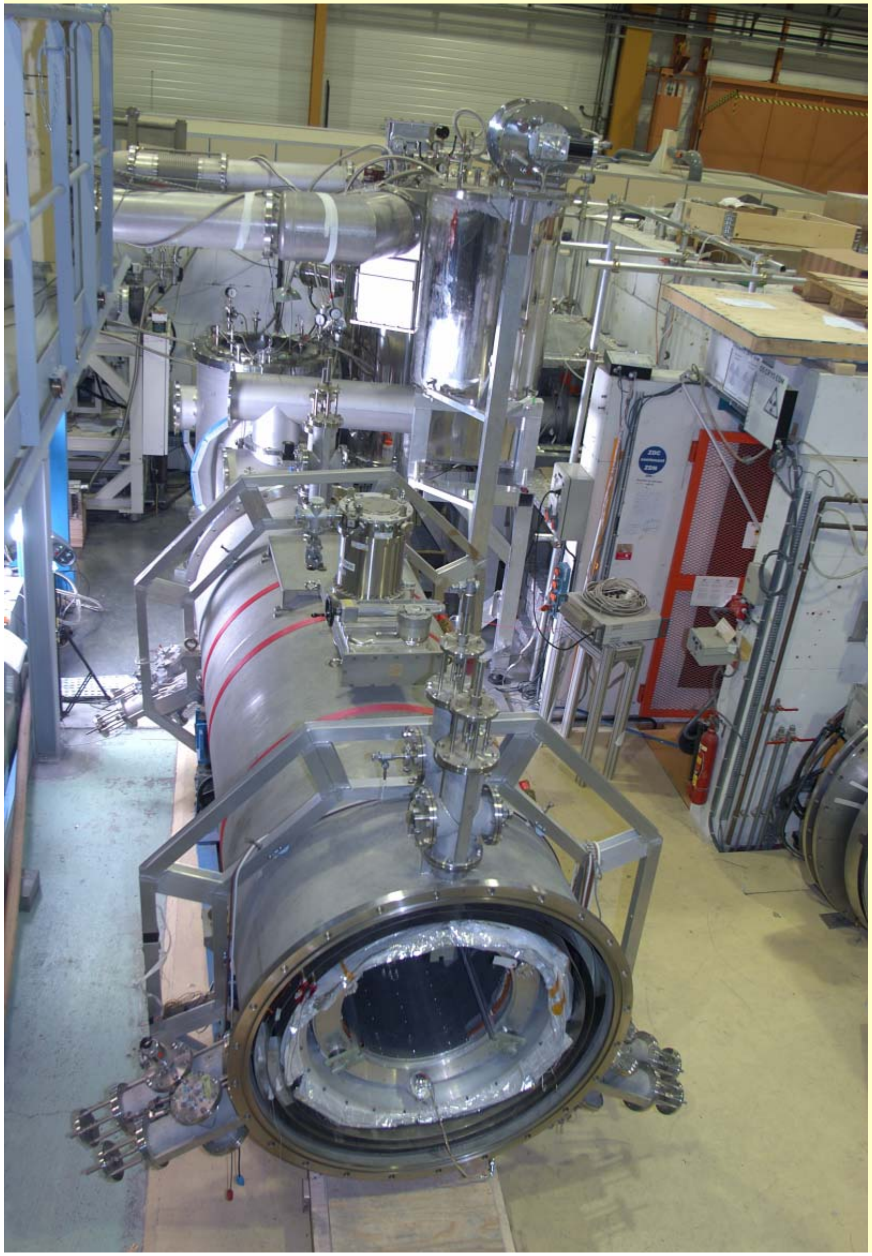


Rutherford Appleton Laboratory
University of Sussex
University of Oxford
Institut Laue Langevin
University of Kure (Japan)

whole experiment in superfluid He at 0.5 K

- production of UCN
- storage & Larmor precession of UCN
- SQUID magnetometry
- detection of UCN

CryoEDM



- Completed constructed, beginning commissioning/start of exploitation
- still requires tuning to deliver a competitive EDM measurement
- apparatus in a position to make an EDM measurement first half 2009 and deliver improved limits

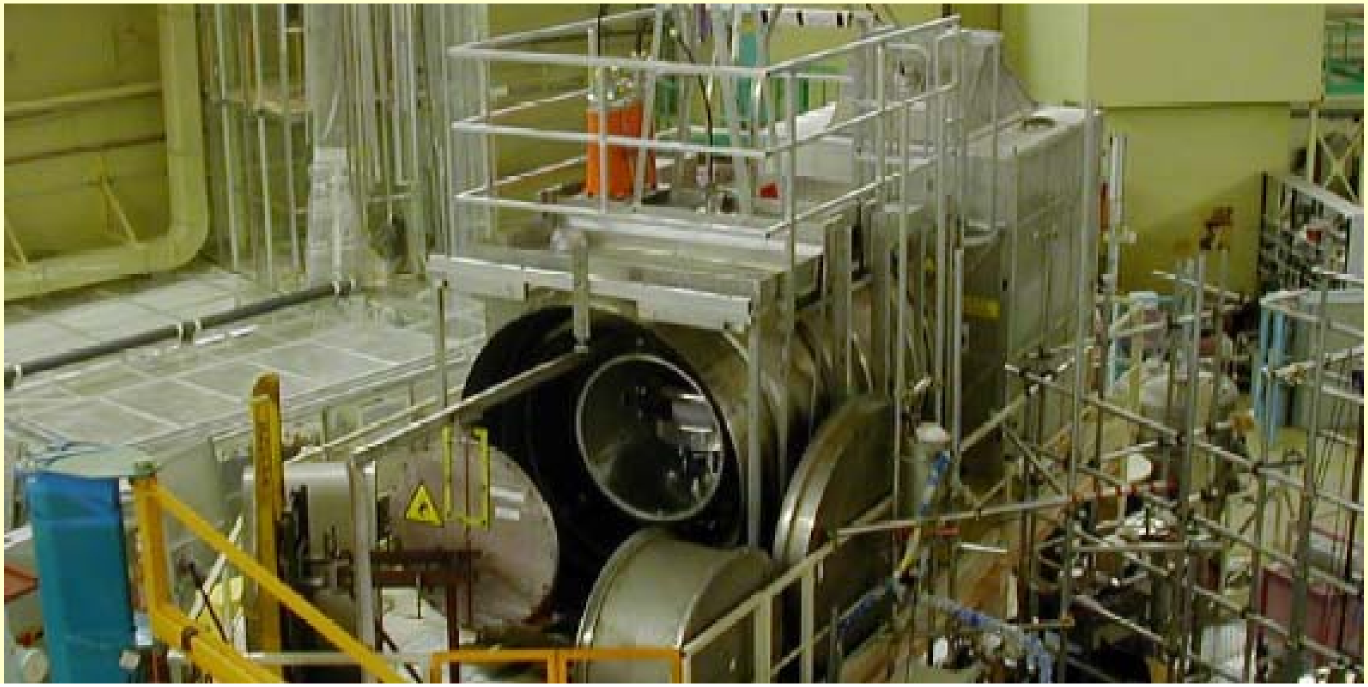
On H53 beam: sensitivity ~ 10^{-27} *e* cm
On new beam: sensitivity ~ 10^{-28} *e* cm

