Neutron Physics

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5 lectures:

1. Physics/Technology of Cold and Ultracold Neutrons
2. Electroweak Standard Model Tests [neutron beta decay]
3. Nuclear physics/QCD [weak interaction between nucleons]
4. Physics Beyond the Standard Model [EDM/T violation, B]
5. Other interesting stuff that neutrons can do [NNN interaction, searches for extra dimensions,…]

Physics Beyond SM with Neutrons: T/B Violation

1. Some facts about T violation
2. Connection with Big Bang Theory: Baryon Asymmetry
3. Neutron electric dipole moment searches
4. Neutron-antineutron oscillations

Thanks for slides to: Jen-chieh Peng (Illinois), Philip Harris (Sussex), Yuri Kamyshkov (Tennessee), Albert Young (NC State), Tony Mann (Tufts)

T/CPT Invariance: Some Facts

Classical Mechanics: T=motion reversal: $x \rightarrow x$, $p \rightarrow -p$, $s \rightarrow -s$

Quantum Mechanics: demand same behavior for operators $\rightarrow$
$[p,x]=-ih$, $[p', x']=T\,[p,x]T^{-1}=[-p,x] \rightarrow T i\, T^{-1}=-i$, T is an antiunitary operator, no conserved quantum number. T=UK, U unitary

$T^2=\pm 1$ for even/odd # of spin 1/2 particles

T reverses initial and final states: $|\psi'\rangle = T\,|\psi\rangle$, $|\varphi'\rangle = T|\varphi\rangle \rightarrow$
$\langle\psi'|\varphi'\rangle = \langle T\psi|T|\varphi\rangle = \langle U\psi^*|U|\varphi^*\rangle = \langle\psi^*|U^\dagger U|\varphi^*\rangle = \langle\psi|\varphi\rangle^* = \langle\varphi|\psi\rangle$
$\rightarrow$ for an odd system $|\psi\rangle$ and $T\,|\psi\rangle$ are orthogonal (Kramers theorem)

Relativistic QFT: CPT theorem says CPT is conserved for systems (1) described by local field operators, (2) invariant under Lorentz transformations, and (3) with a Hermitian Hamiltonian

T Invariance: Some Consequences

A system with spherical symmetry cannot possess a static EDM (in the absence of an accidental degeneracy) if the dynamics are T invariant

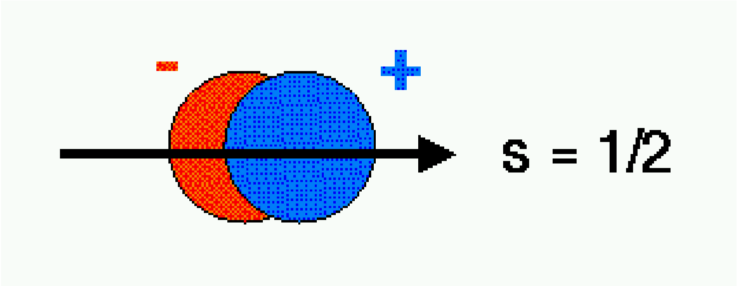
$T E T^{-1}=E$, $T D T^{-1}=D$, $T J T^{-1}=-J$, rotational invariance: $D \sim J$,
$T H T^{-1} = H$, $H = D \bullet E \rightarrow D = 0$ (D also violates P)

T invariant dynamics implies detailed balance, but not the other way around!(ex: thermal equilibrium can give detailed balance even if forcces violate T)

$$S_{ba} = \langle \psi_b^- \mid \psi_a^+ \rangle = \langle T\psi_a^+ \mid T\psi_b^- \rangle = e^{i(\varphi_b - \varphi_a)} \langle \psi_{`a}^- \mid \psi_{`b}^+ \rangle$$
$$= e^{i(\varphi_b - \varphi_a)} S_{`a\,`b}$$

Neutron Electric Dipole Moment

$$q_n = \int \rho(x) d^3x = (-0.4 \pm 1.1) \times 10^{-21} e$$



$$\vec{d}_n = \int \vec{x} \rho(x) d^3x = d_n \hat{s}$$

Non-zero d_n violates both P and T

Under a parity operation:

$$\hat{s} \to \hat{s}, \quad \vec{E} \to -\vec{E}$$

$$\vec{d}_n \cdot \vec{E} \to -\vec{d}_n \cdot \vec{E}$$

Under a time-reversal operation:

$$\hat{s} \to -\hat{s}, \quad \vec{E} \to \vec{E}$$

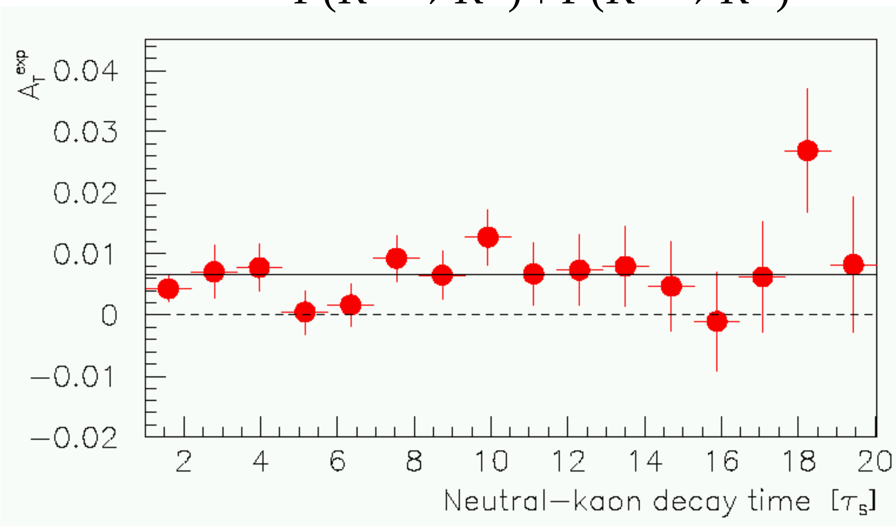
$$\vec{d}_n \cdot \vec{E} \to -\vec{d}_n \cdot \vec{E}$$

CP-Violation Experiments

Neutral Kaon System

Observation of T-violation at CPLEAR

$$A_T = \frac{P(\overline{K}^0 \to K^0) - P(K^0 \to \overline{K}^0)}{P(\overline{K}^0 \to K^0) + P(K^0 \to \overline{K}^0)}$$

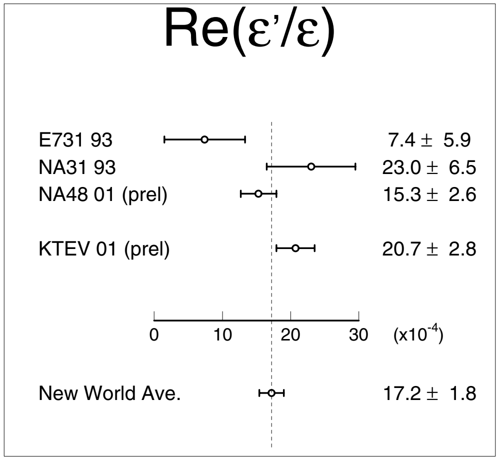


$$\langle A_T^{\exp} \rangle = (6.6 \pm 1.3) \times 10^{-3}$$

(PLB 444(1998)43)

