Muon Decay Distributions

$$\mu \to e \nu_\mu \nu_e$$

- Energy dependence
- Angular dependence
- Called Michel parameters

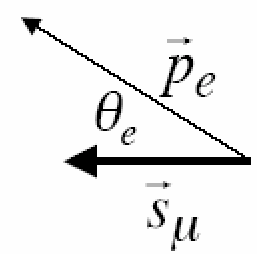
$$\frac{dN_e}{d\Omega_e dE_e} \propto x^2 \left[3 - 3x + \frac{2}{3}\rho(4x-3) + 3\eta x_o \left(\frac{1-x}{x}\right) + P_\mu \xi \cos\theta_e \left(1 - x + \frac{2}{3}\delta(4x-3)\right)\right]$$

$$x \equiv \frac{E_e}{E_e^{\max}}$$

Spectral shape in x, $\cos\theta_e$ is characterized in terms of four parameters -- ρ, η, ξ, δ

P_μ is the muon polarization

$$x_o \equiv \frac{m_e}{E_e^{\max}}$$



D. Koetke (TWIST)

Useful References

- http://www.krl.caltech.edu/ucn/

- "Fundamental neutron physics",
  J.S. Nico and W.M. Snow, Ann. Rev. Nucl. Part. Sci. 55, 27 (2005).

- "Low energy tests of the weak interaction",
  J. Erler and M.J. Ramsey-Musolf, Prog. Part. Nucl. Phys. 54, 351 (2005)

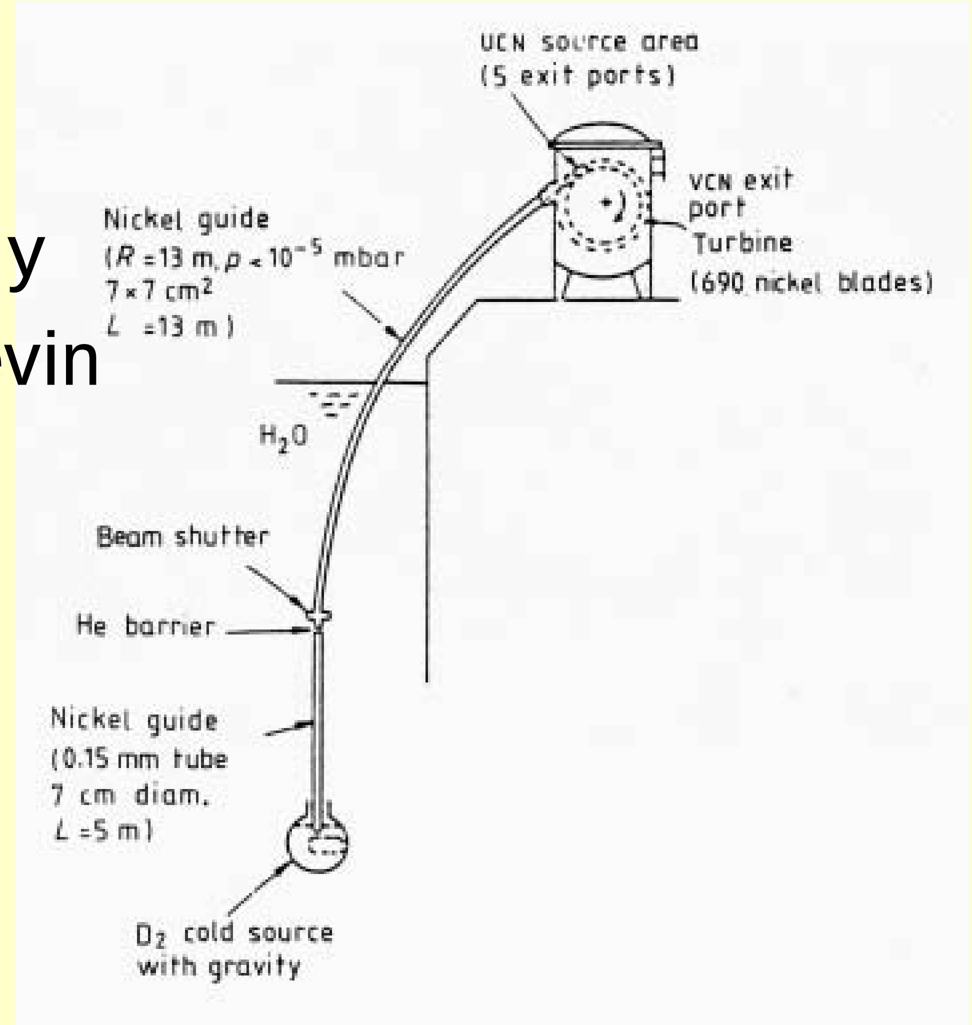
- "Demonstration of a solid deuterium source of ultracold neutrons“,
  A. Saunders *et al.*, Phys. Lett. B 593, 55 (2004)

- "Measurement of electron backscattering in the energy range of neutron beta decay",
  J.W. Martin *et al.*, Phys. Rev. C 68, 055503 (2003).

- "Measurements of ultracold neutron lifetimes in solid deuterium",
  C.L. Morris *et al.*, Phys. Rev. Lett. 89, 272501 (2002).

Ultra-Cold Neutrons: UCN

- Previous record density at Institut Laue-Langevin (ILL) reactor in Grenoble



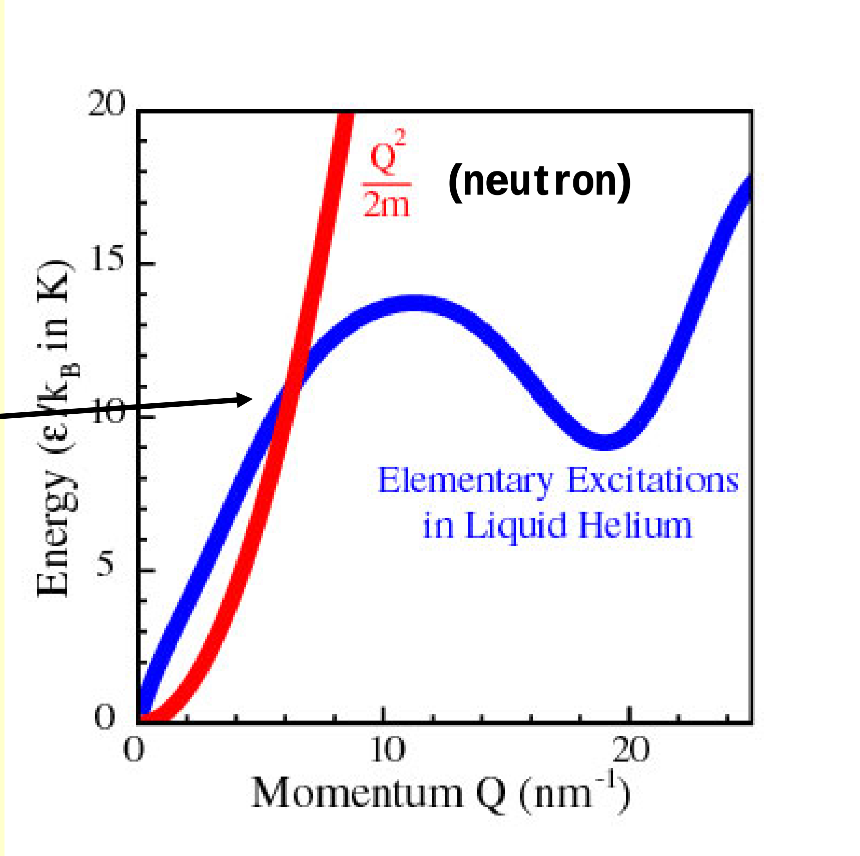
≈ 40 UCN/cm^3 stored in bottle

(1971)

Can we make more UCN?

Higher Density UCN Sources

- Use non-equilibrium system
  (aka Superthermal)
  - **Superfluid ^4He (T<1K)**

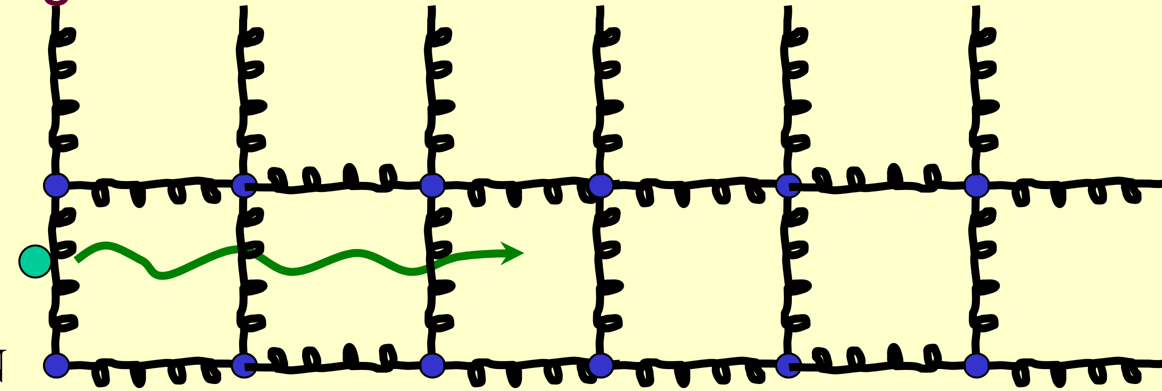


11K (9Å) incident n produces phonon & becomes UCN

Very few 11K phonons if T<1K

∴ minimal upscattering

- **Solid deuterium (SD_2)** Gollub & Boning(83)
  - Small absorption probability
  - Faster UCN production
  - Small Upscattering if $T < 6K$



New UCN Sources

- Superthermal ^4He
  - Neutron lifetime experiment at National Institute of Standards and Technology (NIST) Research reactor
  - Under development for neutron electric dipole moment experiment at Spallation Neutron Source (SNS) and ILL
- Superthermal SD_2
  - Neutron EDM at Paul Scherrer Institute
  - Neutron decay correlation at LANSCE

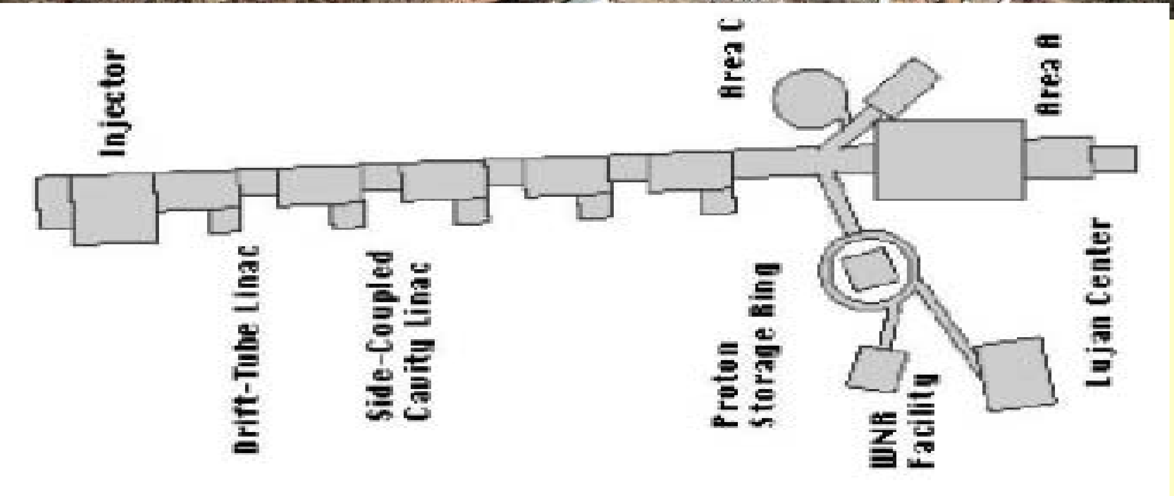
LANSCE

(Los Alamos Neutron Science CEnter)