Neutron EDM at PSI

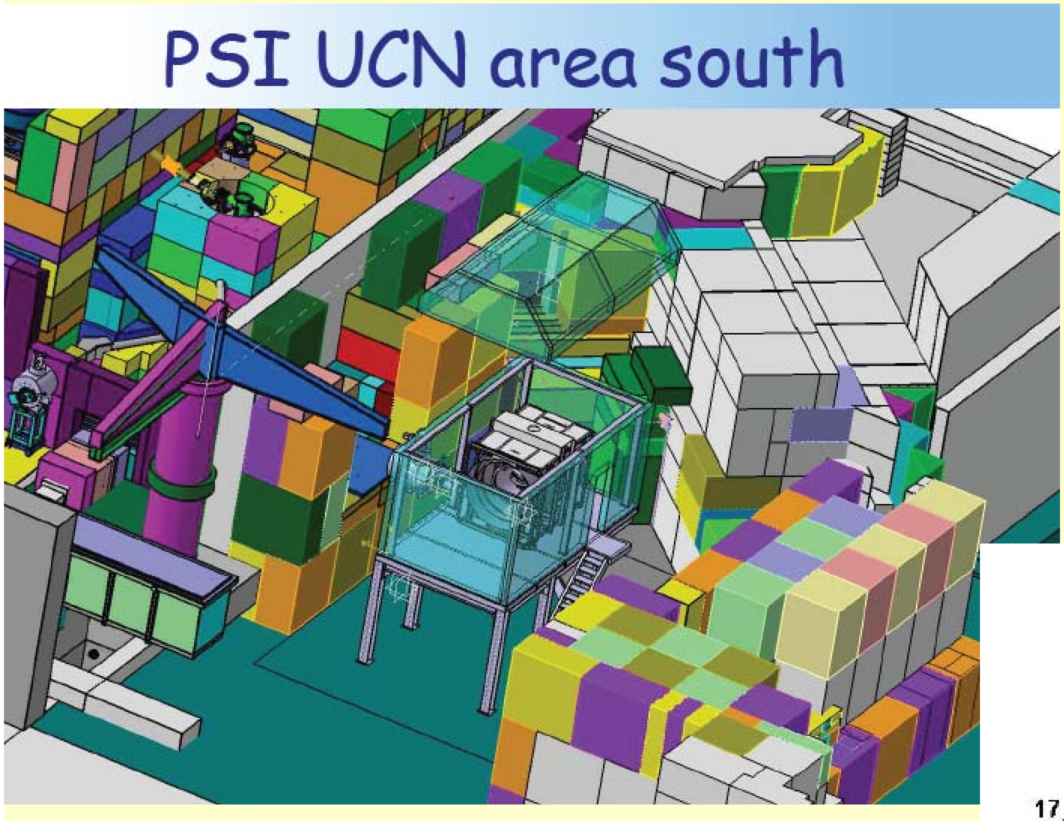
Paul Scherrer Institut

Using new PSI UCN Facility using Solid D_2

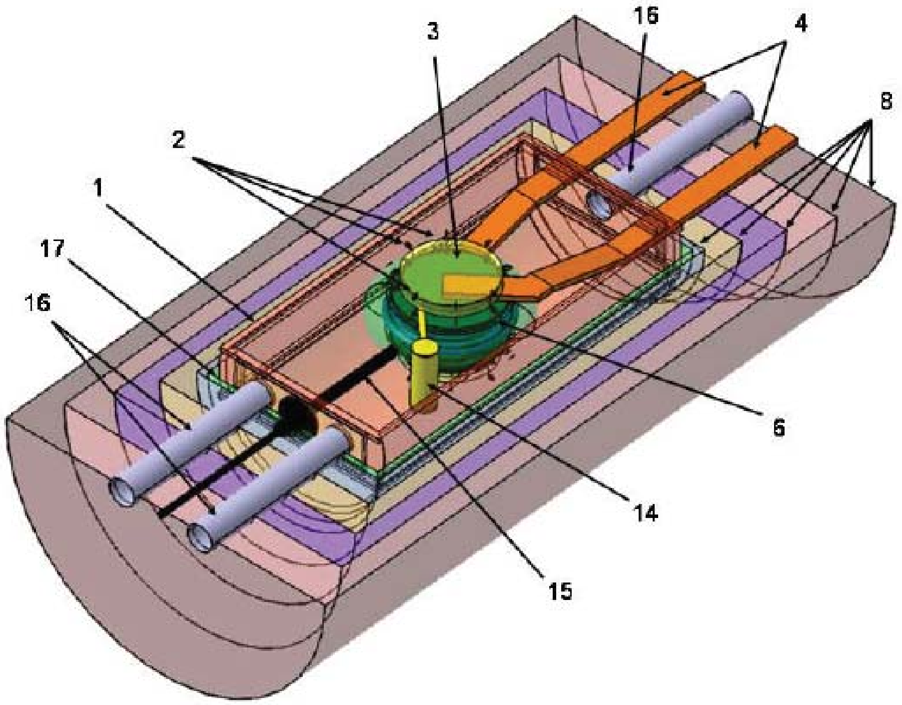
(Based on Los Alamos-et al Concept for UCNA)



Neutron EDM at PSI



- Initial data will use original apparatus from ILL with magnetic upgrades
- New apparatus being designed for higher sensitivity



Crystal-diffraction neutron EDM project @ ILL

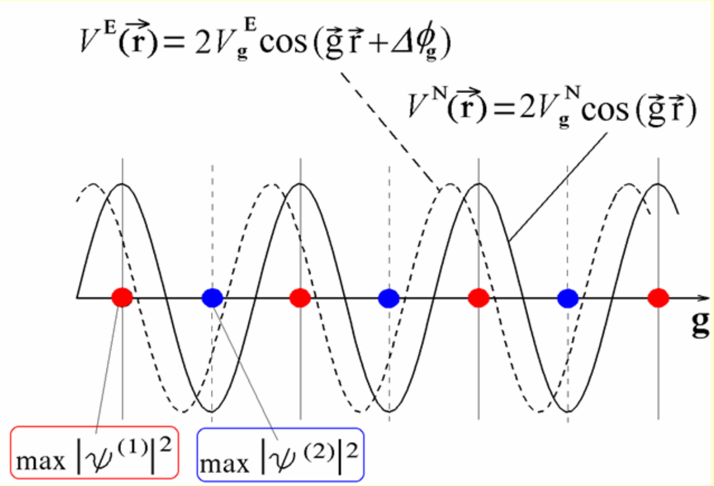
Sensitivity $\sigma^{-1} \sim E\tau\sqrt{N}$

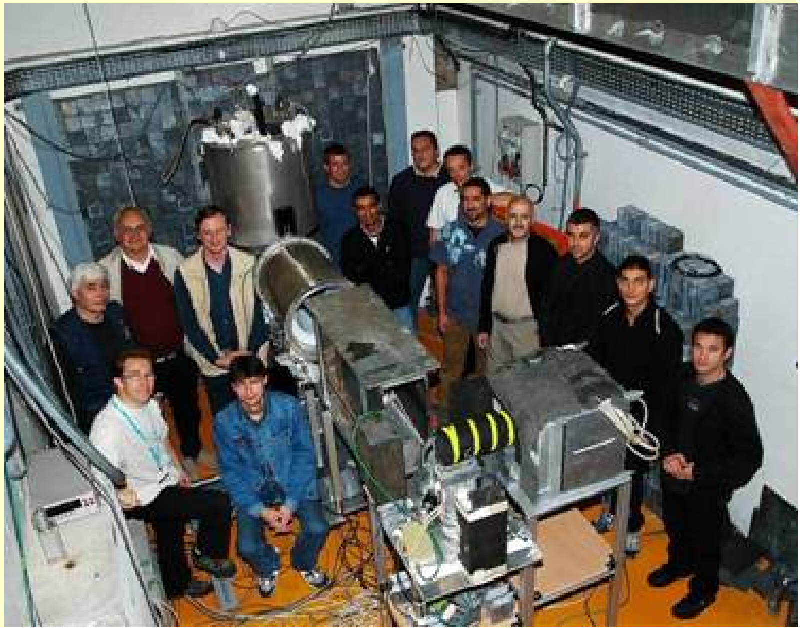
Max for UCN method	Max for Crystal-diffraction
E ~ 10^3 V/cm	E ~ 10^9 V/cm
τ ~ 1000s (time of life)	τ ~ 10^{-2}s (time of absorption)
Eτ ~ 10^7(V·s)/cm	**Eτ ~ 10^7(V·s)/cm**