Observation of Direct CP-violation

$$R = \frac{\Gamma(K_L \to \pi^+\pi^-)/\Gamma(K_S \to \pi^+\pi^-)}{\Gamma(K_L \to \pi^0\pi^0)/\Gamma(K_S \to \pi^0\pi^0)}$$



$$\mathrm{Re}(\varepsilon' / \varepsilon) = (17.2 \pm 1.8) \times 10^{-4}$$

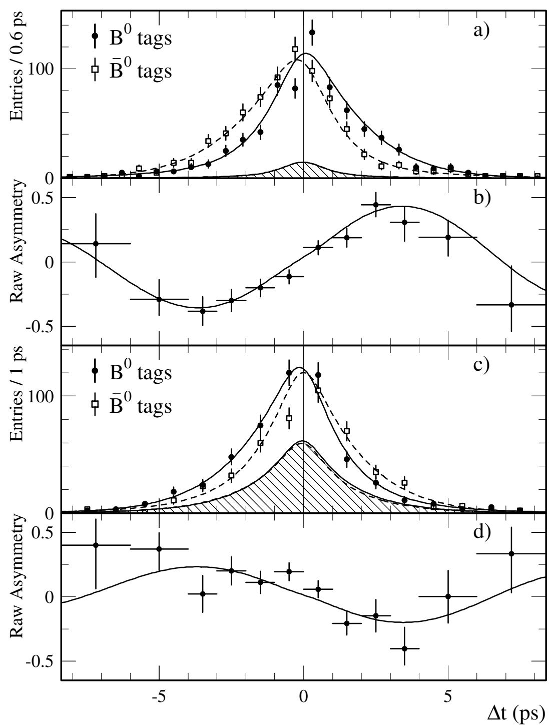
(hep-ex/0110020)

CP-Violation Experiments

Neutral B-Meson System

Observation of CP-violation at BaBar and Belle

$$A_{CP}(\Delta t) = \frac{f_+(\Delta t) - f_-(\Delta t)}{f_+(\Delta t) + f_-(\Delta t)} = -\eta_f \sin 2\beta \sin(\Delta m_d \Delta t)$$



BaBar: $\sin 2\beta = 0.741 \pm 0.067 \pm 0.034$

(hep-ex/0207042)

Belle: $\sin 2\beta = 0.719 \pm 0.074 \pm 0.035$

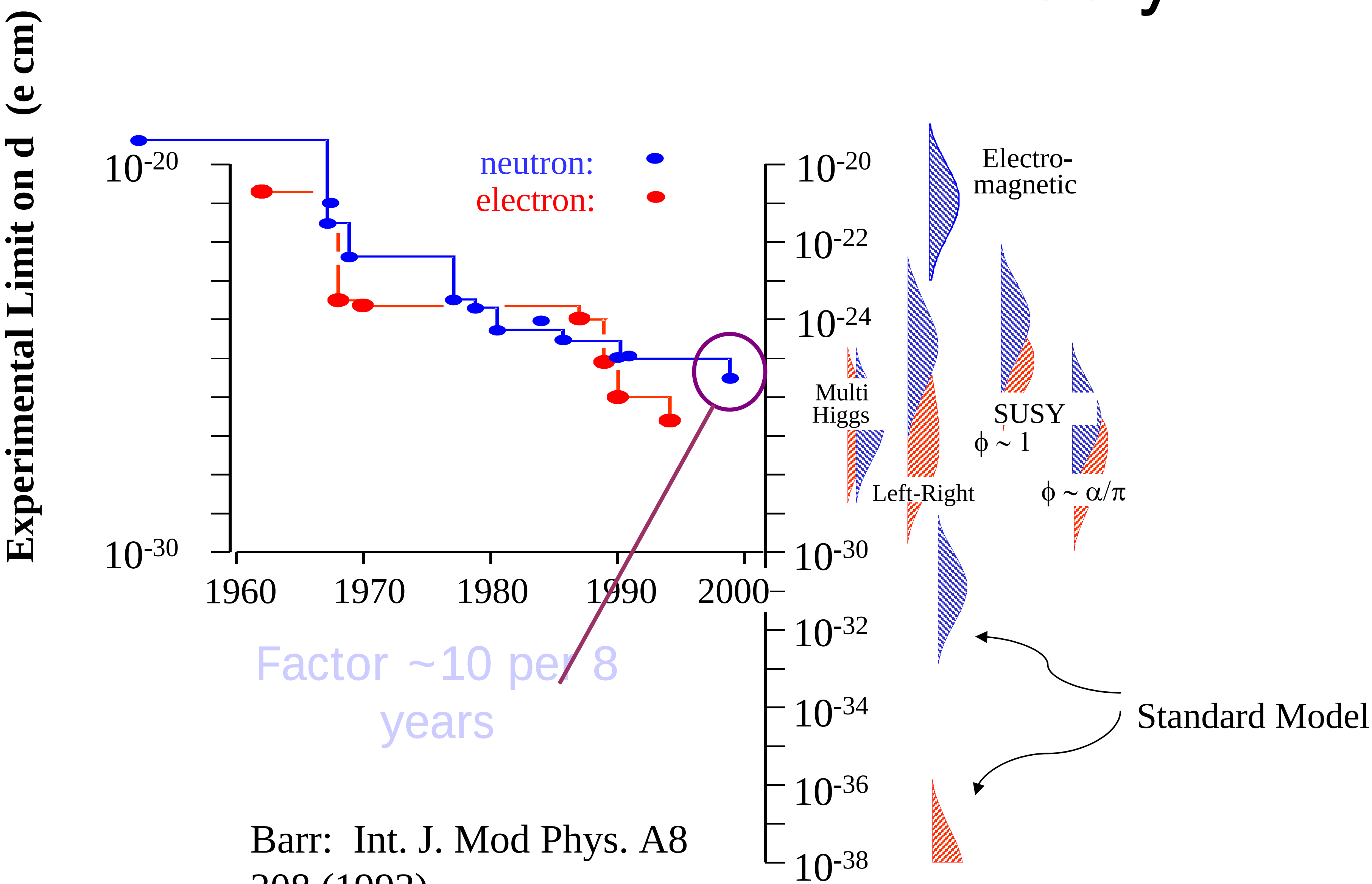
(hep-ex/0207098)

EDM candidates

- Neutron: Intrinsic EDM
- Electron/muon: Intrinsic EDM
- Atoms: P, T violating nucleon-nucleon or nucleon-electron interaction
- Ions?

- all sensitive to different physics beyond SM
- each gives new window on T
- must measure all to distinguish between T violation models

EDM limits: the first 50 years



Factor ~10 per 8 years

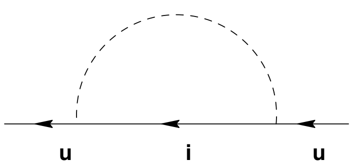
Barr: Int. J. Mod Phys. A8 208 (1993)

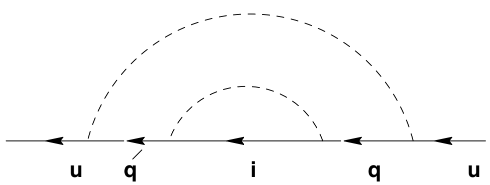
Neutron EDM in Standard Model

1) Electroweak Process

a) Contributions from single quark's EDM:

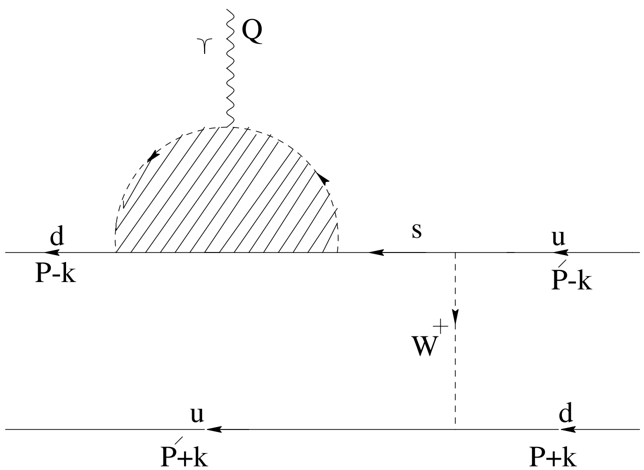
$$d_n \approx \frac{1}{3} d_u - \frac{4}{3} d_d$$





One and two-loop contributions are zero.
Three-loop contribution is ~10^{-34} *e•cm*

b) Contributions from diquark interactions:



$$d_n = \frac{38}{9\pi^3} (G_F m_N^2)^2 \frac{m_t^2}{m_s^2} \frac{m_N^2}{m_W^2} \frac{\Lambda}{m_N^4} \frac{e}{m_N} (\mathrm{Im} V)$$

$$\mathrm{Im} V = c_1 s_1^2 c_2 s_2 c_3 s_3 \sin(\delta)$$

d_n ~ 10^{-32} *e•cm*

(hep-ph/0008248)

Neutron EDM in Standard Model

2) Strong Interaction

θ term in the QCD Lagrangian :

$$L_\theta = \frac{\theta\ g_s^2}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu}$$

θ term's contribution to the neutron EDM :

$$d_n = \frac{e}{m_p} \frac{g_{\pi NN} \bar{g}_{\pi NN}}{4\pi^2} \ln \frac{m_\rho}{m_\pi}$$

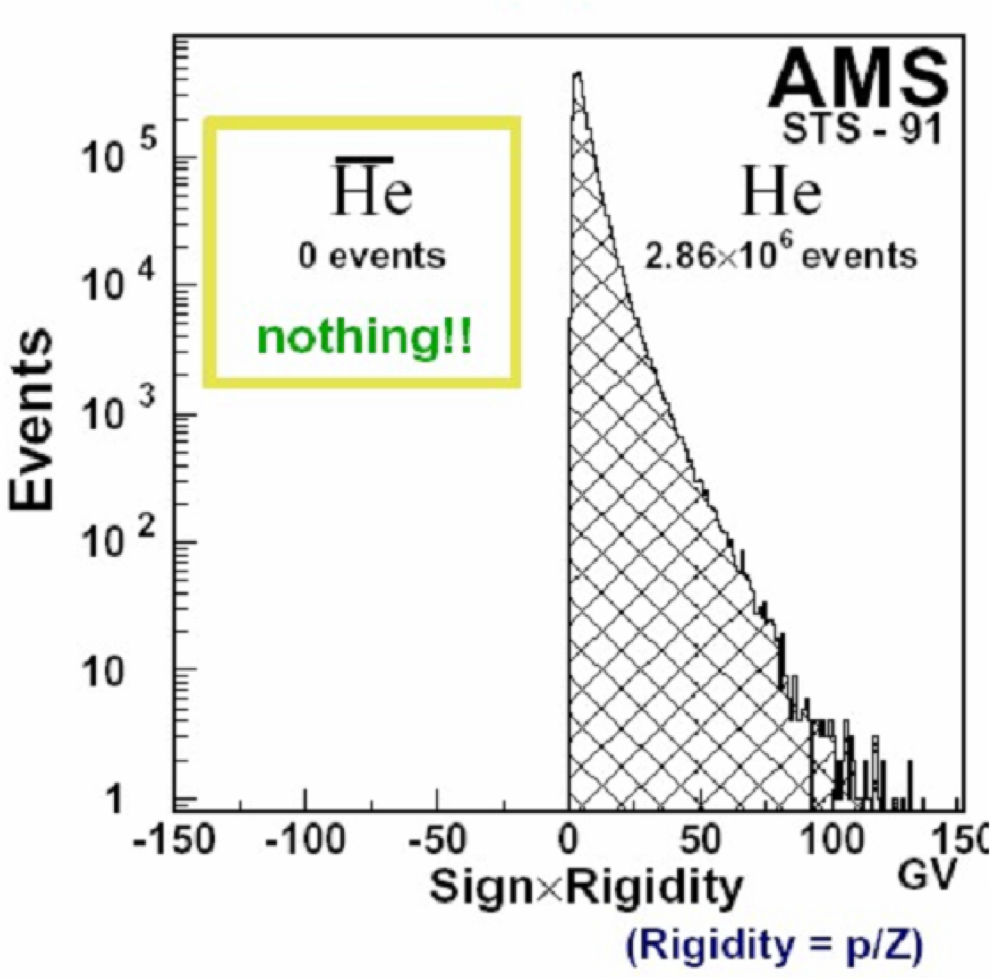
$$\bar{g}_{\pi NN} = -\theta \frac{m_u m_d}{m_u + m_d} \frac{\sqrt{2}}{f_\pi} \frac{M_\Xi - M_\Sigma}{m_s}$$

$d_n < 10^{-25}$ e•cm -> | θ | < 3 x 10^{-10}

Spontaneously broken Pecci-Quinn symmetry?

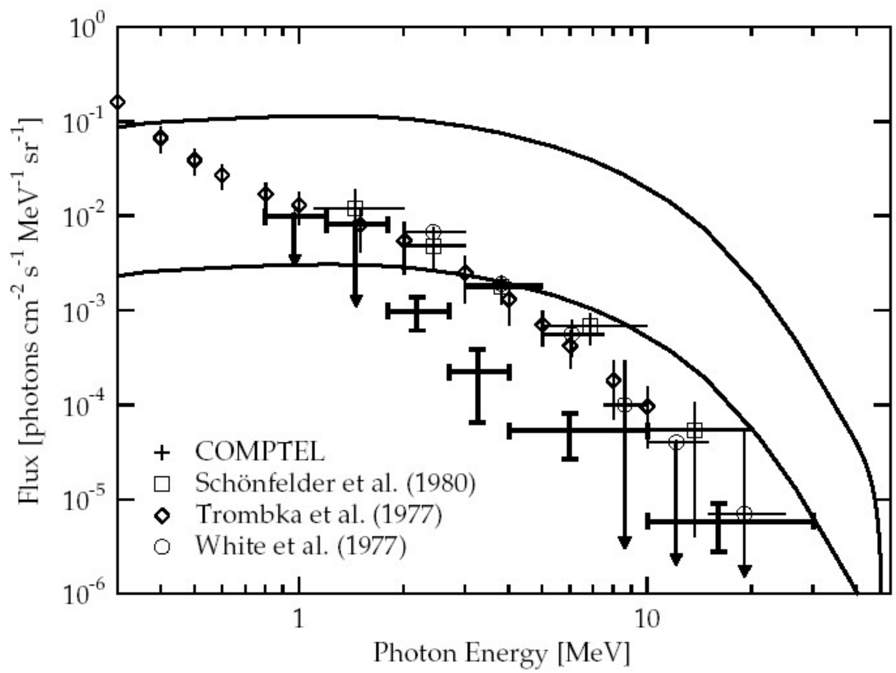
No evidence of a pseudoscalar axion!

Where's the antimatter?



"Search for antihelium in cosmic rays"
Phys. Lett. B461 (1999) 387.