Proton Linac (½ mile long) 1 mA of 0.8 GeV protons

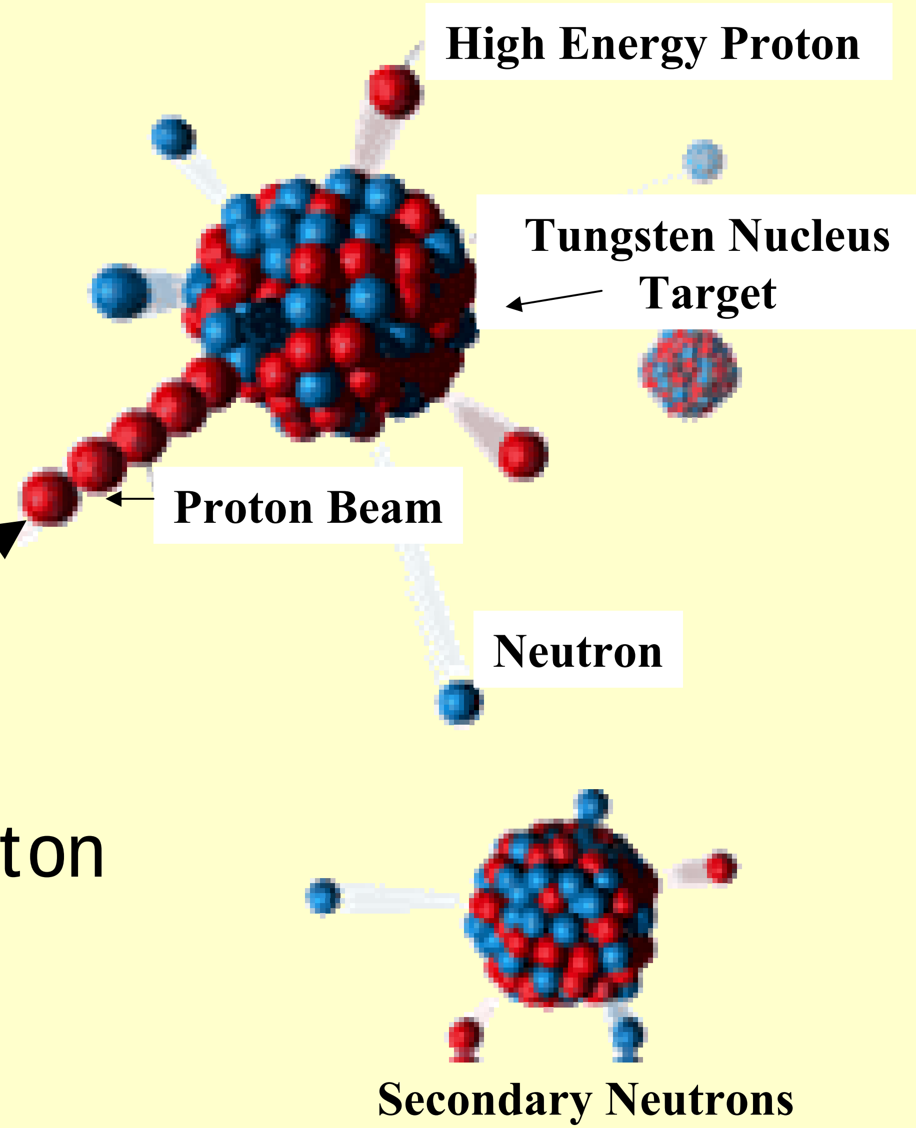
UCN Source

Thanks Google Maps



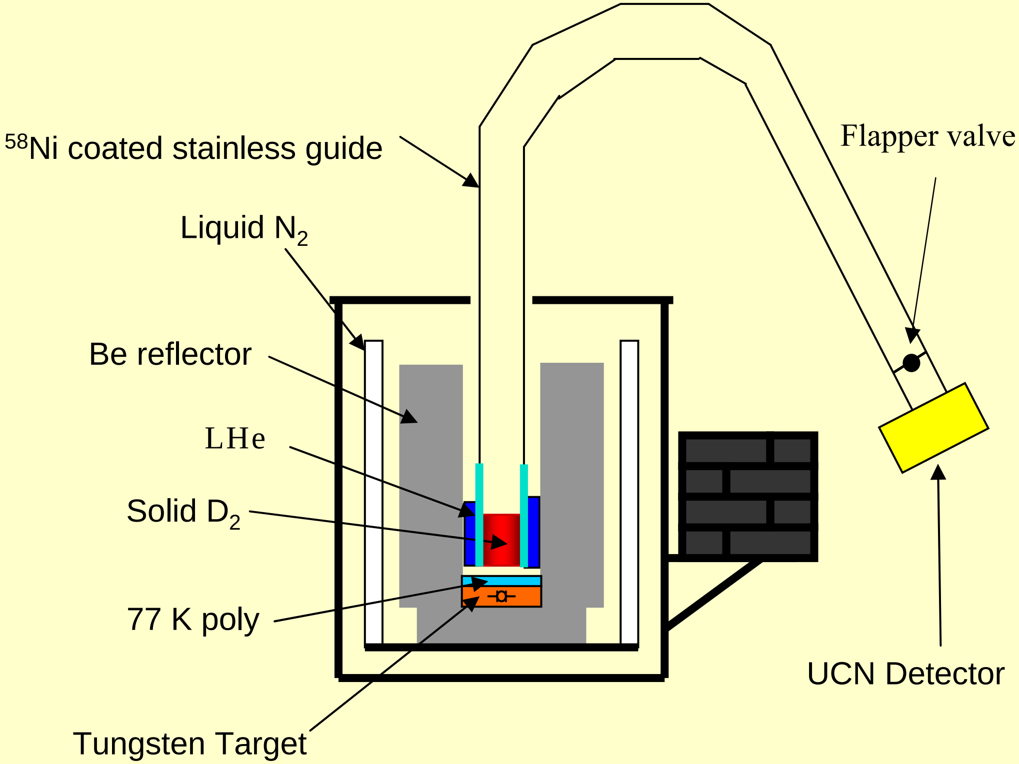
High Intensity Pulsed Neutrons

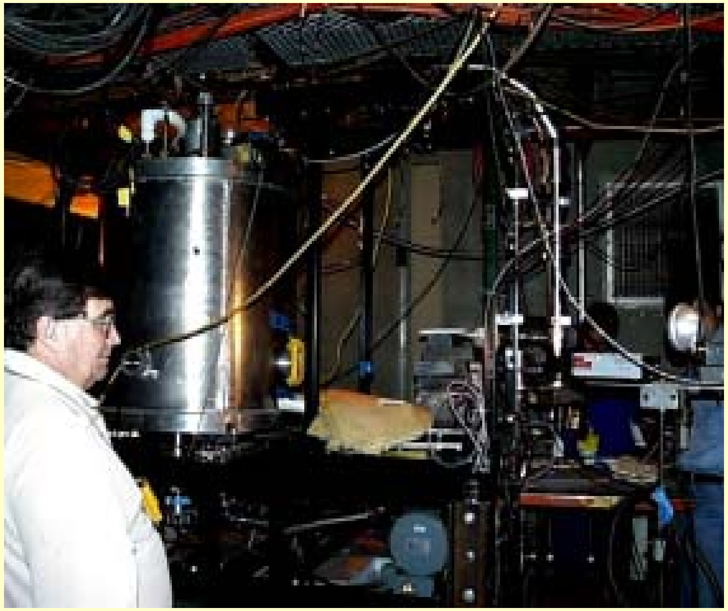
- Proton-induced spallation



~ 20 n's/incident proton

Schematic of prototype SD_2 source



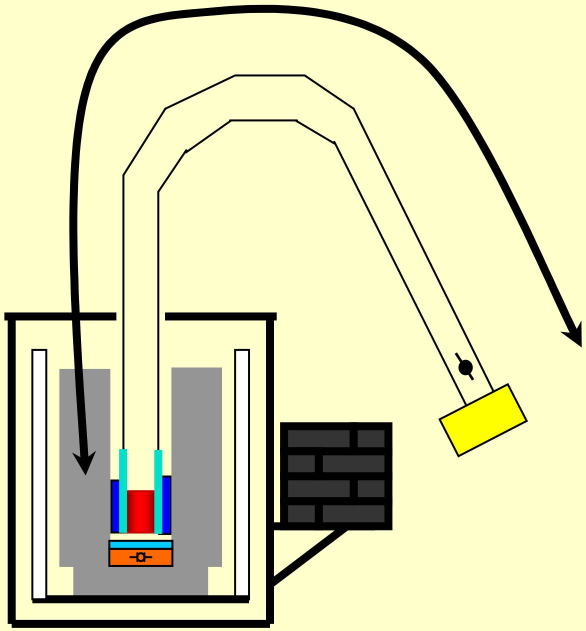


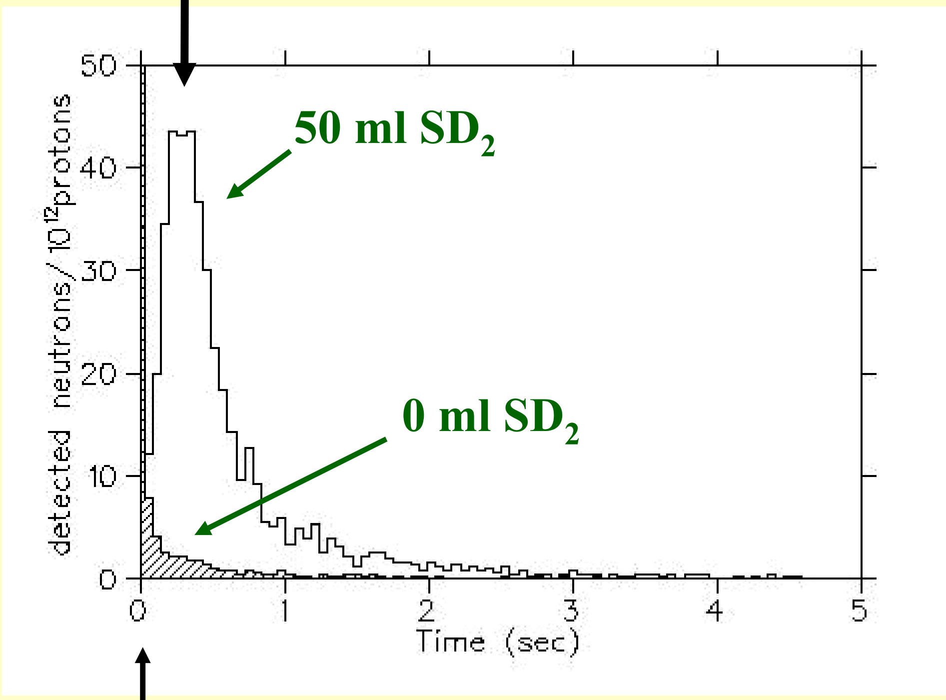
(LANL/Caltech/ILL/Kyoto/Princeton/VaTech/NCState collaboration)

First UCN detection

Total flight path ~ 2 m

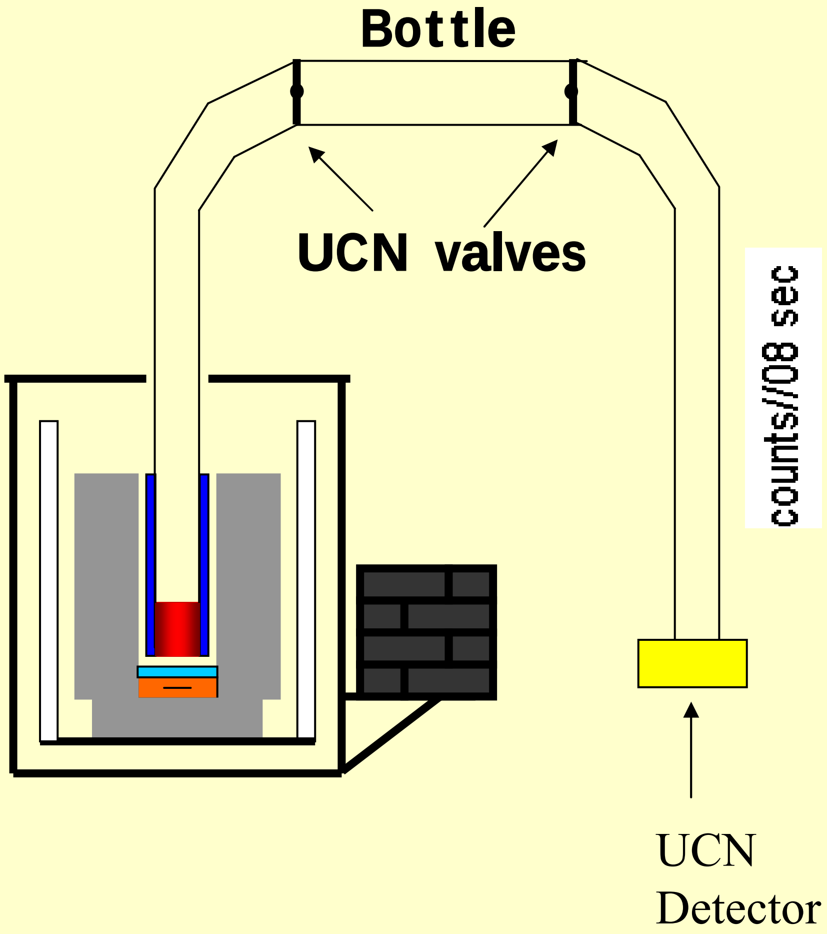
$$2\,\mathrm{m}\left(\frac{1}{6\,\mathrm{m/s}}\right) = 0.33\,\mathrm{sec}$$