PNPI
V.V. Fedorov,
E.G. Lapin,
I.A. Kusnetsov,
S.Yu. Semenikhin,
V.V. Voronin
Yu.P. Braginets
ILL
M. Jentschel,
E. Lelievre-Berna,
V. Nesvizhevsky,
A. Petoukhov,
T. Soldner

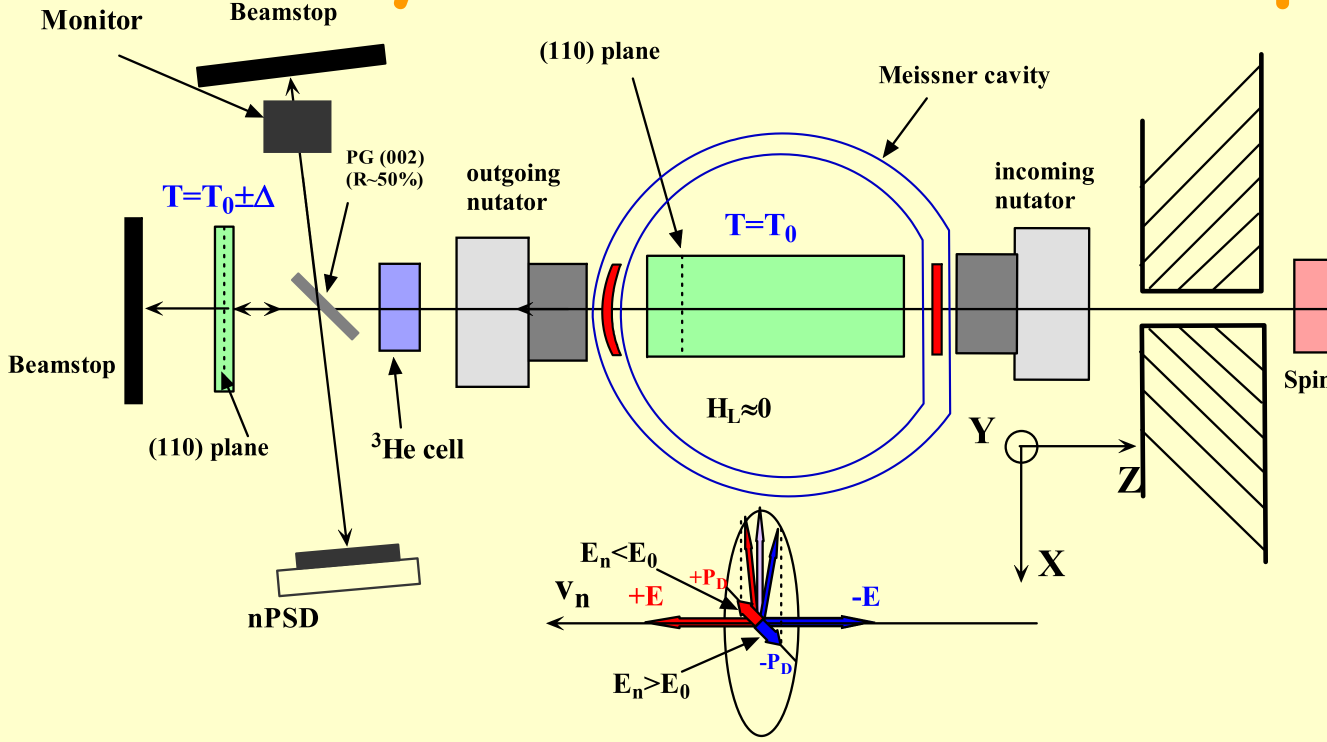
In the non-centrosymmetric crystal

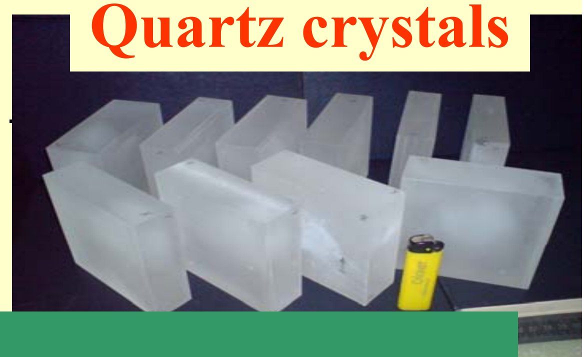
neutron is moving under strong electric field if the electric planes deviate from the nuclear ones spatially, because of the neutron concetration on (or between) the nuclear planes





Layout of the ILL experiment





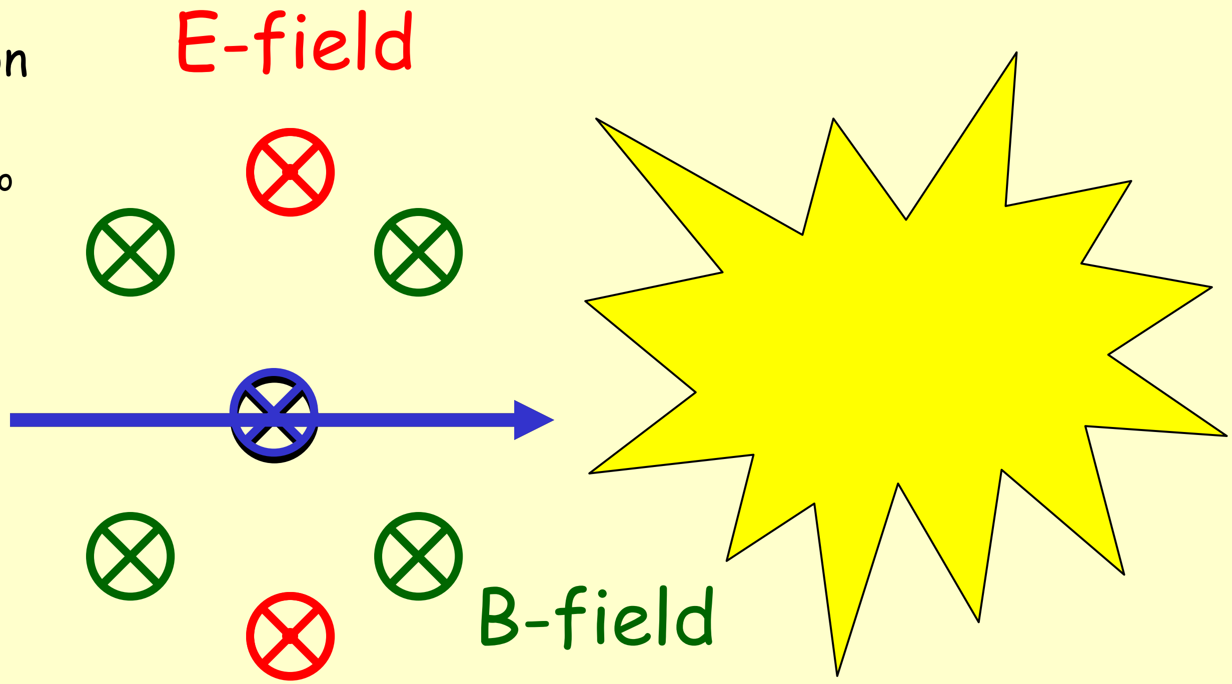
NOTE:

Centro-symmetric experiment being studied for NIST

New Technique for n-EDM

1. Inject polarized neutron & polarized ^3He
2. Rotate both spins by 90^o
3. Measure $n+^3He$ capture vs. time

   (note: $\sigma_{\downarrow\uparrow} >> \sigma_{\uparrow\uparrow}$)
4. Flip E-field direction