Diffuse γ-ray flux
expected from annihilation



Cohen, De Rujula, Glashow;
astro-ph/9707087

Sakharov conditions for Baryon Asymmetry in Big Bang

A.D. Sakharov, JETP Lett. 5, 24-27, 1967

1. Baryon number violation
   – Not allowed at tree level, but permitted in higher-order processes in SM
2. Departure from thermal equilibrium
   – Expansion of Universe
   – Phase transitions
3. T violation
   – Note SM CPv is orders of magnitude too small to explain observed asymmetry – we need new physics.
   – Whatever model you choose, the larger-than-SM CPv brings with it a larger-than-SM EDM

Physics Motivation for Neutron EDM Measurement

- Time Reversal Violation
- Physics Beyond the Standard Model
  - Standard Model predicts $d_n \sim 10^{-31}$ e•cm
  - Super Symmetric Models predict $d_n \leq 10^{-25}$ e•cm
- Baryon Asymmetry of universe
  - Require CP violation beyond the SM

	SM Prediction	Experiment
e	10^{-40} e•cm	10^{-27} e•cm
p	10^{-38} e•cm	10^{-19} e•cm
n	10^{-31} e•cm	10^{-25} e•cm

List of Neutron EDM Experiments

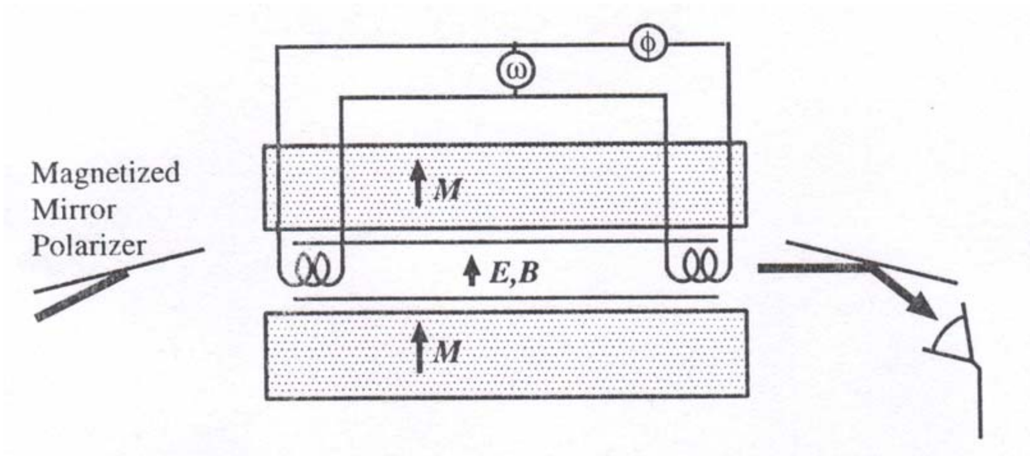
Ex. Type	<v>(m/cm)	E (kV/cm)	B (Gauss)	Coh. Time (s)	EDM (e.cm)	year
Scattering	2200	10^{25}	--	10^{-20}	$< 3 \times 10^{-18}$	1950
Beam Mag. Res.	2050	71.6	150	0.00077	$< 4\times 10^{-20}$	1957
Beam Mag. Res.	60	140	9	0.014	$< 7 \times 10^{-22}$	1967
Bragg Reflection	2200	10^{9}	--	10^{-7}	$< 8 \times 10^{-22}$	1967
Beam Mag. Res.	130	140	9	0.00625	$< 3 \times 10^{-22}$	1968
Beam Mag. Res.	2200	50	1.5	0.0009	$< 1 \times 10^{-21}$	1969
Beam Mag. Res.	115	120	17	0.015	$< 5 \times 10^{-23}$	1969
Beam Mag. Res.	154	120	14	0.012	$< 1 \times 10^{-23}$	1973
Beam Mag. Res.	154	100	17	0.0125	$< 3 \times 10^{-24}$	1977
UCN Mag. Res.	<6.9	25	0.028	5	$< 1.6 \times 10^{-24}$	1980
UCN Mag. Res.	<6.9	20	0.025	5	$< 6 \times 10^{-25}$	1981
UCN Mag. Res.	<6.9	10	0.01	60-80	$< 8 \times 10^{-25}$	1984
UCN Mag. Res.	<6.9	12-15	0.025	50-55	$< 2.6 \times 10^{-25}$	1986
UCN Mag. Res.	<6.9	16	0.01	70	$< 12 \times 10^{-26}$	1990
UCN Mag. Res.	<6.9	12-15	0.018	70-100	$< 9.7 \times 10^{-26}$	1992
UCN Mag. Res.	<6.9	4.5	0.01	120-150	$< 6.3 \times 10^{-26}$	1999

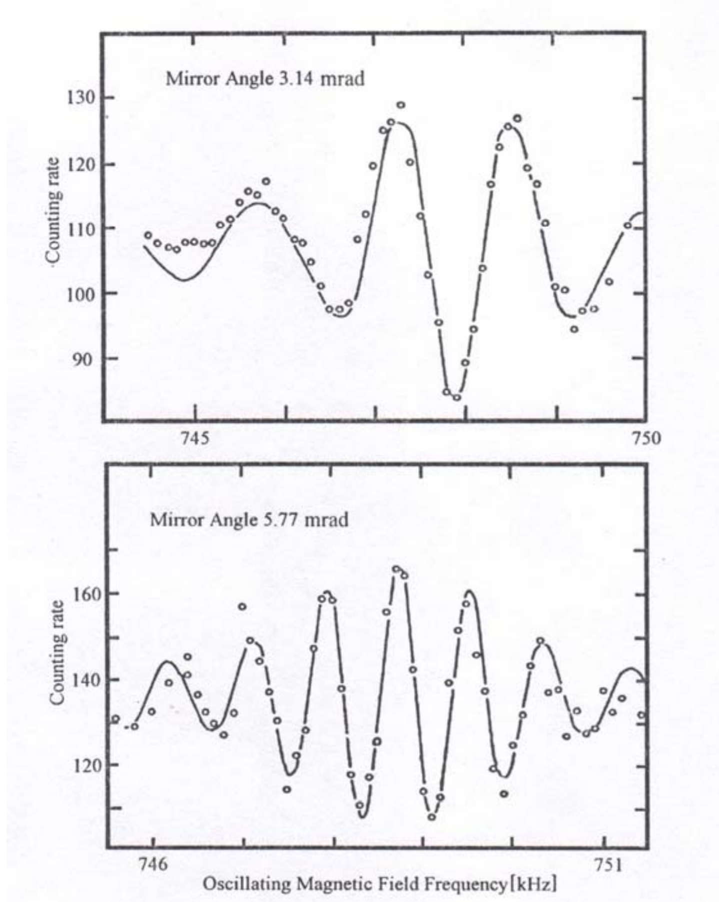
$$H = -\vec{\mu} \cdot \vec{B} \pm \vec{d} \cdot \vec{E}$$

B = 1mG => 3 Hz neutron precession freq.

d = 10^{-26} e•cm, E = 10 KV/cm => 10^{-7} Hz shift in precession freq.