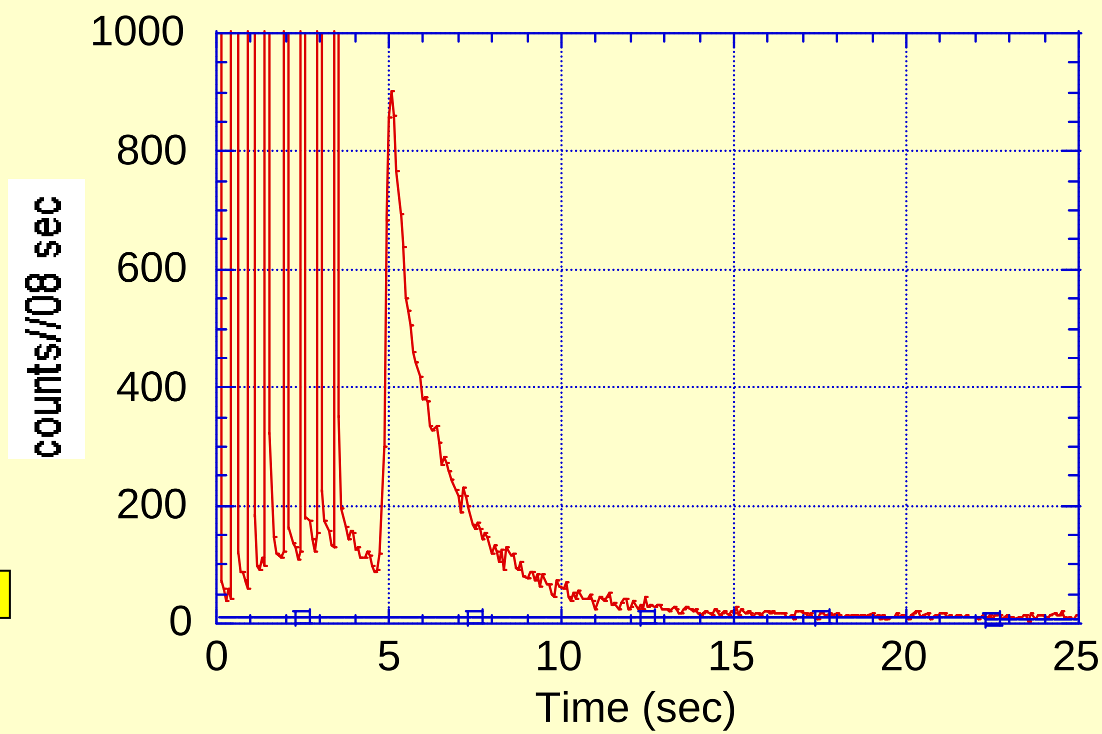




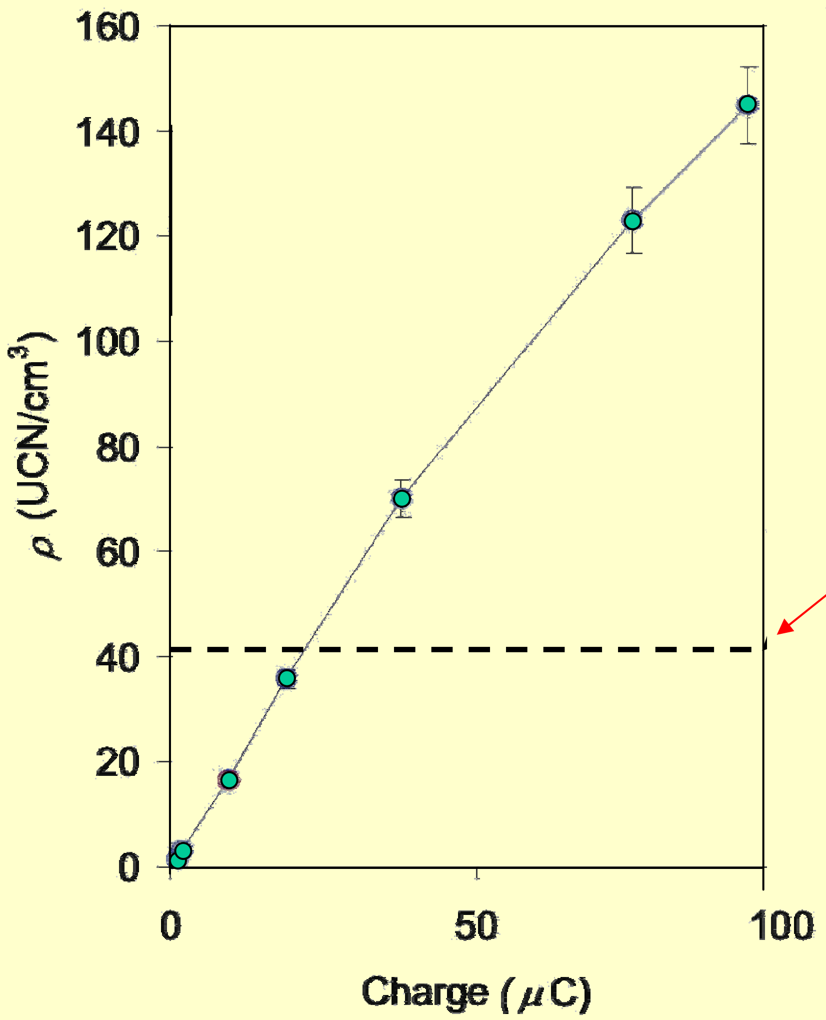
Proton pulse at t = 0

Bottled UCN


Bottle
UCN valves
UCN
Detector


counts//08 sec
1000
800
600
400
200
0
0
5
10
15
20
25
Time (sec)

New World Record UCN Density

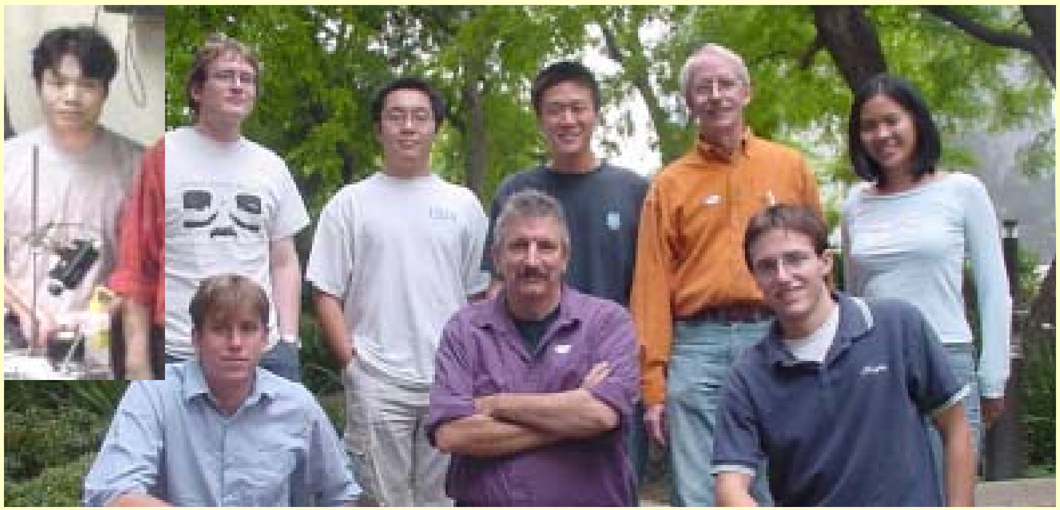


Previous record for bottled UCN = 41 UCN/cm^3 (at ILL)

Measurements of Ultra Cold Neutron Lifetimes in Solid Deuterium [PRL 89,272501 (2002)]

Demonstration of a Solid Deuterium Source of Ultra-Cold Neutrons [Phys. Lett. B 593, 55 (2004)]

The Caltech UCN group



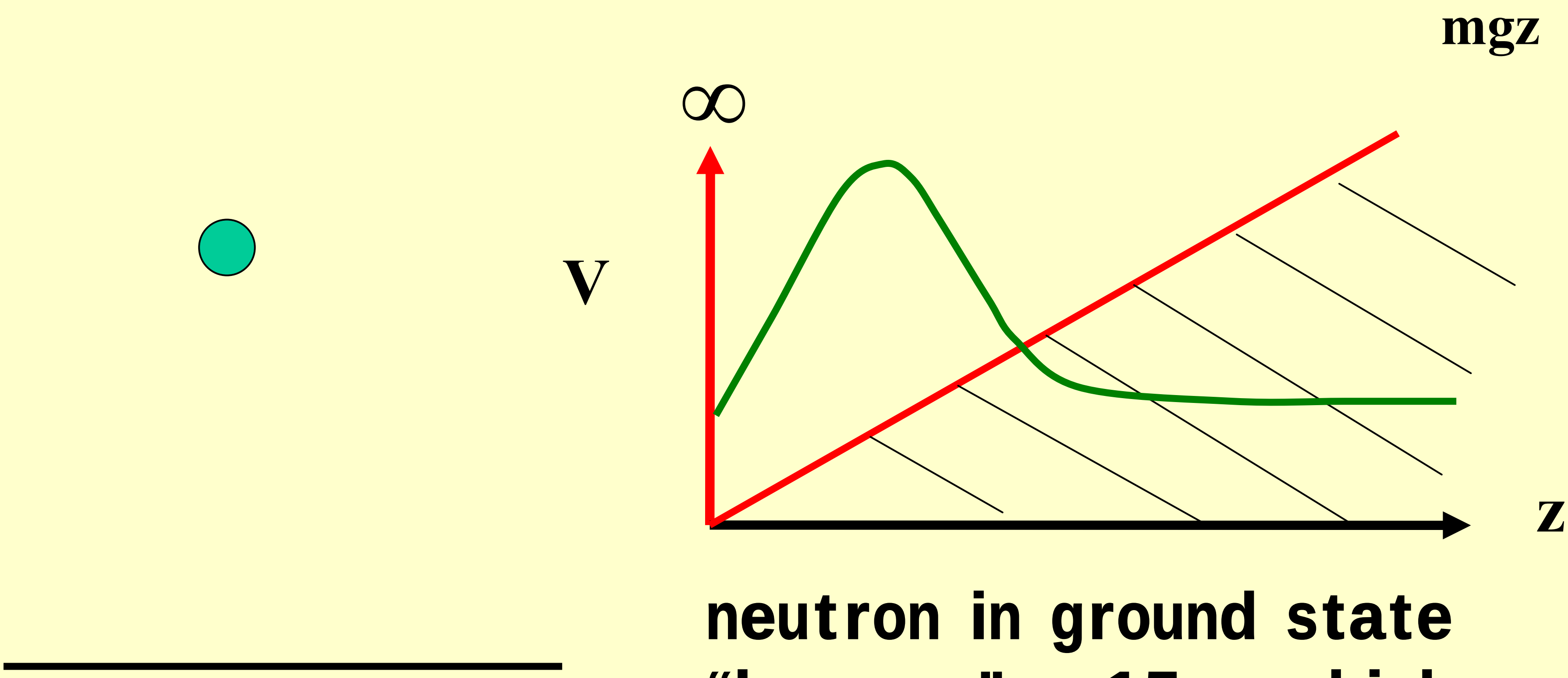
Nick Hutzler
Gary Cheng
Jenny Hsiao
Riccardo Schmid
Kevin Hickerson
Junhua Yuan
Brad Plaster
Bob Carr
Jianglai Liu
Michael Woods
BF