^3He functions as "co-magnetometer"

New Technique for n-EDM:

R. Golub & S. K. Lamoreaux, Phys. Rep. 237, 1 (1994)

- Use Superthermal (non-equilibrium) system to produce UCN
  - Superfluid ^{4}He can yield ~1000 more UCN than conventional UCN source
- Higher Electric fields in ^{4}He
  - Breakdown voltage may be 10x vacuum breakdown
- ^{3}He comagnetometer measures B-field at same location as neutrons
  - *Very* small amount of ^{3}He in ^{4}He
  - Use SQUIDs to measure ^{3}He precession – calibrates B-field since $\omega_3 \propto |\vec{B}|$
- $\vec{n} + {}^3\vec{He} \Rightarrow t + p$ has $\sigma_{\uparrow\downarrow} >> \sigma_{\uparrow\uparrow}$
  - Detect capture via scintillation of ^{4}He
    - UV photons converted to visible in tetraphenyl butadiene - TPB)
    - Measures difference of ω_n and ω_3
- "Dressed" spin technique suppresses sensitivity to fluctuations in B-field
  - Additional RF field can match ^{3}He and neutron precession frequency

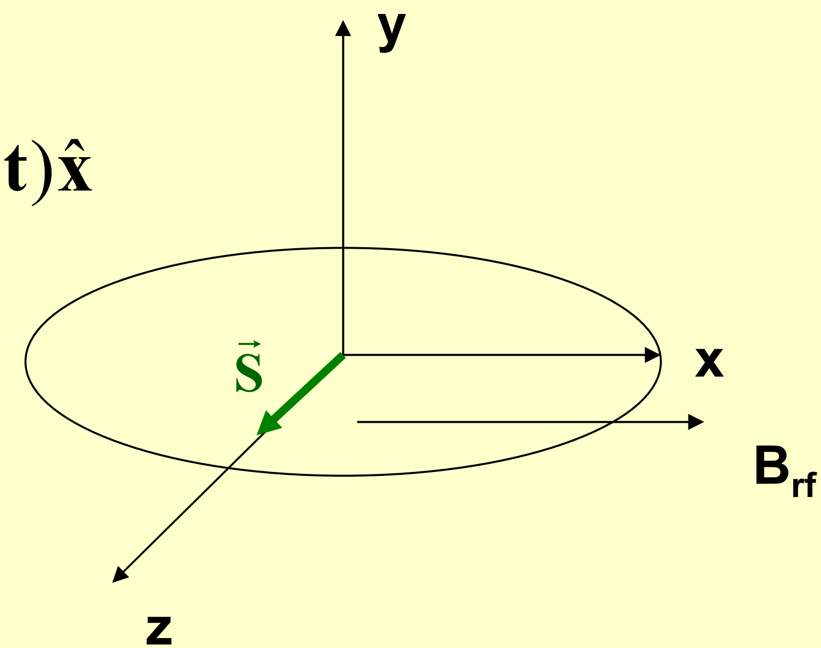
“Dressed Spins”

- By applying a strong non-resonant RF field, the effective precession frequencies can be modified or “dressed”

Classical spin in AC B-field

Consider

$$\vec{\mathbf{B}} = \mathbf{B}_{rf}\sin(\omega_{rf}\mathbf{t})\hat{\mathbf{x}}$$



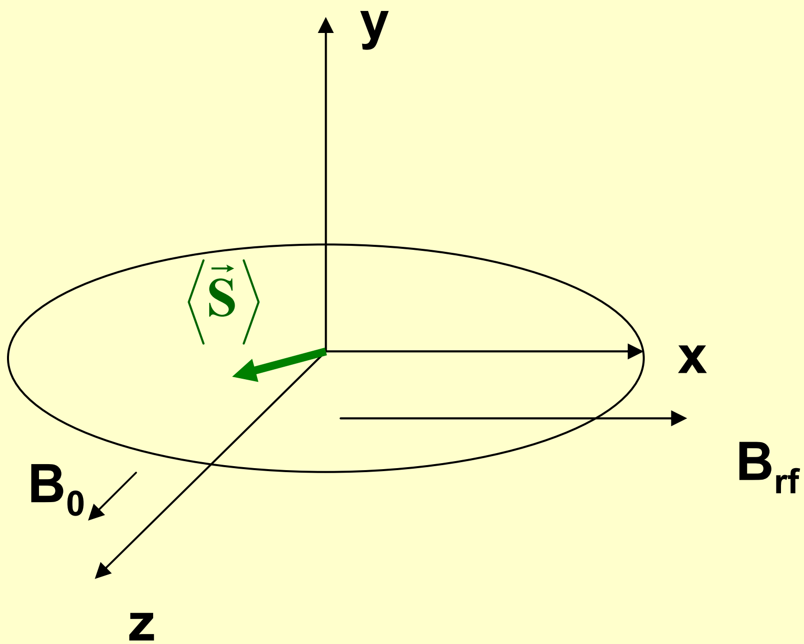
Solution:

$$\mathbf{S}_z = \cos\left[\left(\frac{\gamma\mathbf{B}_{rf}}{\omega_{rf}}\right)\sin(\omega_{rf}\mathbf{t})\right] \quad ; \ \&\ \text{averaging over time:}$$

$$\langle \mathbf{S}_z \rangle = \frac{\omega_{rf}}{2\pi}\int_0^T \mathbf{S}_z\mathbf{dt} \equiv \frac{1}{2\pi}\int_0^{2\pi}\cos\left[\frac{\gamma\mathbf{B}_{rf}}{\omega_{rf}}\sin(\theta)\right]\mathbf{d}\theta \equiv \mathbf{J}_0\left(\frac{\gamma\mathbf{B}_{rf}}{\omega_{rf}}\right) = \mathbf{J}_0(\mathbf{x})$$

Classical spin in AC B-field

- Now apply a very small B-field along z = B_0



- Reduced spin $\langle S_z \rangle = J_0(x)$ begins to precess about z-axis with reduced frequency ~ $\gamma B_0 J_0(x)$

Classical spin in AC B-field

- For particular values of the dressing field, the neutron and ^{3}He precession frequencies are equal

$$\gamma_3 \mathbf{J}_0\left(\frac{\gamma_3 \mathbf{B}_{\mathbf{rf}}}{\omega_{\mathbf{rf}}}\right) = \gamma_{\mathbf{n}} \mathbf{J}_0\left(\frac{\gamma_{\mathbf{n}} \mathbf{B}_{\mathbf{rf}}}{\omega_{\mathbf{rf}}}\right)$$

- Can modulate the dressing field around a relative precession of zero.
  - Reducing effect of external B-fields
  - Measure this parameter vs. direction of E-field

- Challenging technical issues must be overcome
  - Uniformity of the RF field must be better than 0.1%
  - Eddy currents will heat conductors