Neutron Beam EDM Experiments



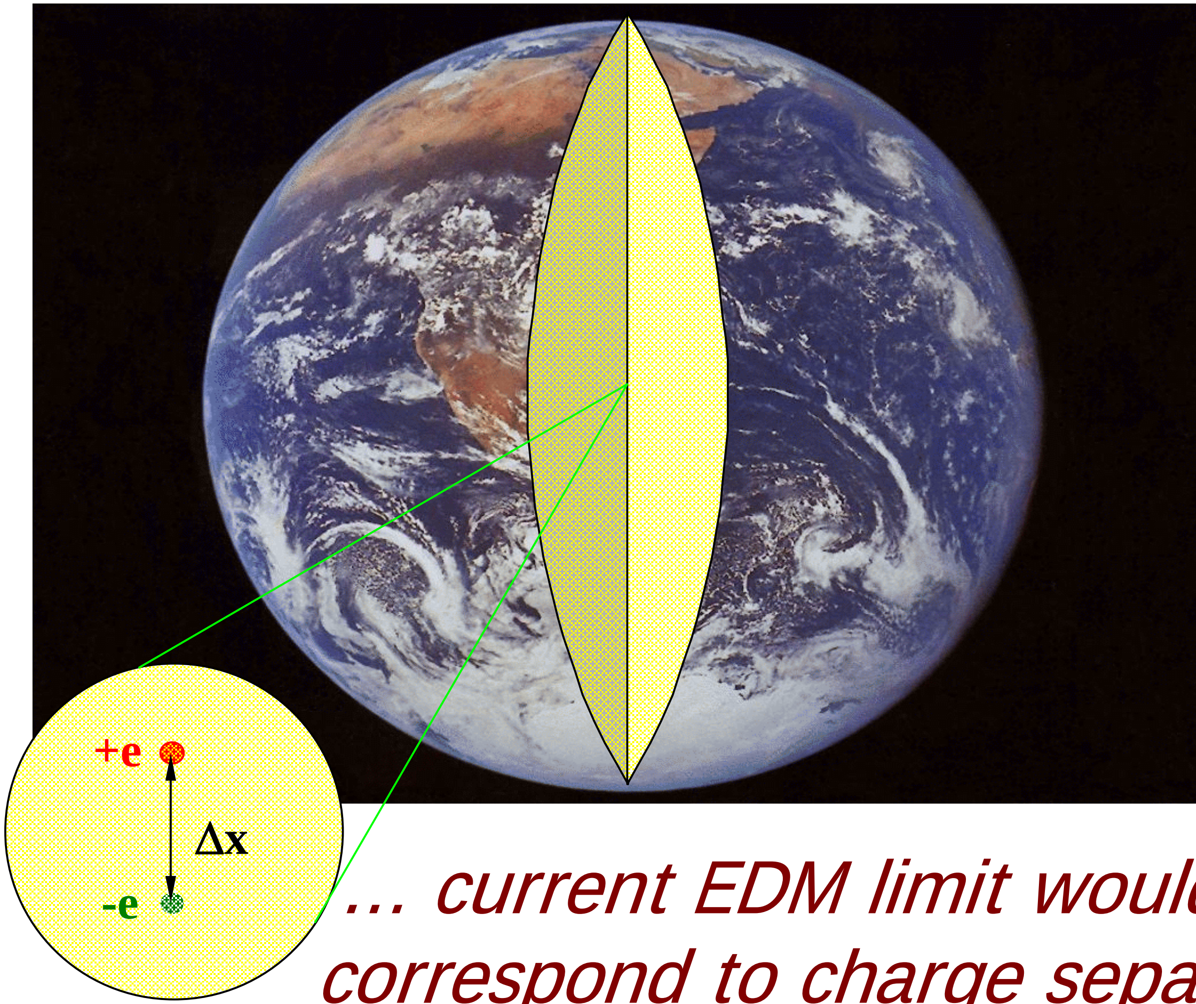


Limitations:

- Short duration between the two RF pulses
- Systematic error due to motional magnetic field (v x E)

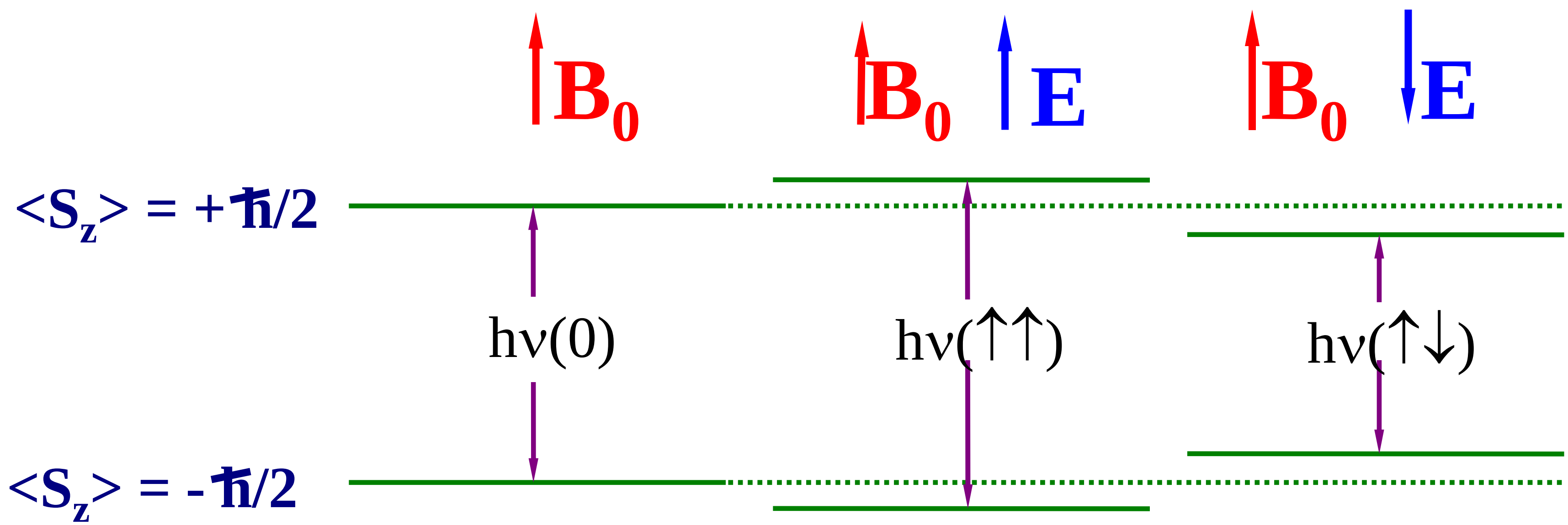
Both can be improved using lower-energy neutrons

Reality check



… current EDM limit would correspond to charge separation of $\Delta x \approx 10\mu$