Physics with higher density UCN Sources

- Macroscopic Quantum States
- Neutron decay (lifetime & correlations)
  - Solid Deuterium Source
- Neutron Electric Dipole Moment (EDM)
  - Superfluid He Source

Macroscopic Quantum States in a Gravity Field

1-d Schrödinger potential problem



neutron in ground state "bounces" ~ 15 μm high

Schrodinger Equation Solutions

$$\frac{-\hbar^2}{2m_I}\frac{\partial^2\Psi}{\partial z^2} + m_G g z \Psi = E\Psi$$

- m_I is inertial, m_G is gravitational mass

- Eigenstates are Airy functions:
  - $\psi(z) = A\phi(z-\delta)$

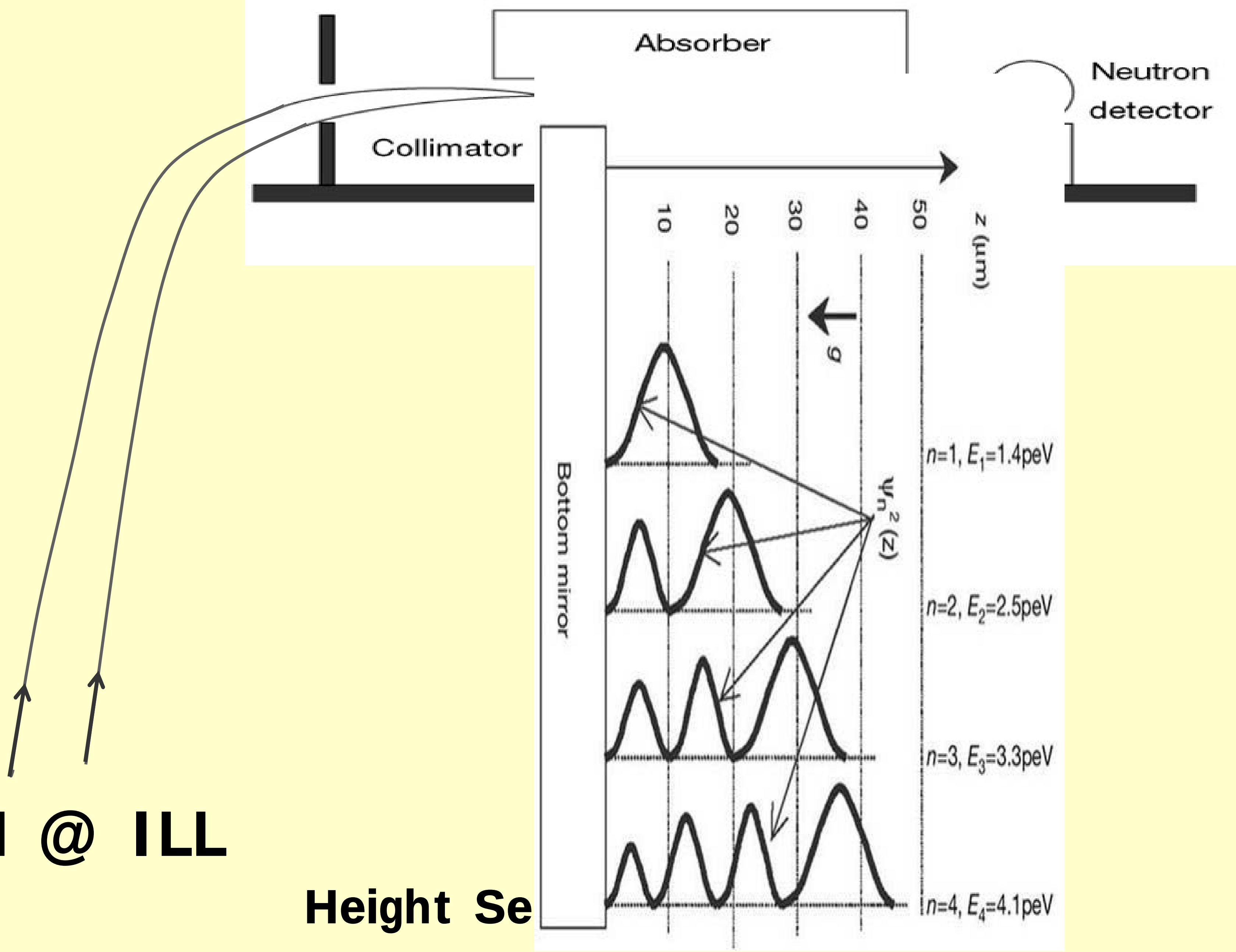
- Eigenenergies are

For Neutrons

$$E_n = \left(\frac{\hbar^2 m_G^2 g^2}{2m_I}\right)^{-1/3} \alpha_n = \left(0.60 \cdot 10^{-12}\ \mathbf{eV}\right)\alpha_n$$

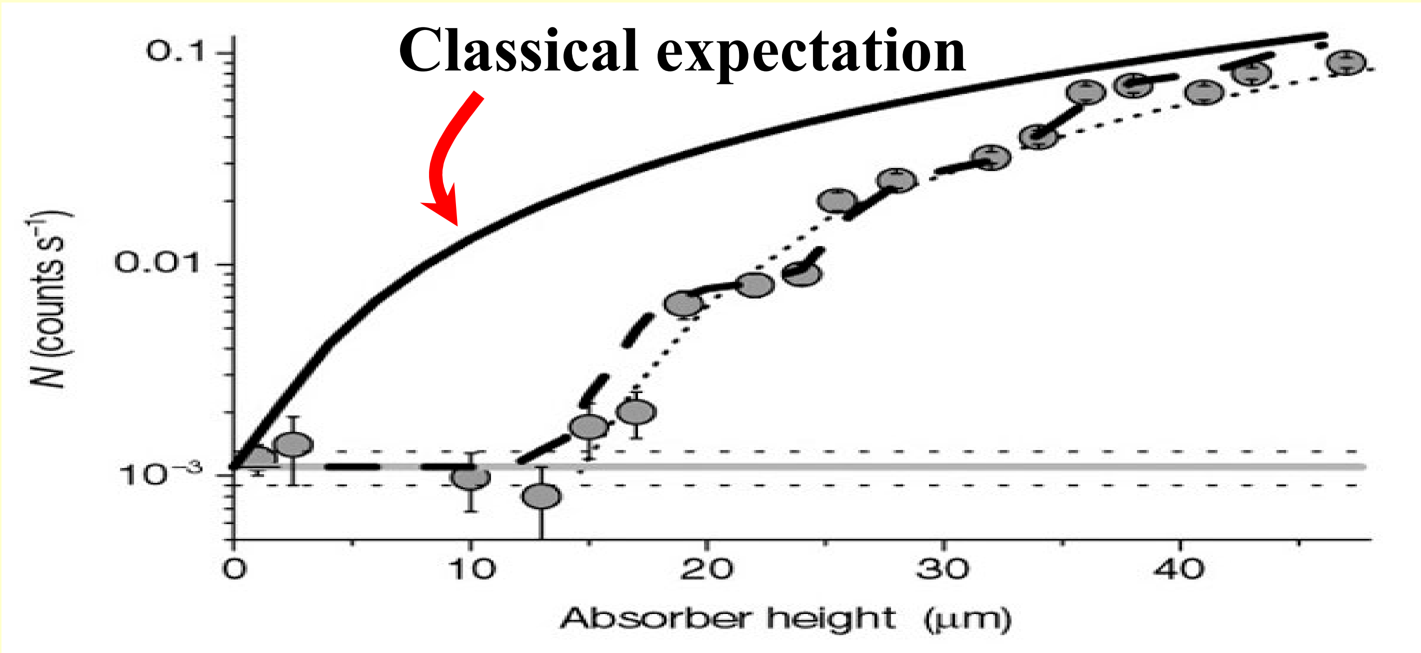
  - Where α_n are the zeros of the Airy function
    - $\alpha_1 = 2.34$, $\alpha_2 = 4.09$, $\alpha_3 = 5.52$

Neutron Energy Levels in Gravity



UCN @ ILL

Height Se



ILL - Nesvizhevsky, et al, Nature 2002

May allow improved tests of Gravity at short distances

(need more UCN!)

Physics with quantum neutron states

- May allow a test of the weak equivalence principle

$$E_n = \left(\frac{m_G}{m_I}\right)^{2/3} \left(\frac{\hbar^2 m_I g^2}{2}\right)^{1/3} \alpha_n$$

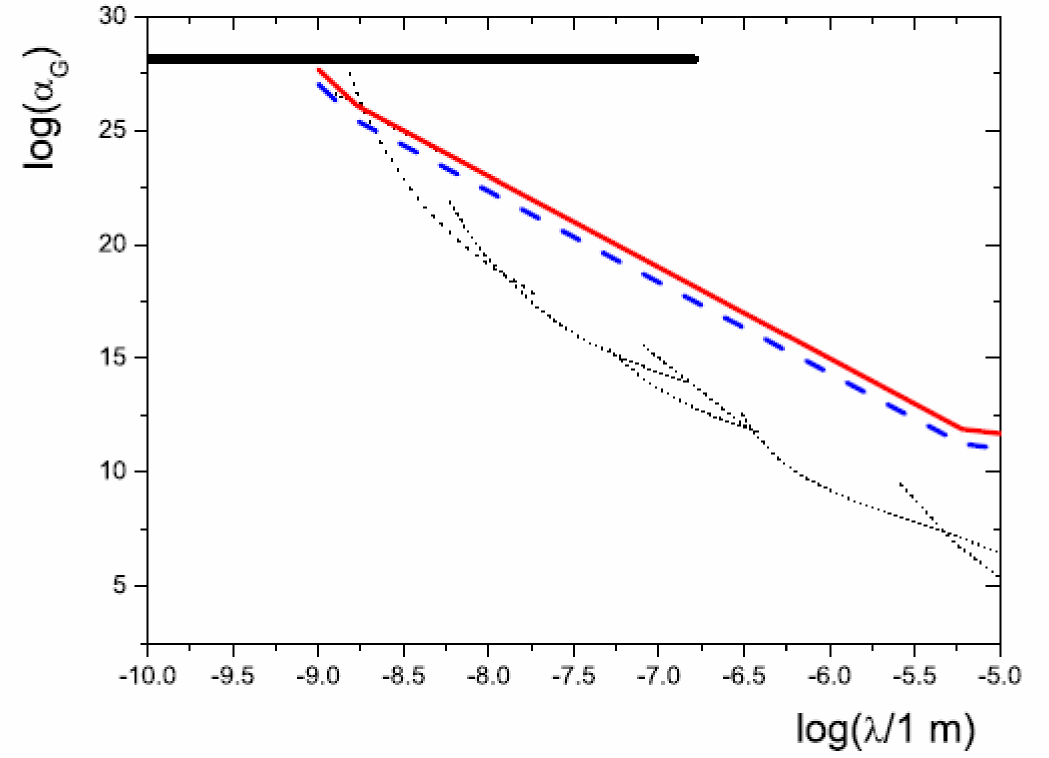
- May improve tests of the behavior of gravity at short distances
  - Small (but finite) extra dimensions may cause gravity to be **much** stronger at short distance

Behavior of gravity at short distance

Class. Quantum Grav. 21 (2004) 4557–4566 PII: S0264-9381(04)78660-8

Constraints on non-Newtonian gravity from the experiment on neutron quantum states in the earth's gravitational field

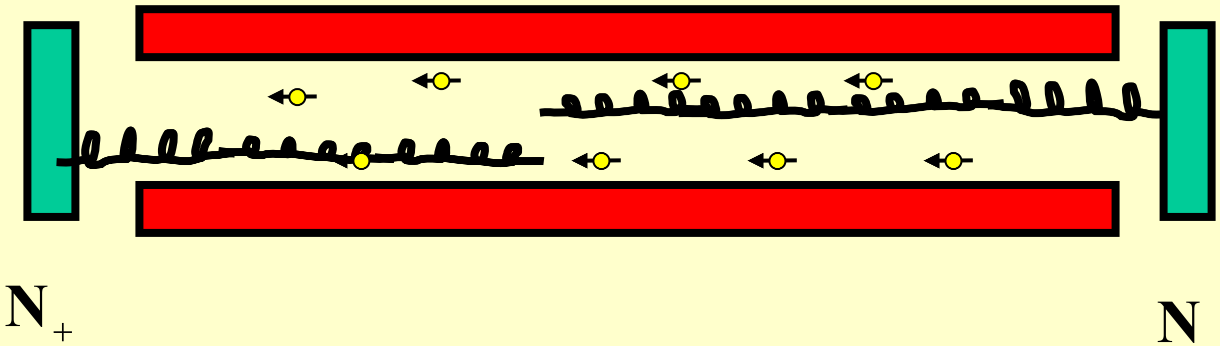
V V Nesvizhevsky[1] and K V Protasov[2]