The SNS nEDM Collaboration

Expertise:
Nuclear
Atomic
Condensed Matter
Low Temperature
Polarized ^{3}He
UCN

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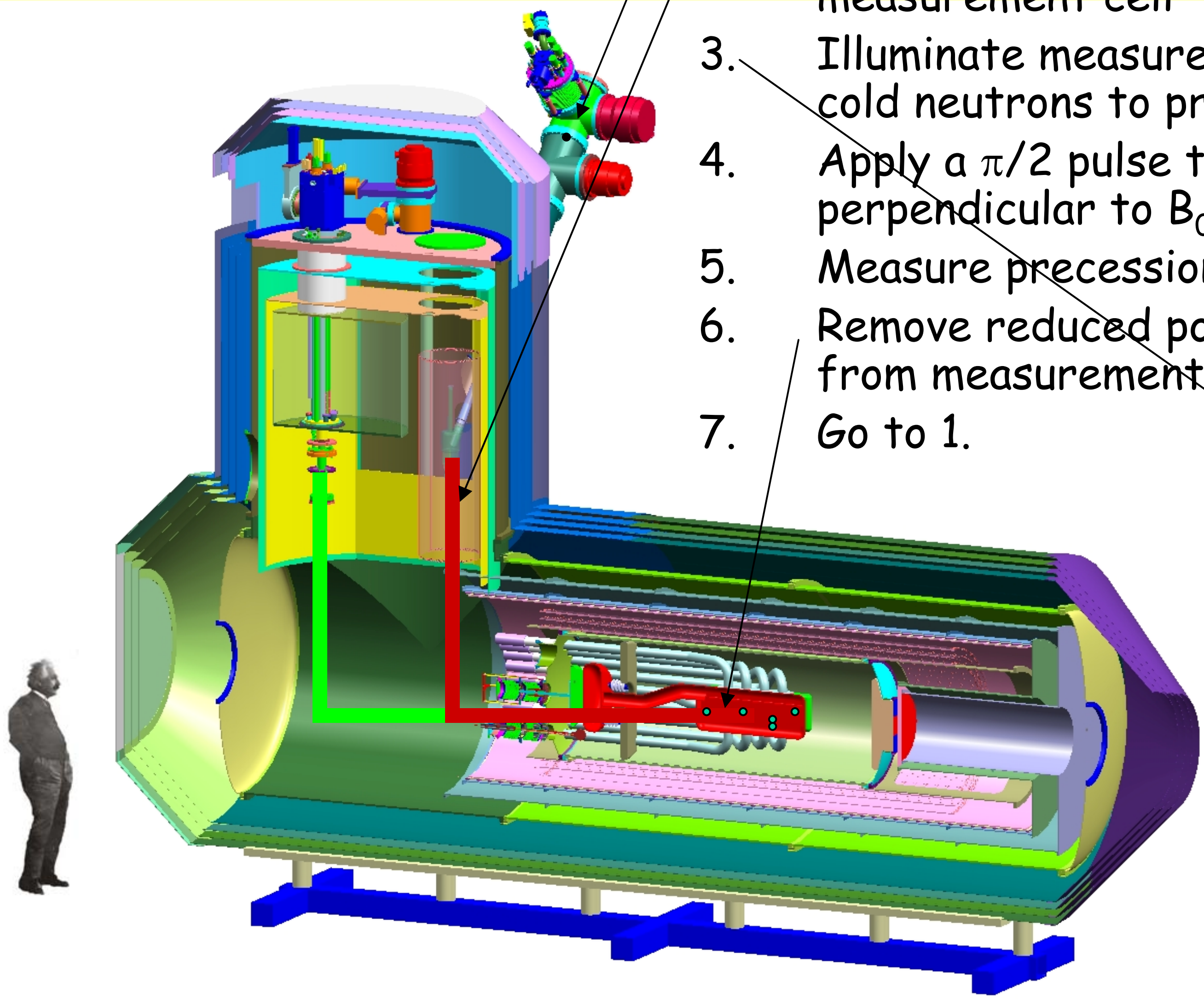
SNS nEDM Measurement cycle

1. Load collection volume with polarized ^{3}He atoms
2. Transfer polarized ^{3}He atoms into the 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. Go to 1.



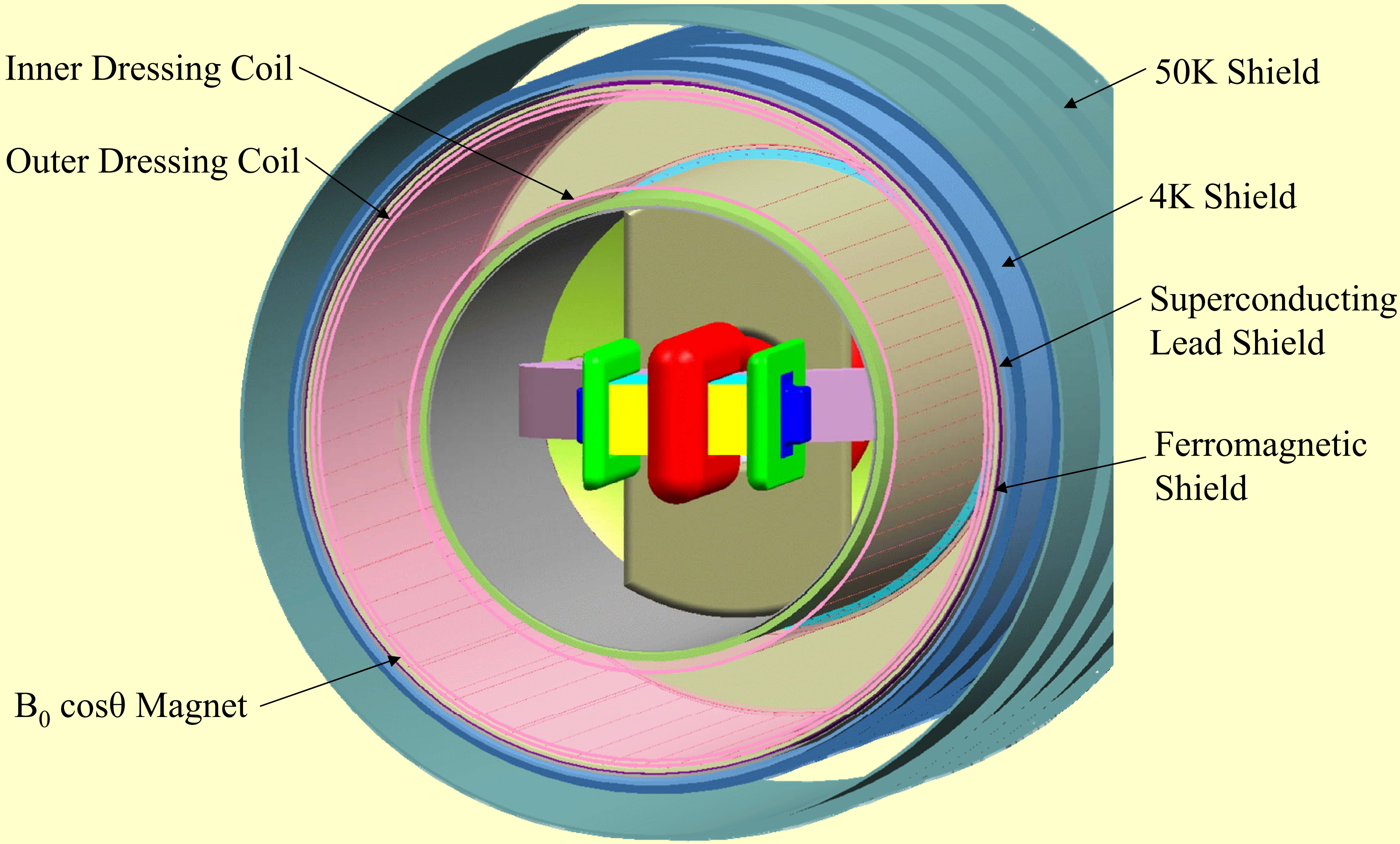
Systematic Effects in EDM

- Variation of B-field
  - Comagnetometer cancels B-field variations
- Leakage currents from Electric Field
  - These produce B-fields that change with E-field (must be less than picoAmps)
- Gravitational offset of n and ^{3}He (~ 10^{-29} e-cm)
- $\vec{v} \times \vec{E}$ effects are the largest sources of systematic error in present ILL exp.
  - $\vec{B}_E = \vec{v} \times \vec{E} \rightarrow$ changes $\vec{\mu}$ precession frequency
  - Geometric phase due to $\vec{B}$ gradients