EDM Measurement principle

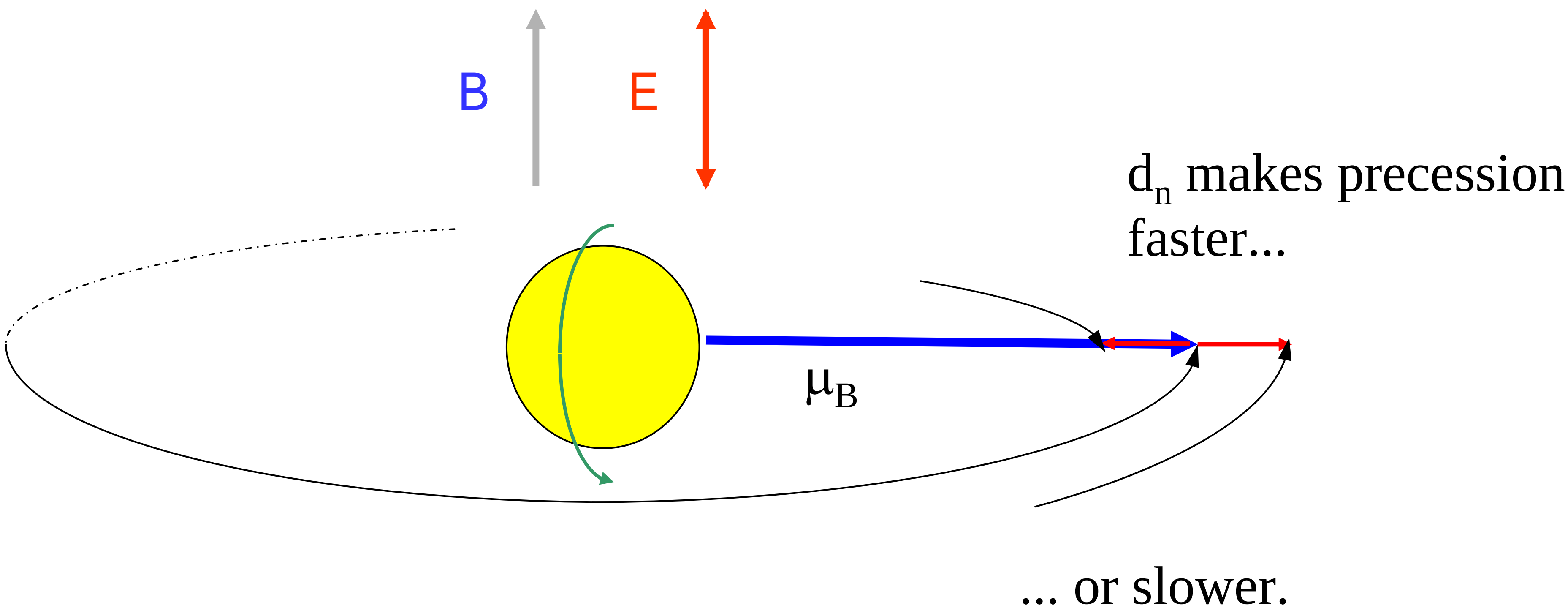


$\nu(\uparrow\uparrow) - \nu(\uparrow\downarrow) = -4\,E\,d/h$

assuming B unchanged when E is reversed.

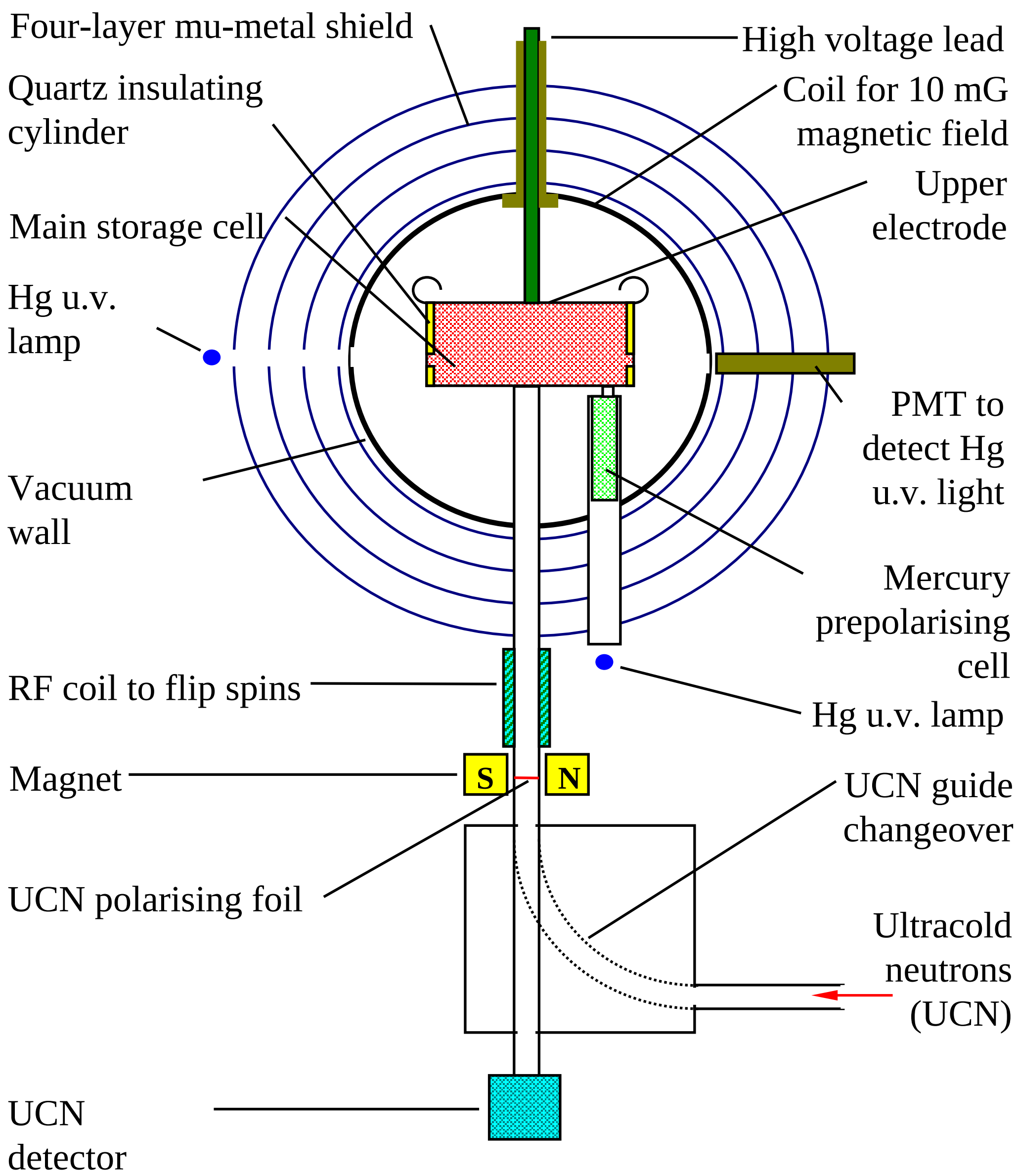
Measurement principle

- Measure Larmor spin precession freq in parallel & antiparallel **B** and **E** fields