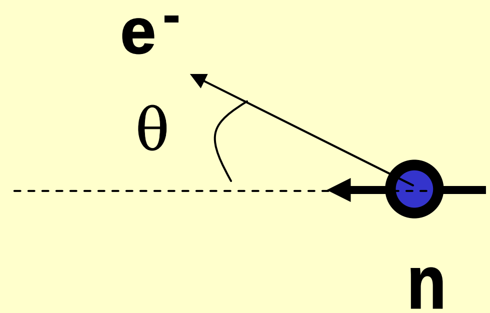


$$V_{\text{eff}}(r) = G\frac{m_1 m_2}{r}\left(1 + \alpha_G\, e^{-r/\lambda}\right).$$

Neutron Decay Correlation with UCN

UCNA – 1st correlation exp with UCN





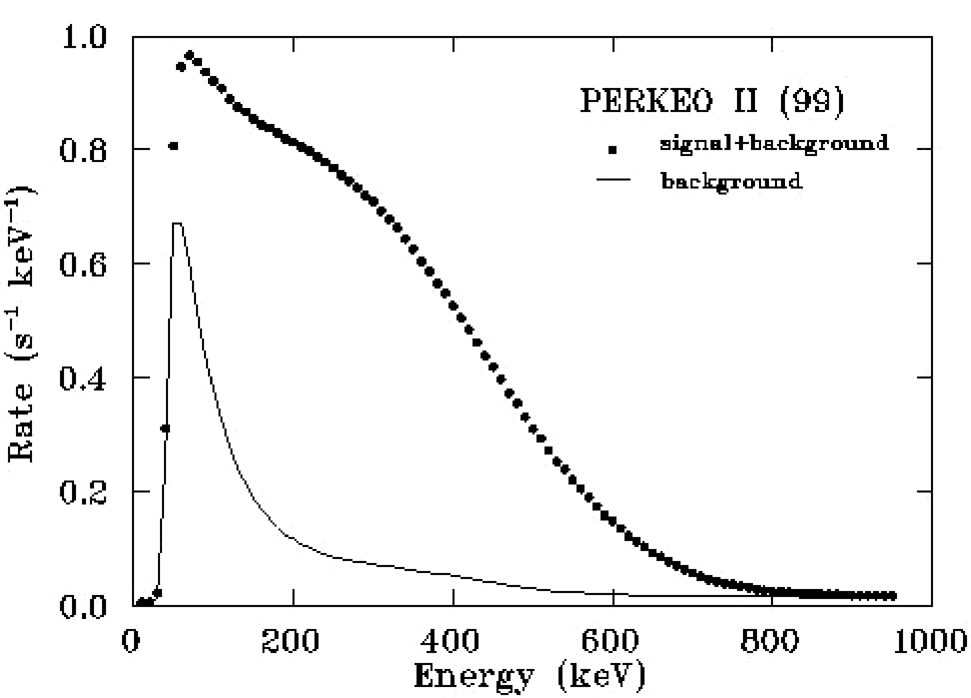
$$N_e = N_0(1 + A\beta\cos\theta)$$

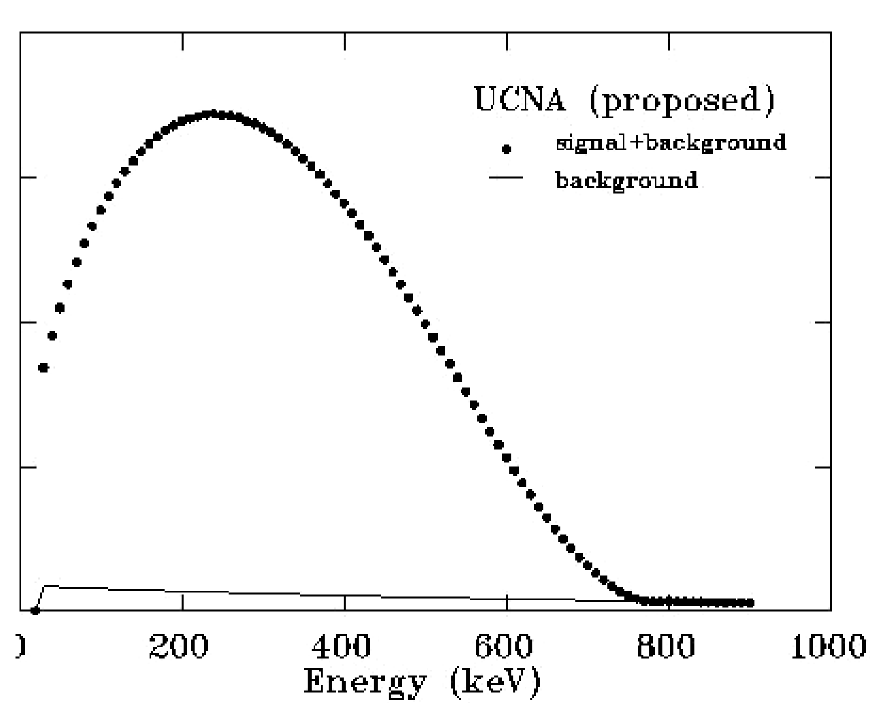
$$A_{exp} = \frac{N_+ - N_-}{N_+ + N_-}$$

$$V_{ud} = f(A, \tau_n, RC)$$

$$RC = \text{Electroweak Radiative Corrections}$$

Reduced Background with pulsed Source of UCN

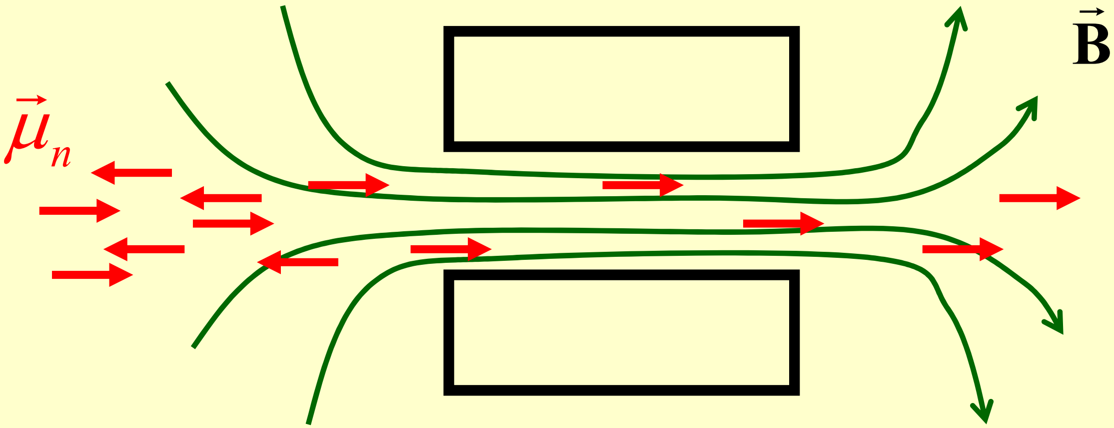




Best previous A-correlation experiment (at Reactor)

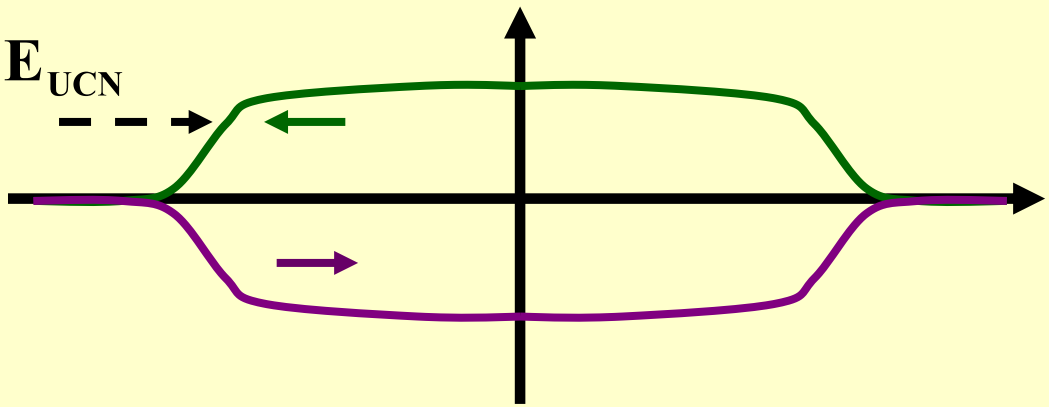
Proposed A-correlation experiment (pulsed source)

UCN Polarization via high B-field



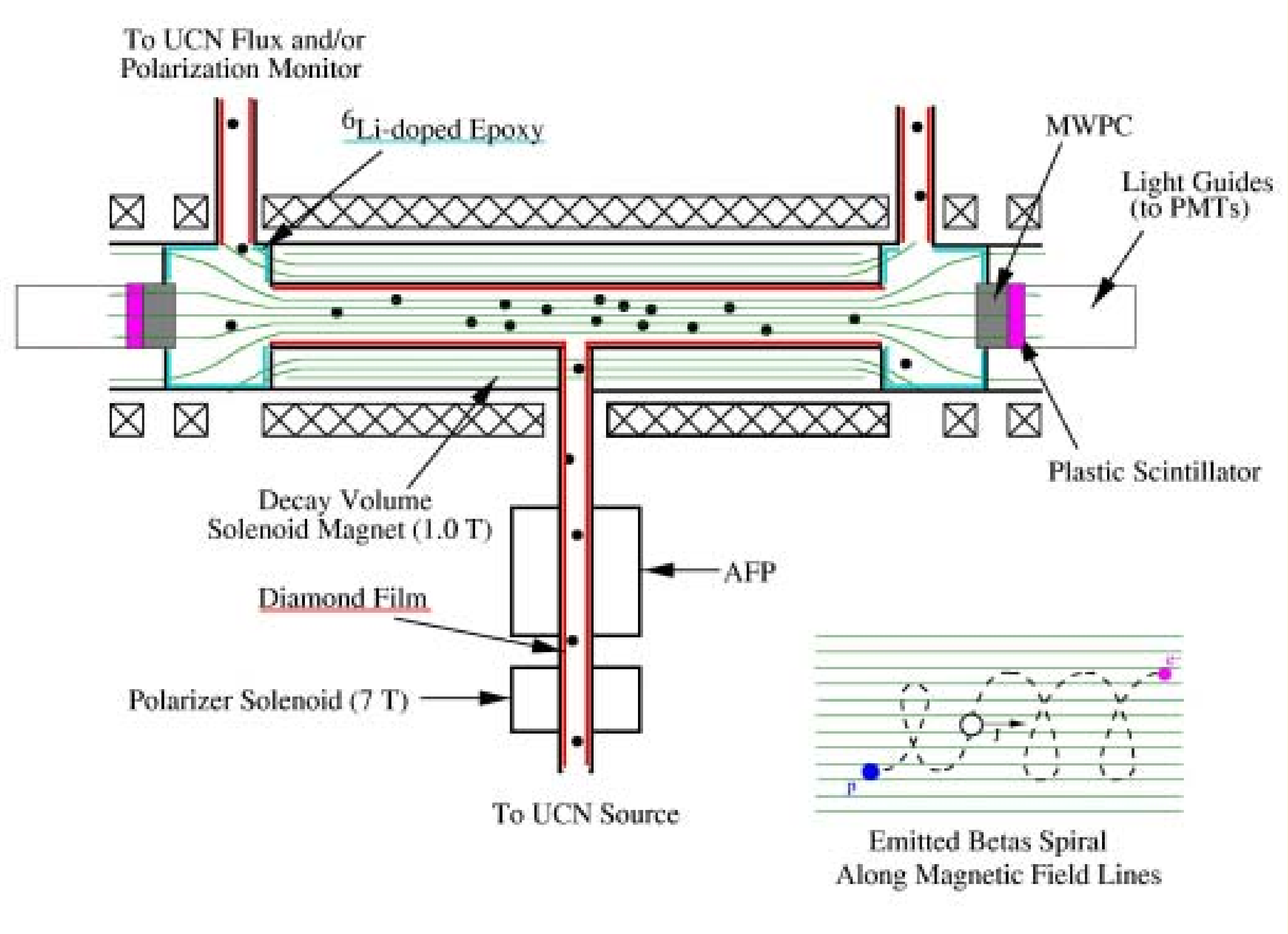
Can produce polarized neutrons with $\vec{P}_n \geq 99.9\%$