Systematic Controls in new EDM experiment

- Highly uniform E and B fields
  - Cosθ coil in Ferromagnetic shield
  - Kerr effect measurement of E-field
- Two cells with opposite E-field
- Ability to vary influence of B_0 field
  - via "dressed spins" (atomic physics trick)
- Control of central temperature
  - Can vary ^{3}He diffusion

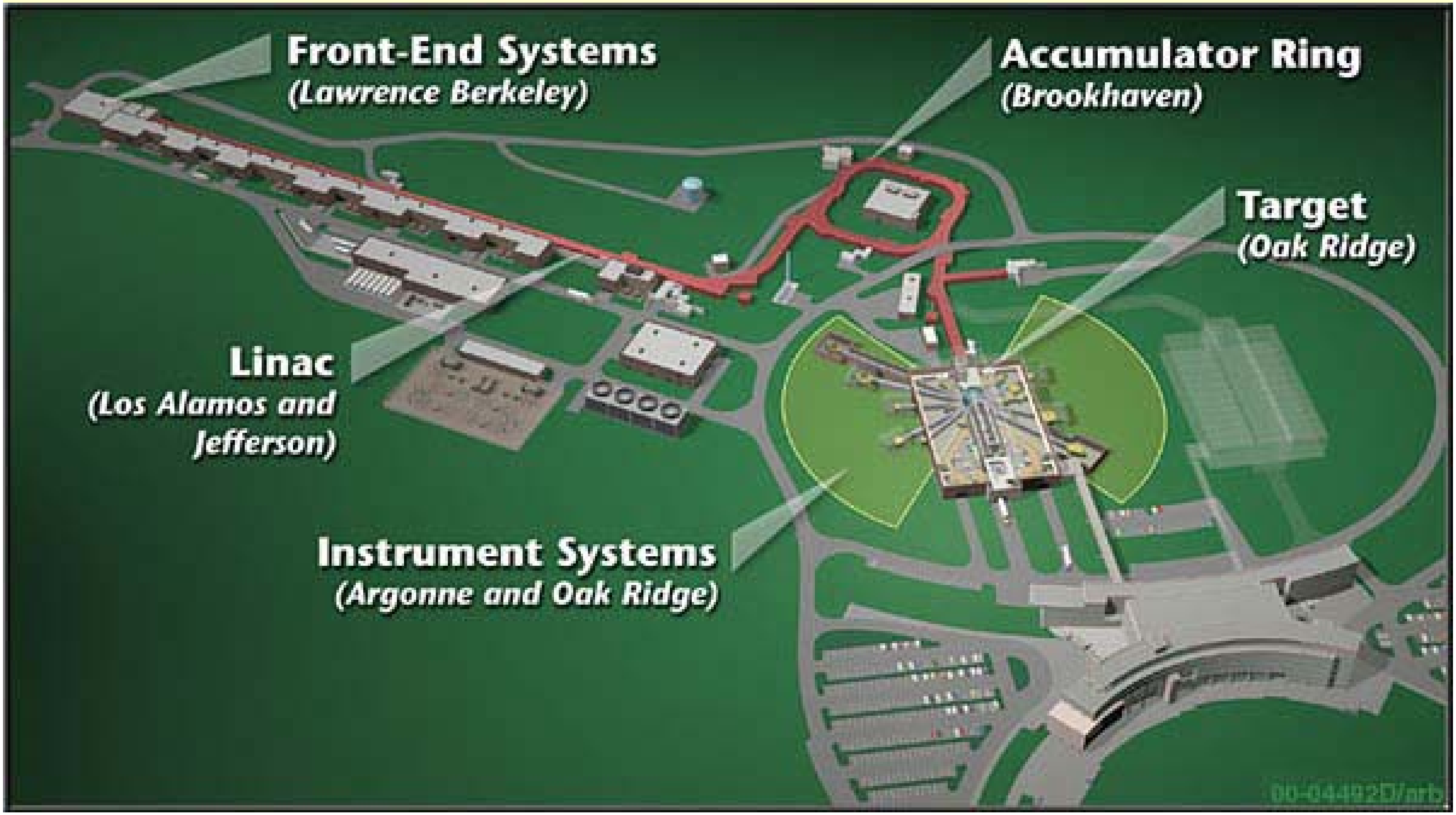
Measurement Cell



Neutrons come from Oak Ridge National Laboratory

Spallation Neutron Source (SNS) at ORNL

1 GeV proton beam with 1.4 MW on spallation target



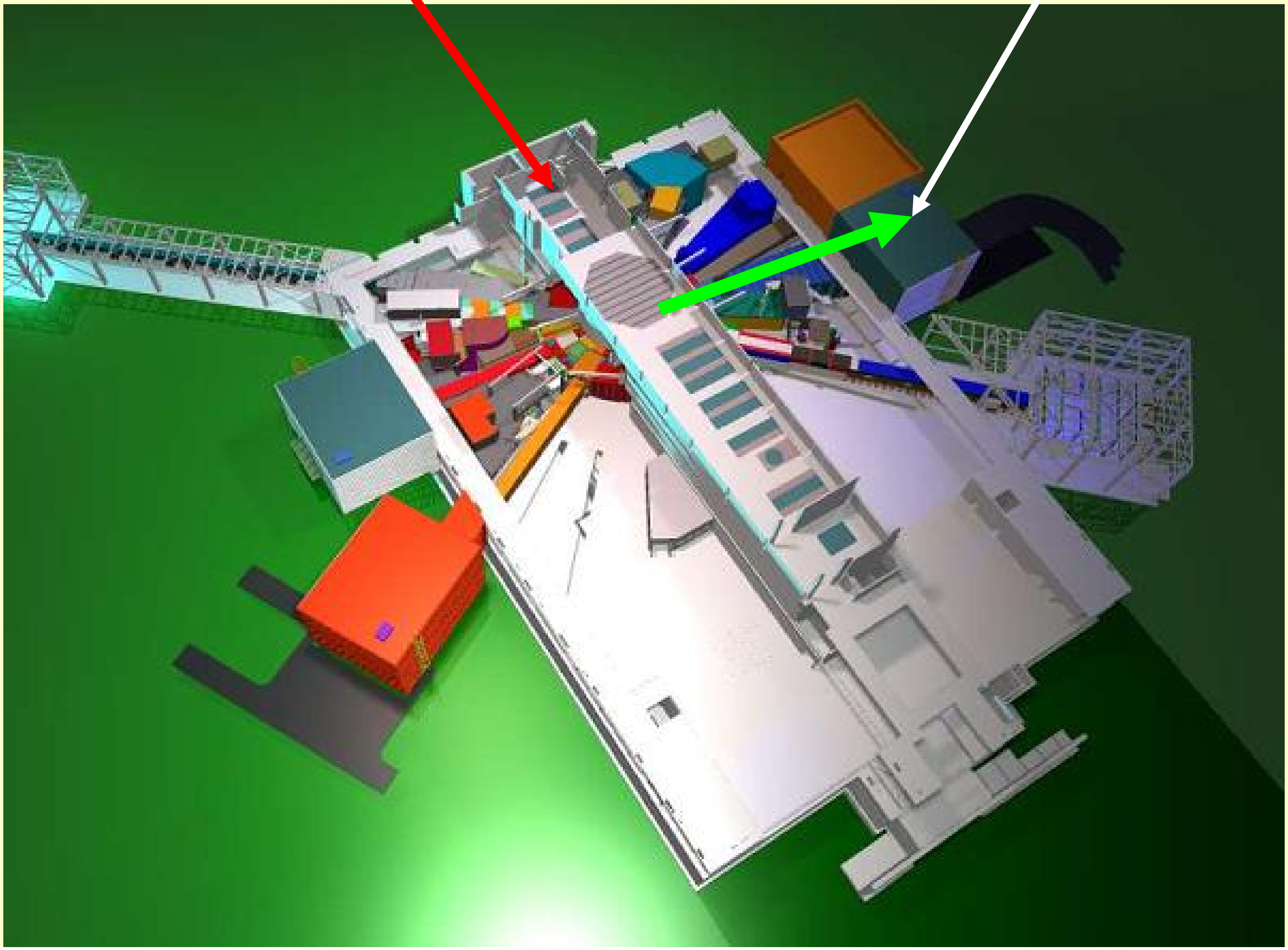
SNS Status

- SNS completed: 2006
- Beam line completed: 2007
- Full design flux: 2009
- SNS Total Project Cost: 1.411B$