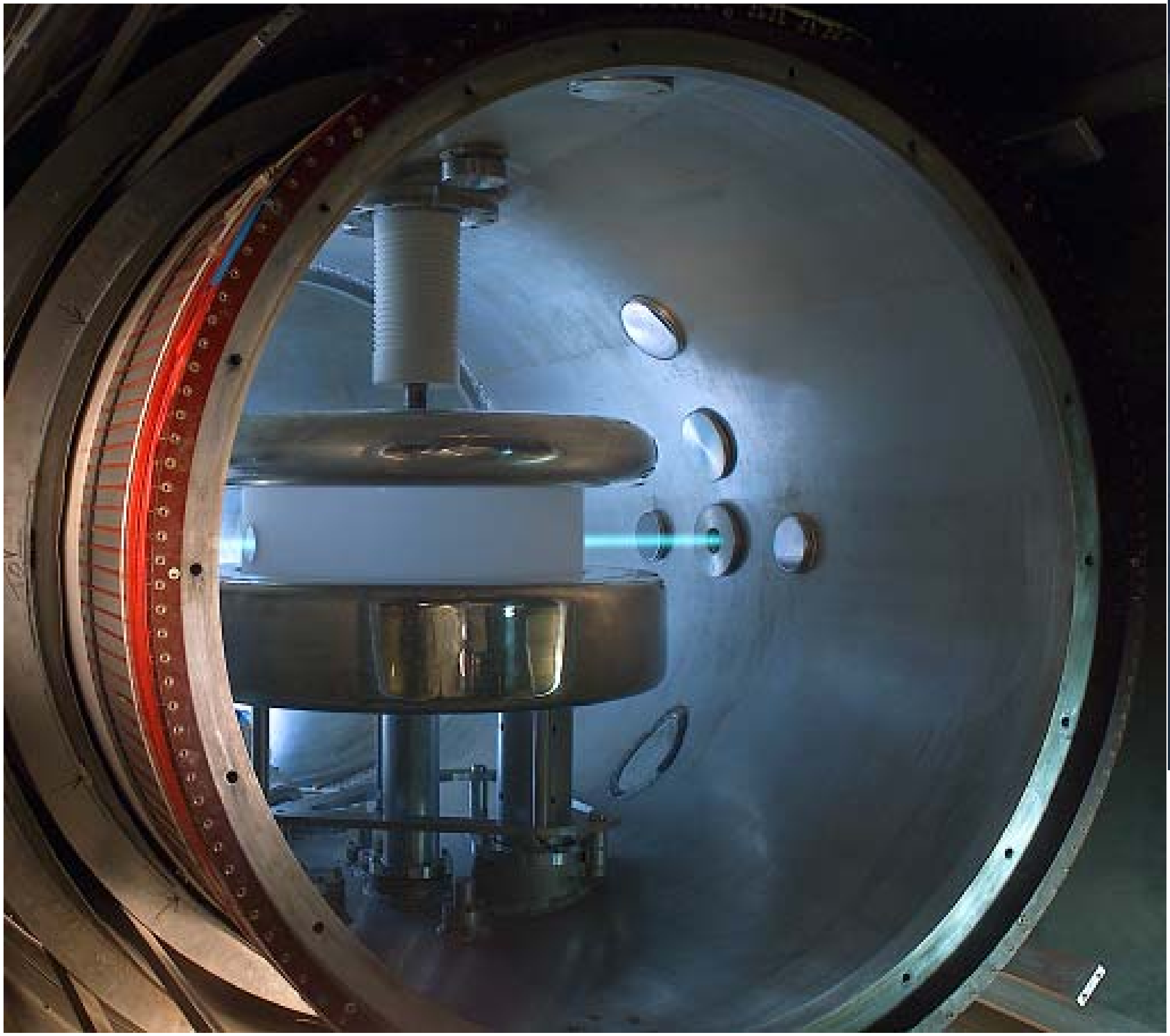


So, reverse E relative to B and look for freq shift.