$$V = -\vec{\mu} \cdot \vec{B} > E_{UCN} \text{ if } B \geq 6\ T$$

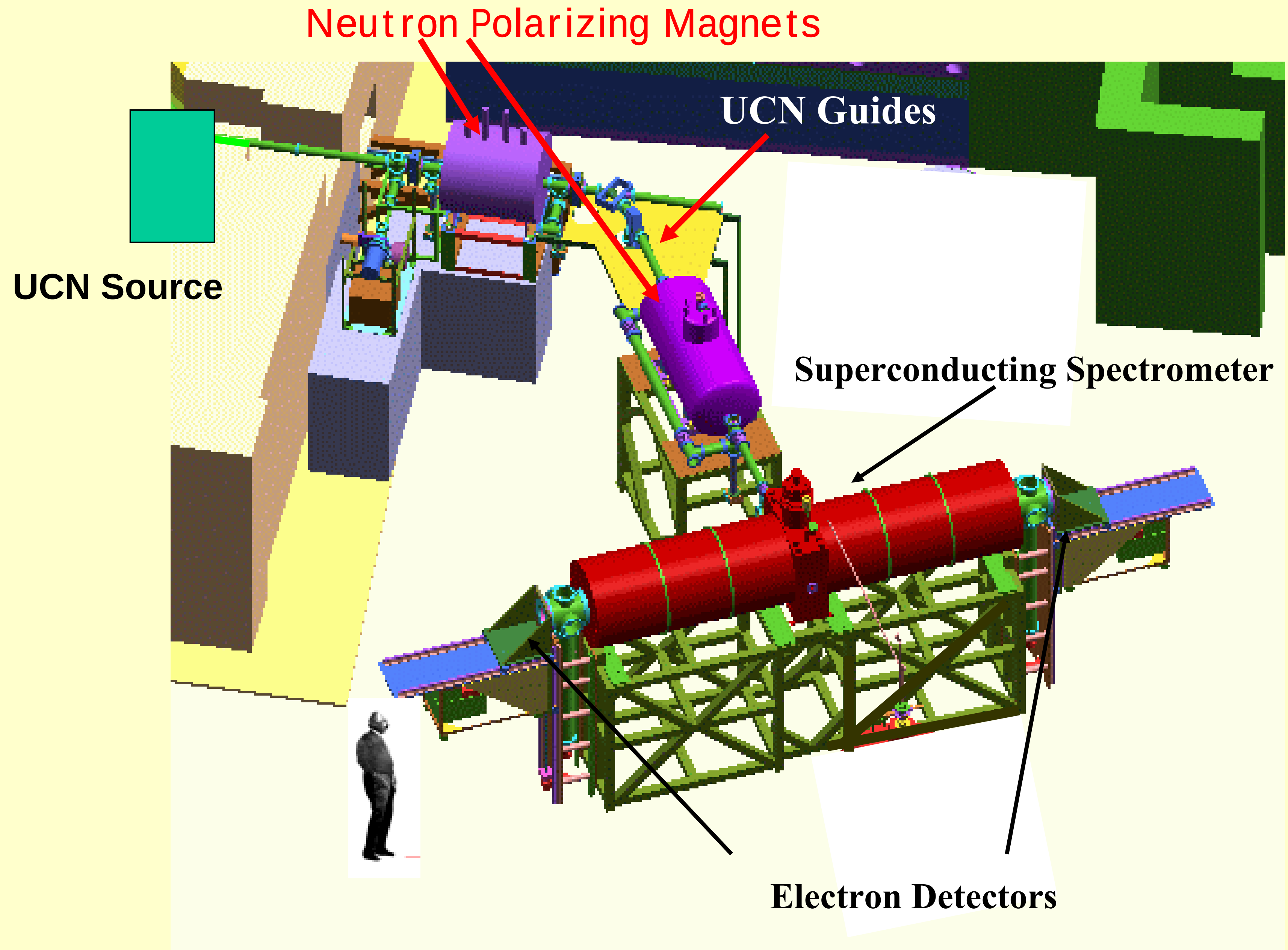


Note: $\vec{\sigma}_n$ anti-parallel to $\vec{\mu}_n$

Experiment Design



Experiment Layout



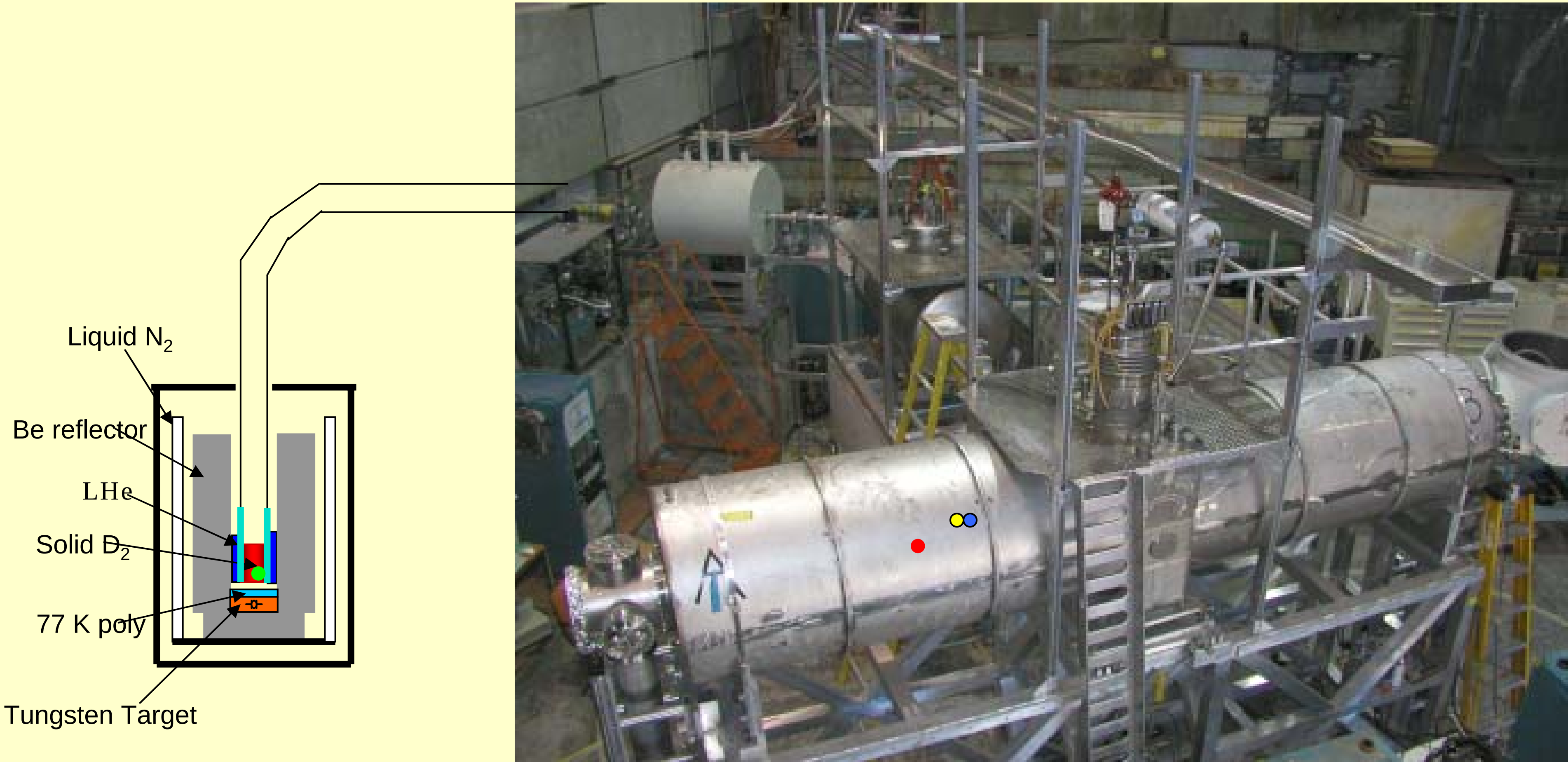
UCNA experiment

Experiment commissioning underway

Initial goal is 0.2% measurement of A-correlation

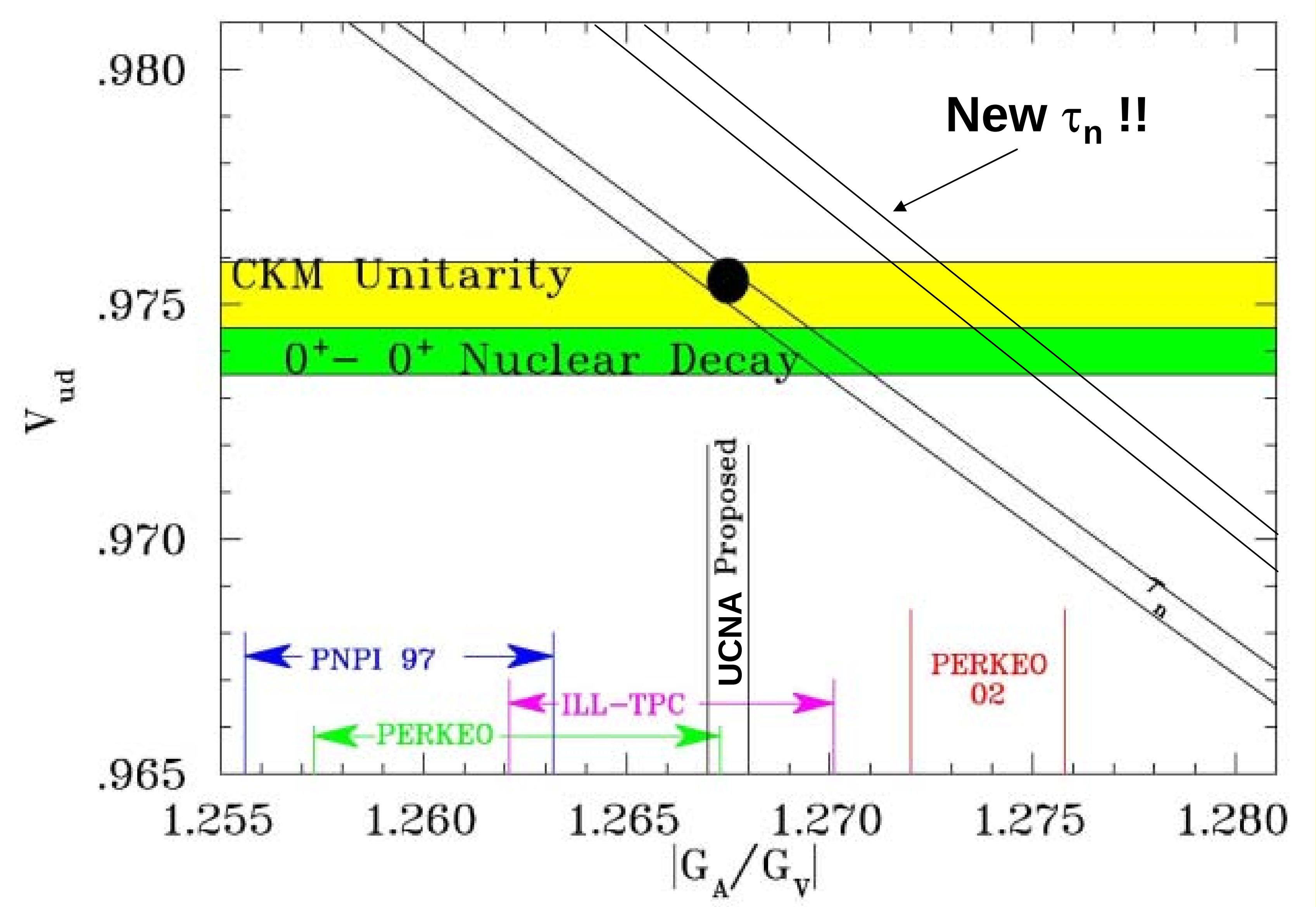
(present measurement ~ 1%)