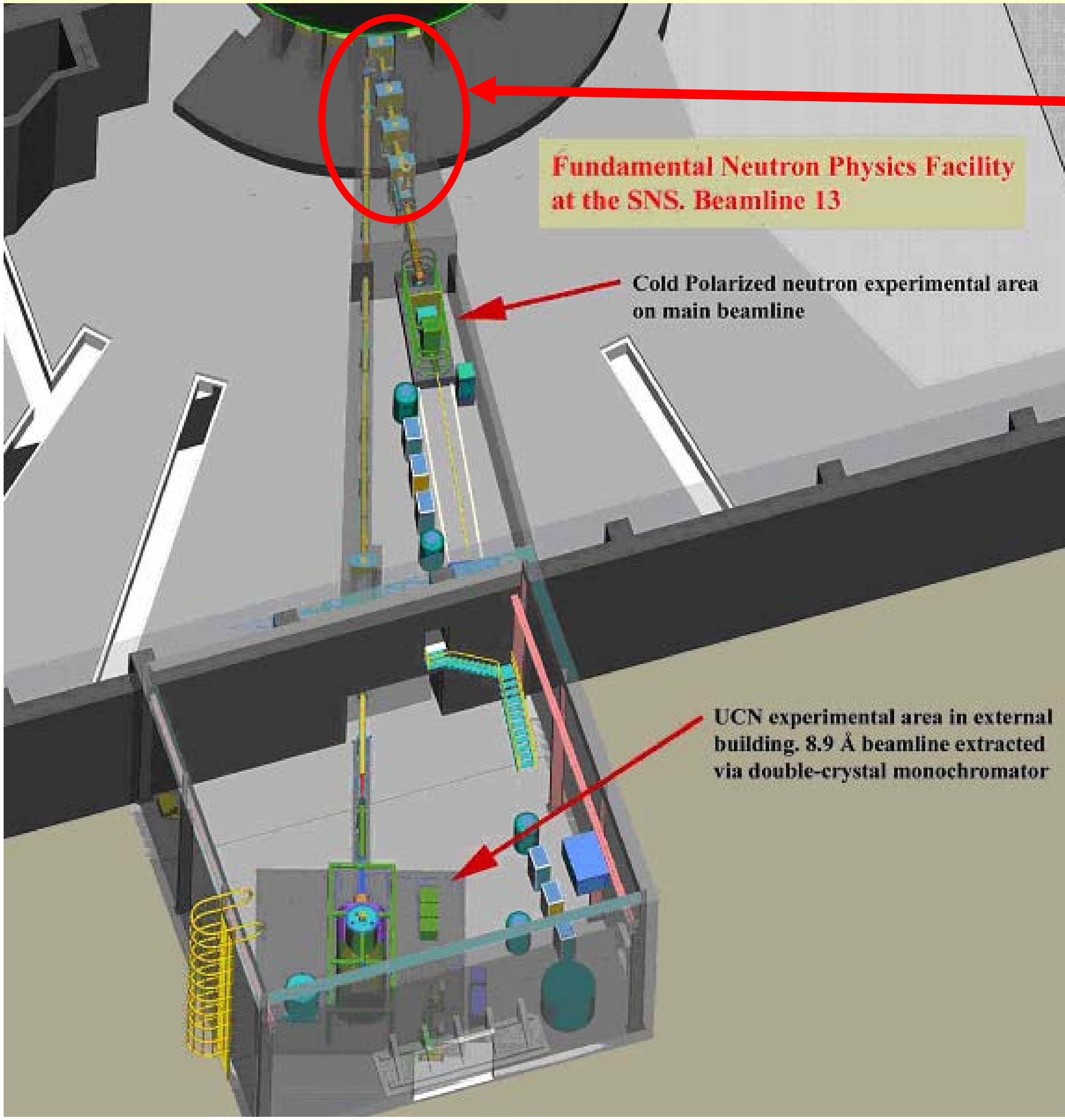
SNS Target Hall

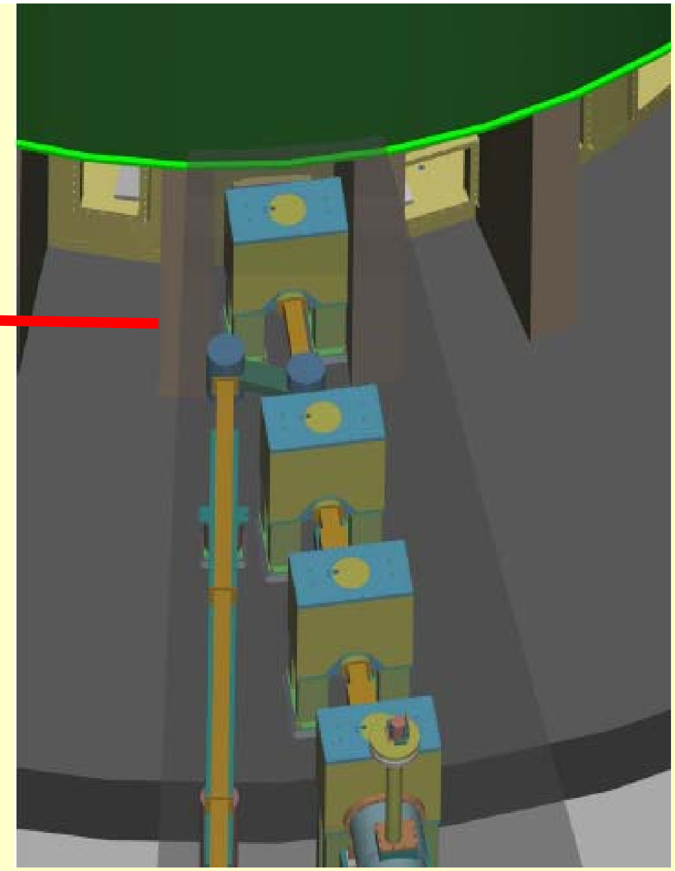
p beam

18 neutron beam ports with 1 for Nuclear Physics



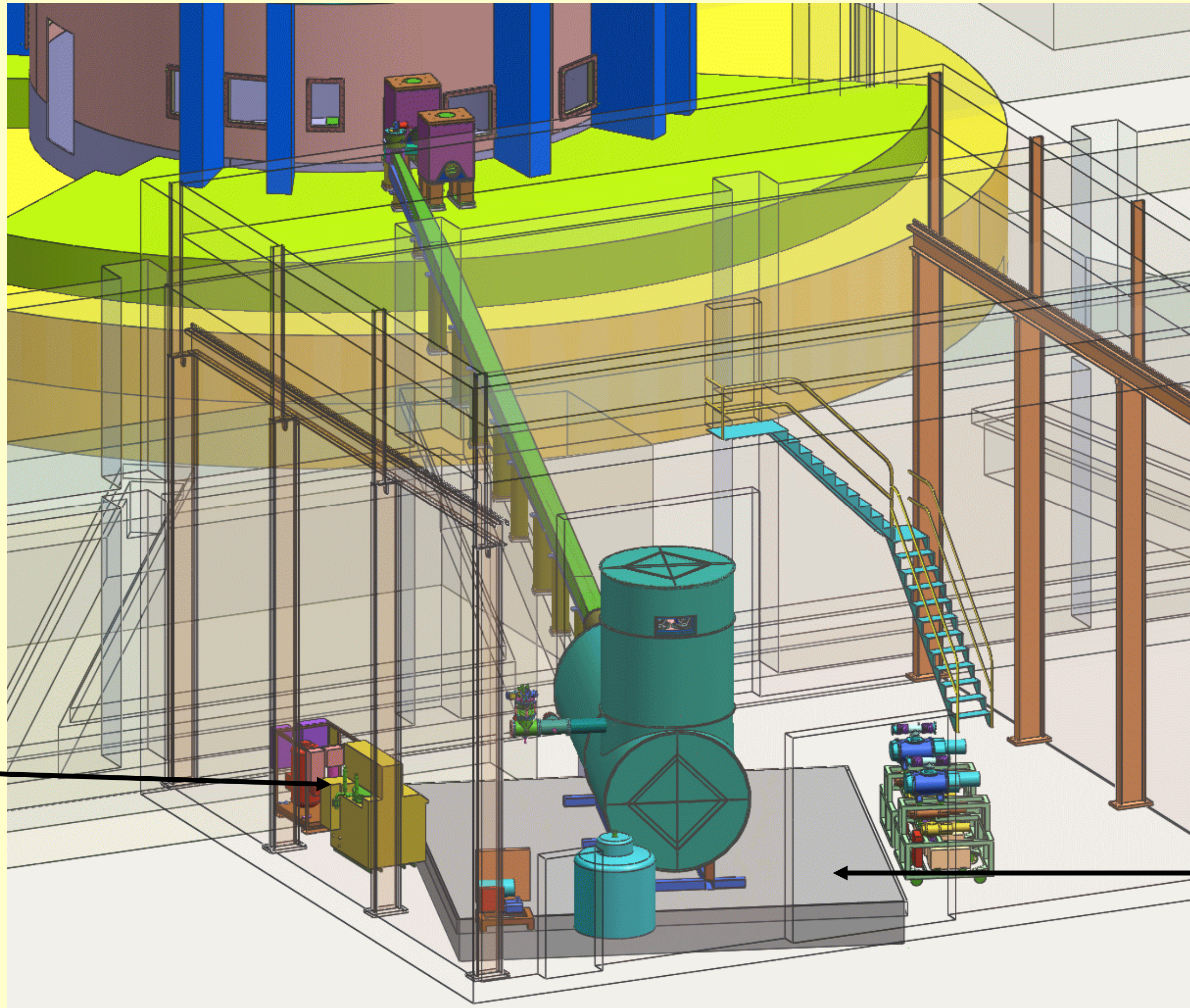
Fundamental Neutron Physics Beamline





Double monochrometer selects 8.9 Å neutrons

EDM Experiment at SNS



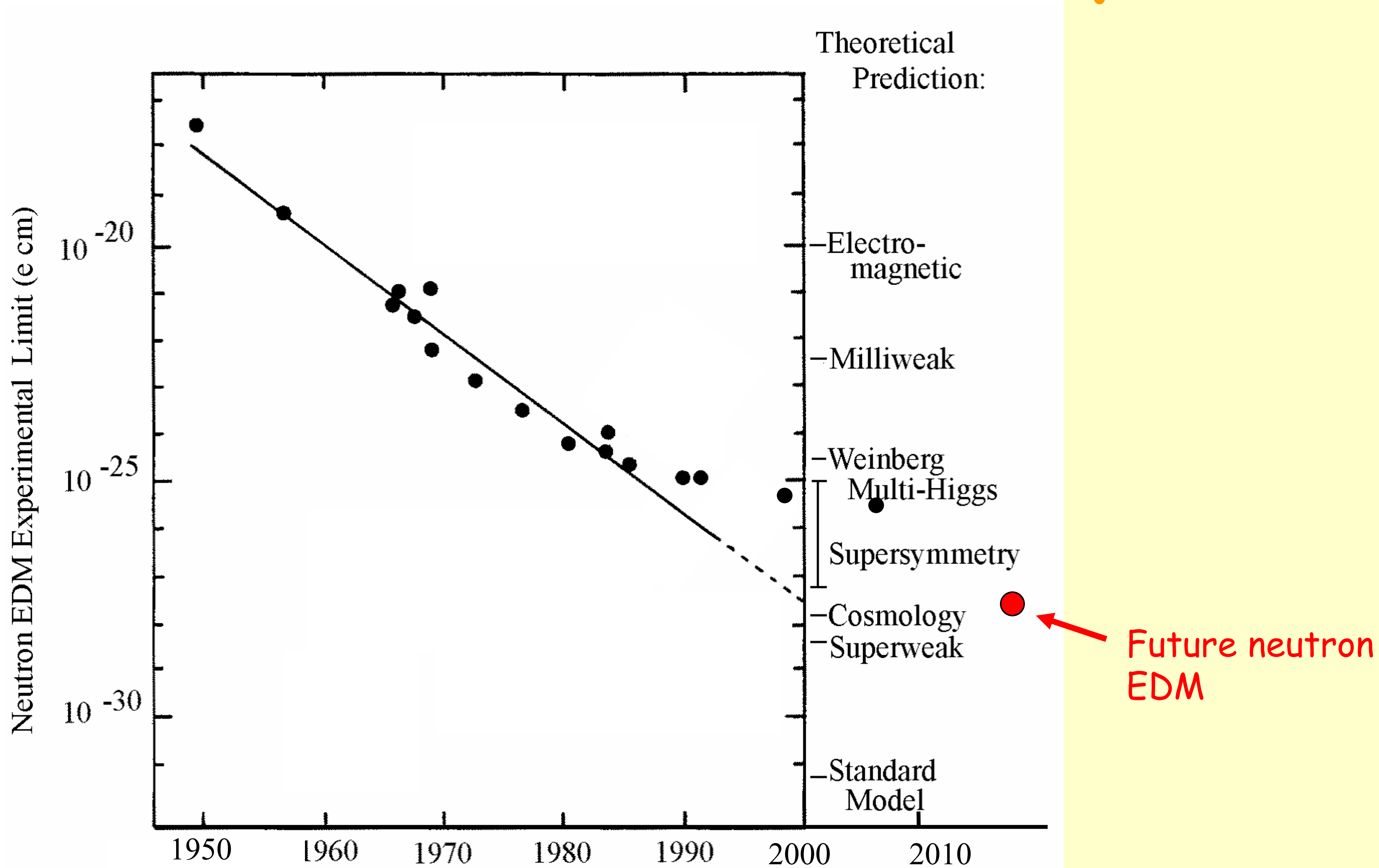
He Liquifier

Isolated floor

Summary of future neutron EDM experiments

Exp	UCN source	cell	Measurement techniques	σ_d (10^{-28} e-cm)
ILL CryoEDM	Superfluid ^4He	^4He	Ramsey technique for ω External SQUID magnetometers	~ 50 < 5
PNPI – I LL – SD_2	ILL turbine PNPI/Solid D_2	Vac.	Ramsey technique for ω $\vec{E}$=0 cell for magnetometer	< 100 < 10
ILL Crystal	Cold n Beam			< 100
PSI EDM	Solid D_2	Vac.	Ramsey technique for ω External Cs & $^3\vec{He}$ magnetom.	~ 50 ~ 5
SNS EDM	Superfluid ^4He	^4He	$^3\vec{He}$ capture for ω $^3\vec{He}$ comagnetometer SQUIDS & Dressed spins	~ 5
TRIUMF/JPARC	Superfluid ^4He	Vac.	Under Development	?

New n-EDM Sensitivity



Summary

- Physics reach of EDM measurements is significant (even after Large Hadron Collider)
  - New sources of CP violation likely in SUSY
- A new neutron EDM experiment with two orders of magnitude improvement
  - Allows possible discovery of new sources of CP violation