UCNA



Most Recent Collaborator

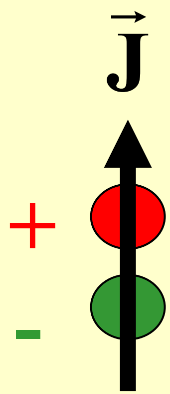
CKM Summary: New V_{us}



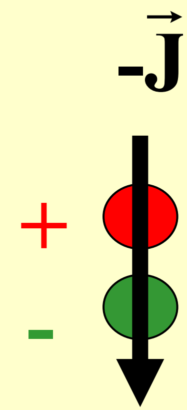
Neutron Electric Dipole Moment (EDM)

- **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 $\overline{K}^0$–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

$$\text{Charge Conjugation}: \hat{C} \bullet \psi_n \Rightarrow \psi_{\bar{n}}$$
$$\text{Parity}: \hat{P} \bullet \psi(x,y,z) \Rightarrow \psi(-x,-y,-z)$$
$$\text{Time Reversal}: \hat{T} \bullet \psi(t) \Rightarrow \psi(-t)$$

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

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

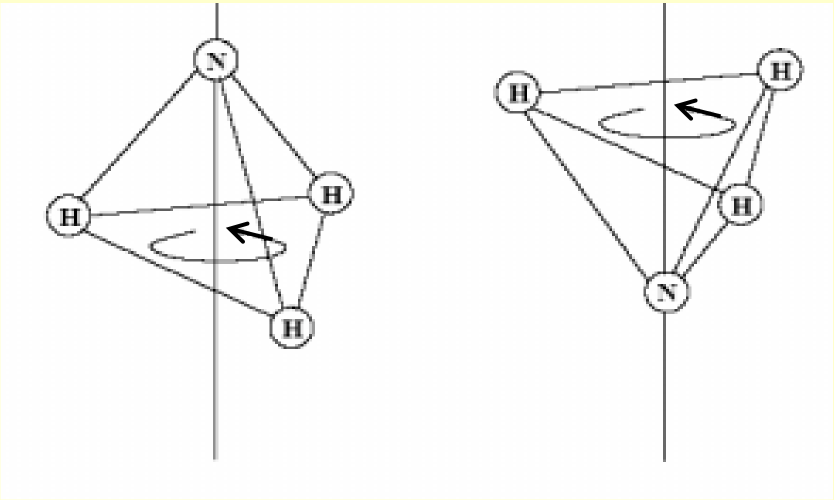
Non-zero d violates T and CP

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

But some molecules have EDMs!

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

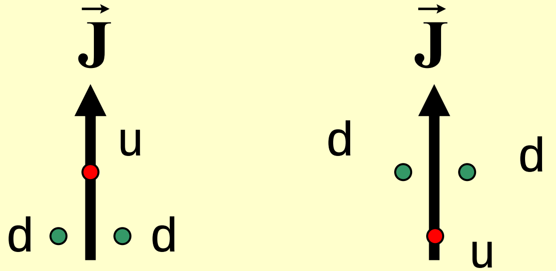
Note: n-EDM $< 3 \times 10^{-26}$ e-cm



NH_3 EDM is not T-odd or CP-odd

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

If Neutron had degenerate state



it would not violate T or CP

CP Violation and the Matter/Antimatter Asymmetry in the Universe

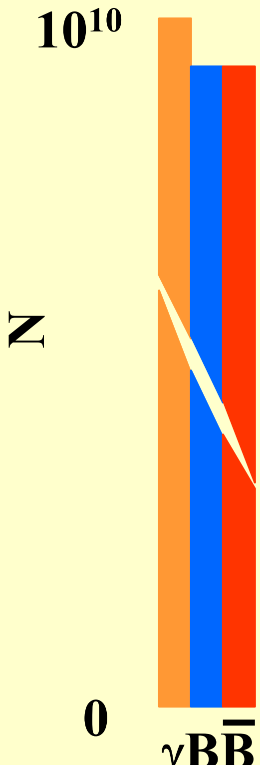
- **Sakharov Criteria**
  - Baryon Number Violation
  - Departure from Thermal Equilibrium
  - CP & C violation

- **Standard Model CP violation is insufficient**
  - Must search for new sources of ~~CP~~
    - B-factories, Neutrinos, EDMs

Electroweak Baryogenesis

Possible source of Matter-Antimatter Asymmetry

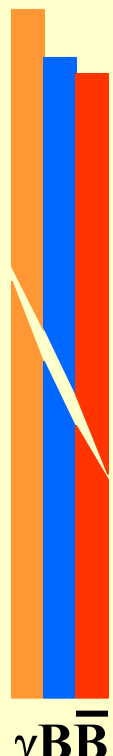
Before Electroweak Phase Transition



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

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

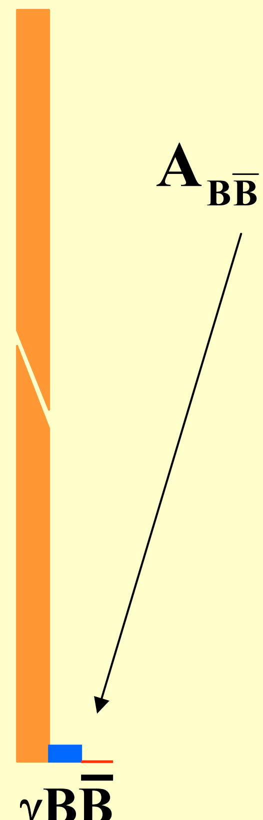
After EW Phase Transition



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

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

Today



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

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

Status of Electroweak Baryogenesis

- Appeared to be "ruled out" several years ago
  - First order phase transition doesn't work for Standard Model with $M_{Higgs} > 120$ GeV
- Recent work has revived EW baryogenesis
  - Minimal Supersymmetric Standard Model (MSSM) parameters ineffective ($\phi_{CP} \ll 1$)
  - First order phase transition still viable

    (with new gauge degrees of freedom)

    Lee, Cirigliano, and Ramsey-Musolf: arXiv:hep-ph/0412354

  - Resonance in MSSM during phase transition

$\mapsto$ Note: Leptogenesis is also possible

How to measure an EDM?

Recall magnetic moment in B field:

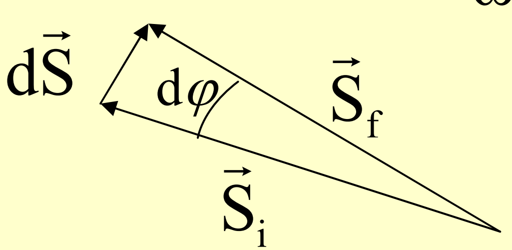
$$\hat{H} = \vec{\mu} \cdot \vec{B}; \qquad \vec{\mu} = 2\left(\frac{\mu_N}{\hbar}\right)\vec{S}$$

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

Classical Picture:

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

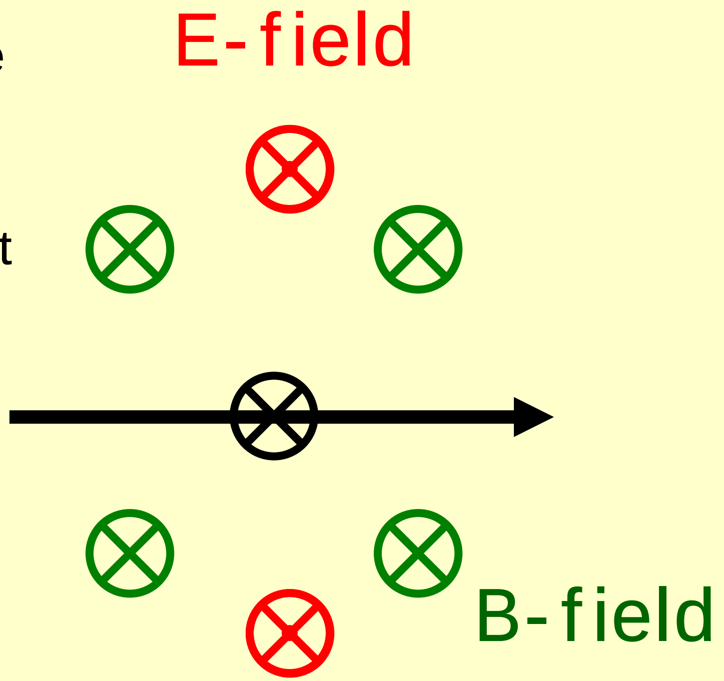
$$\omega = \frac{d\varphi}{dt} = \frac{1}{S}\frac{dS}{dt}$$



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

Simplified Measurement of EDM

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



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

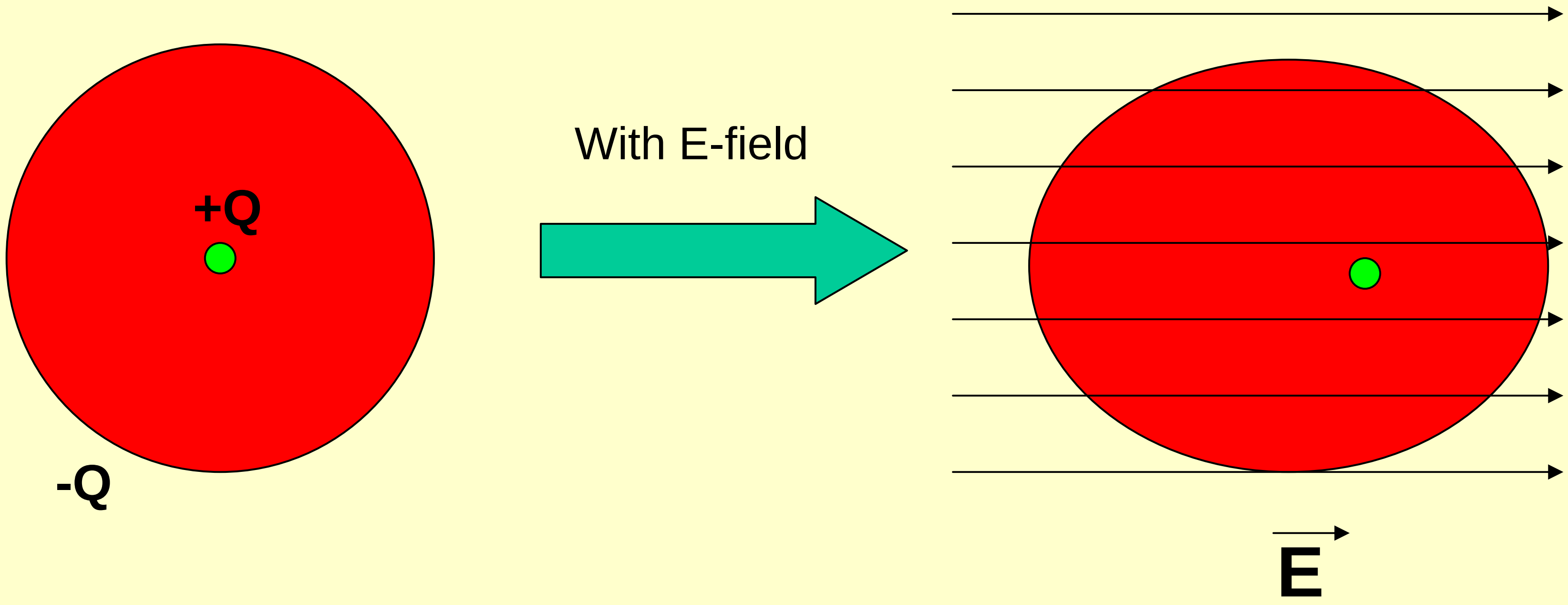
Must know B very well

What systems work well?

- 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
    (magnetic effect with mixing of opposite parity atomic states)

    Thus $d_{Tl} \sim -585\, d_e$ & $|d_e| < 1.6 \times 10^{-27}$ e-cm

  - Suppression for hadronic EDMs in Diamagnetic atoms (eg. Hg) – but Schiff Moment survives
    (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

Experimental EDMs

- **Present best limits come from atomic systems and the free neutron**
  - Paramagnetic atoms (e.g. ^{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 (PbO, YbF)
  - Liquids (^{129}Xe)
  - Solid State systems (Gadolinium-Gallium-Garnet=GGG)
  - Storage Rings (Muons, Deuteron)
  - Radioactive Atoms (^{225}Ra, ^{223}Rn)
  - New Technology for Free Neutrons (PSI, ILL, SNS)

e^- EDM from ^{205}Tl

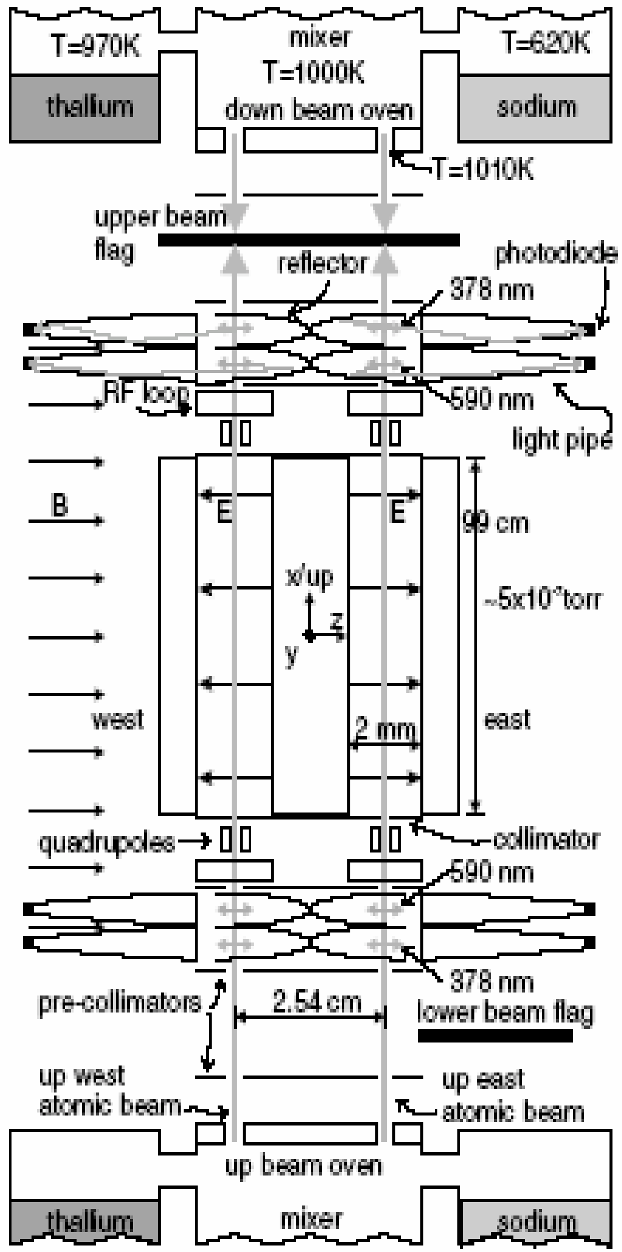
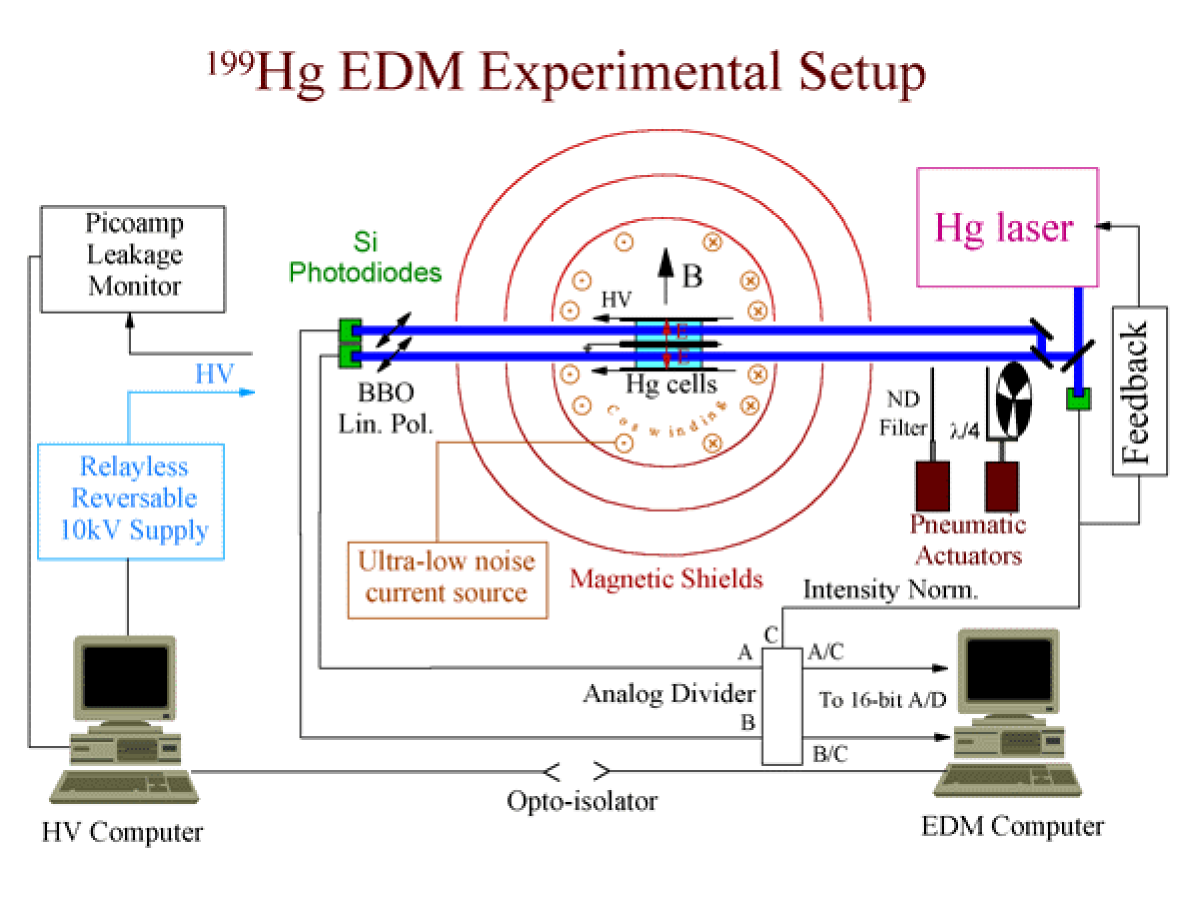
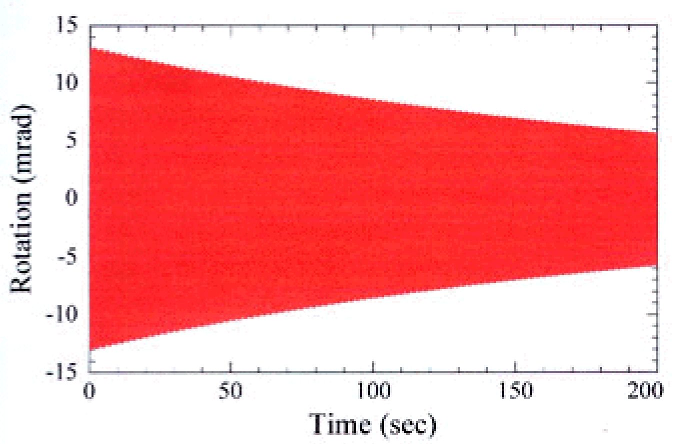


FIG. 1. Schematic diagram of the experiment; not to scale.

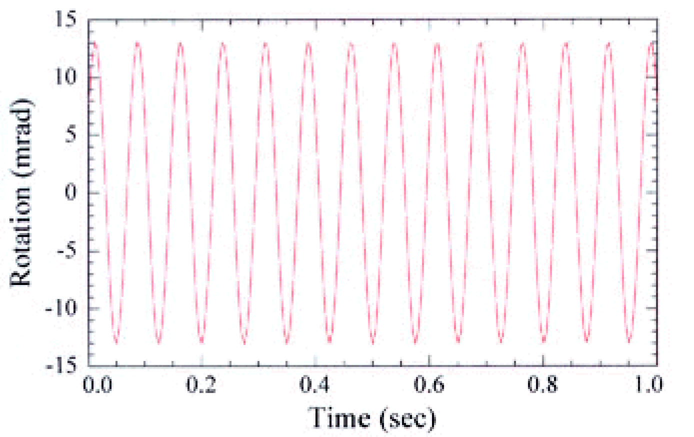
^{199}Hg EDM



199Hg EDM Experimental Setup
Picoamp Leakage Monitor
Si Photodiodes
HV
B
Hg laser
Feedback
BBO Lin. Pol.
Hg cells
ND Filter
λ/4
Relayless Reversable 10kV Supply
Ultra-low noise current source
Magnetic Shields
Pneumatic Actuators
Intensity Norm.
A
C
A/C
Analog Divider
B
To 16-bit A/D
B/C
Opto-isolator
HV Computer
EDM Computer



Rotation (mrad)
Time (sec)



Rotation (mrad)
Time (sec)

ILL-Grenoble neutron EDM Experiment

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

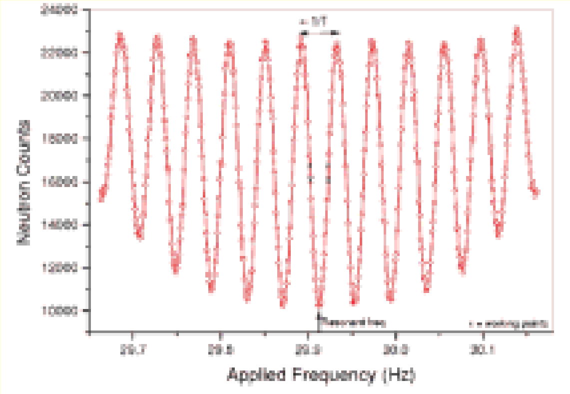
Baker et al. hep-ex/0602020

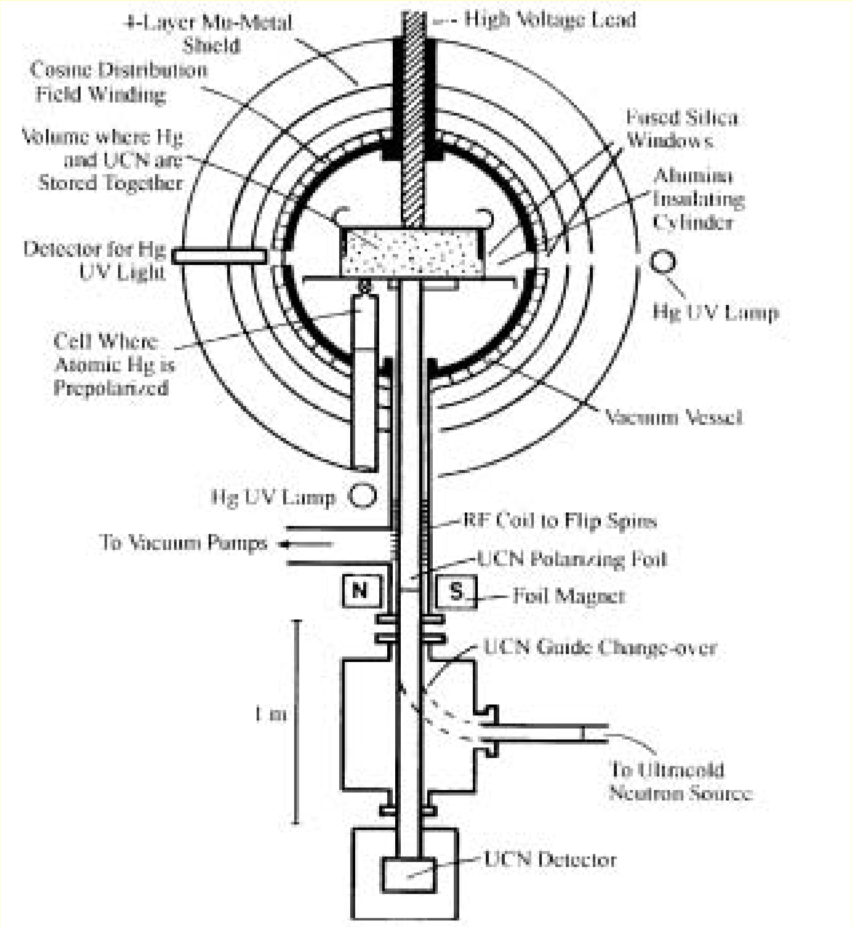
Trapped Ultra-Cold Neutrons (UCN) with N_{UCN} = 0.5 UCN/cc

|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

n-EDM vs Time (Moore's Law)