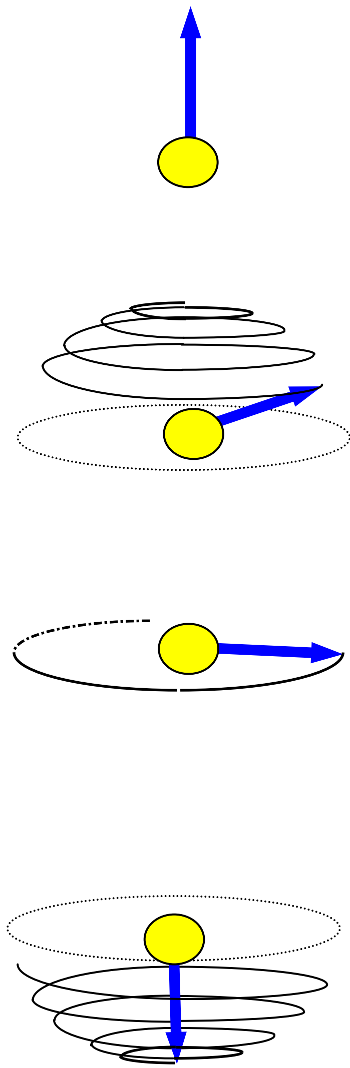
nEDM apparatus at ILL



Neutron storage bottle



Ramsey method of Separated Oscillating Fields

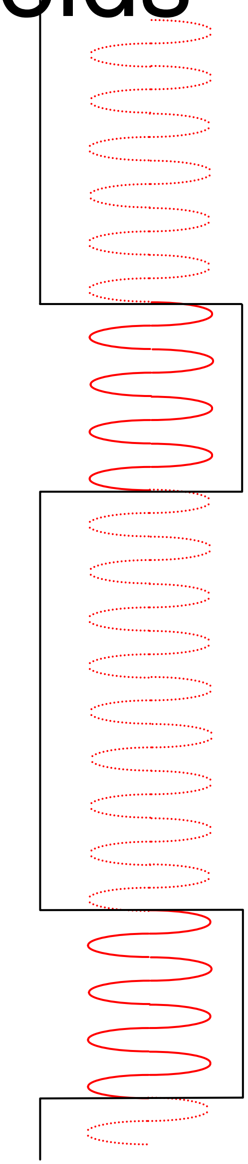


1. *"Spin up" neutron...*

2. *Apply $\pi/2$ spin flip pulse...*

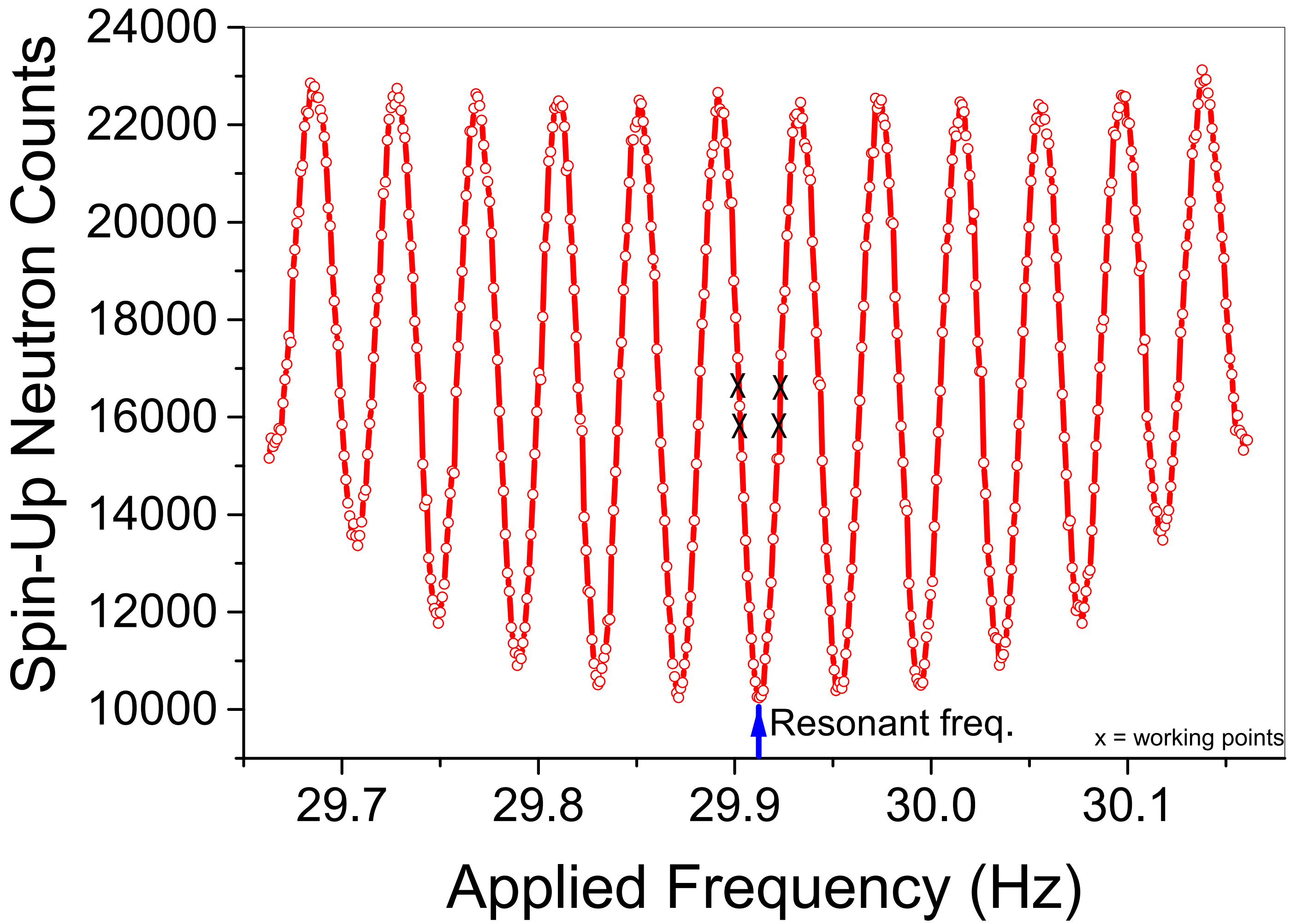
3. *Free precession. ..*

4. *Second $\pi/2$ spin flip pulse.*



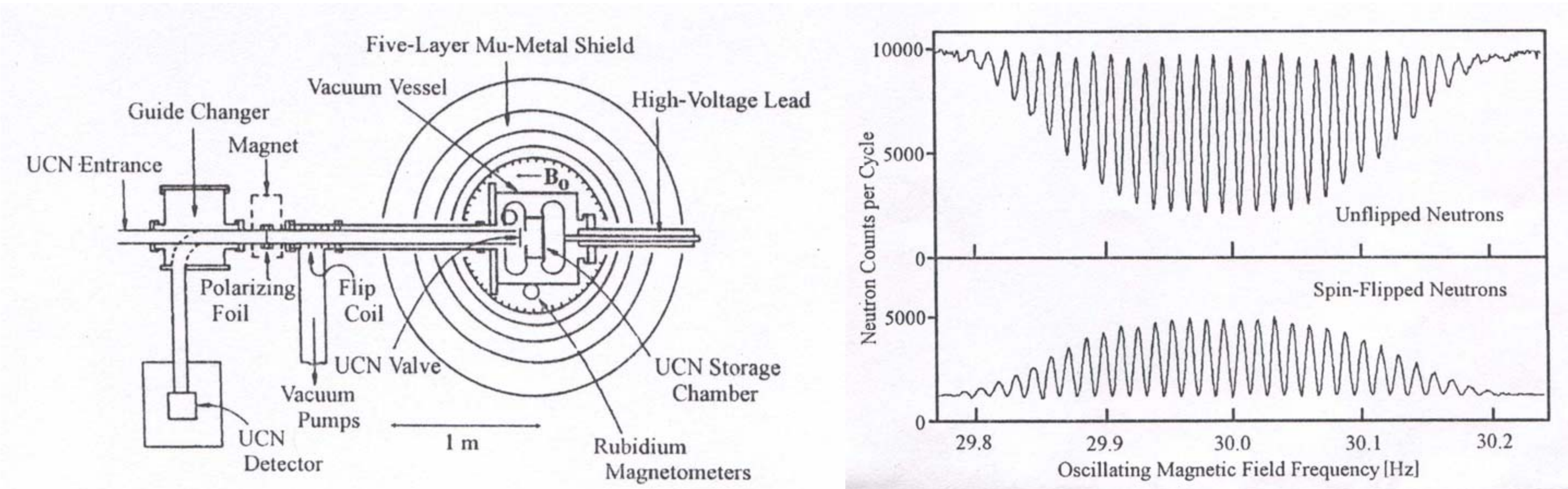
Ramsey resonance

- “2-slit” interference pattern
- Phase gives freq offset from resonance



Neutron EDM Experiment with Ultra Cold Neutrons

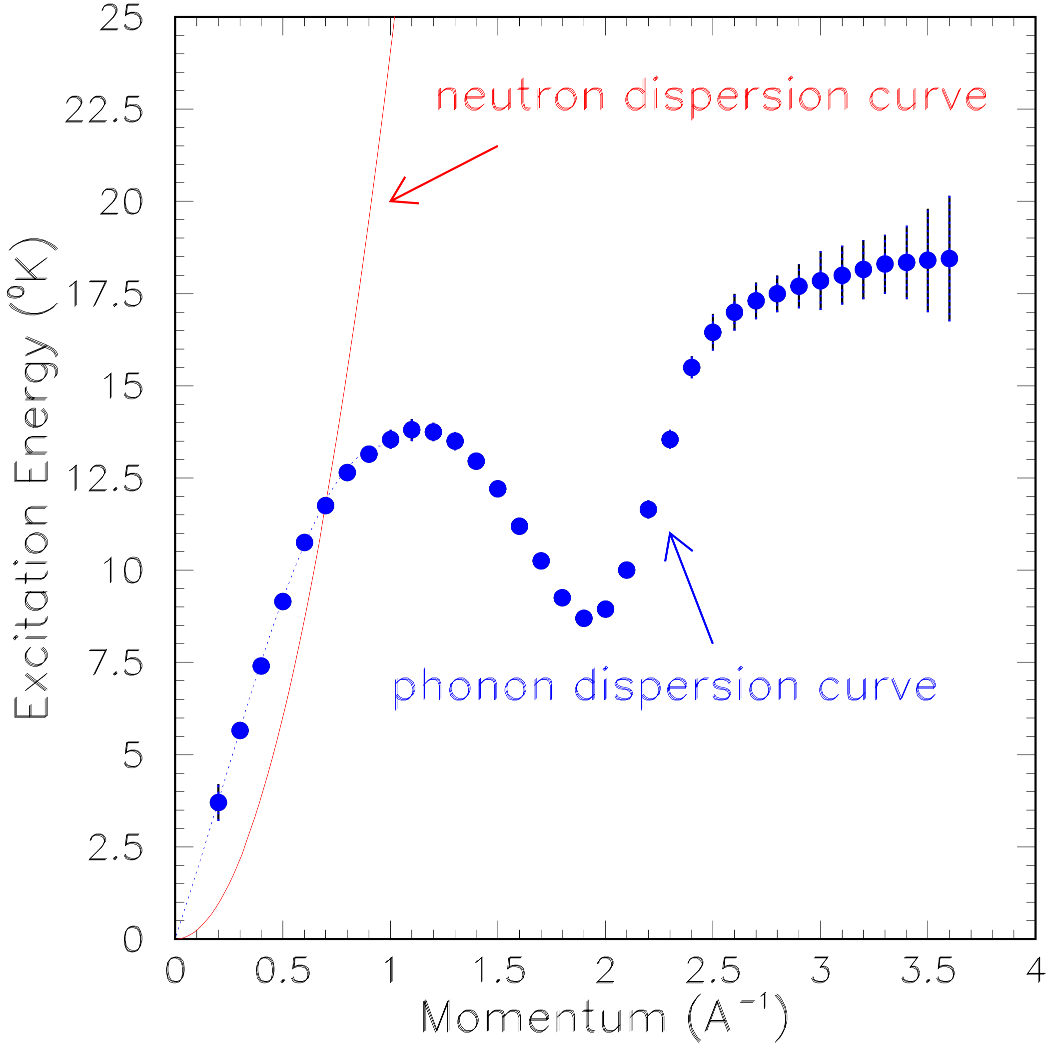
Most Recent ILL Measurement



- Use ^{199}Hg co-magnetometer to sample the variation of B-field in the UCN storage cell
- Limited by low UCN flux of ~ 5 UCN/cm^3
- Figure–of-merit ~ $E(NT)^{1/2}$

A new approach aims at N → 100 N, T → 5 T, E → 5 E

UCN Production in Superfluid ^{4}He

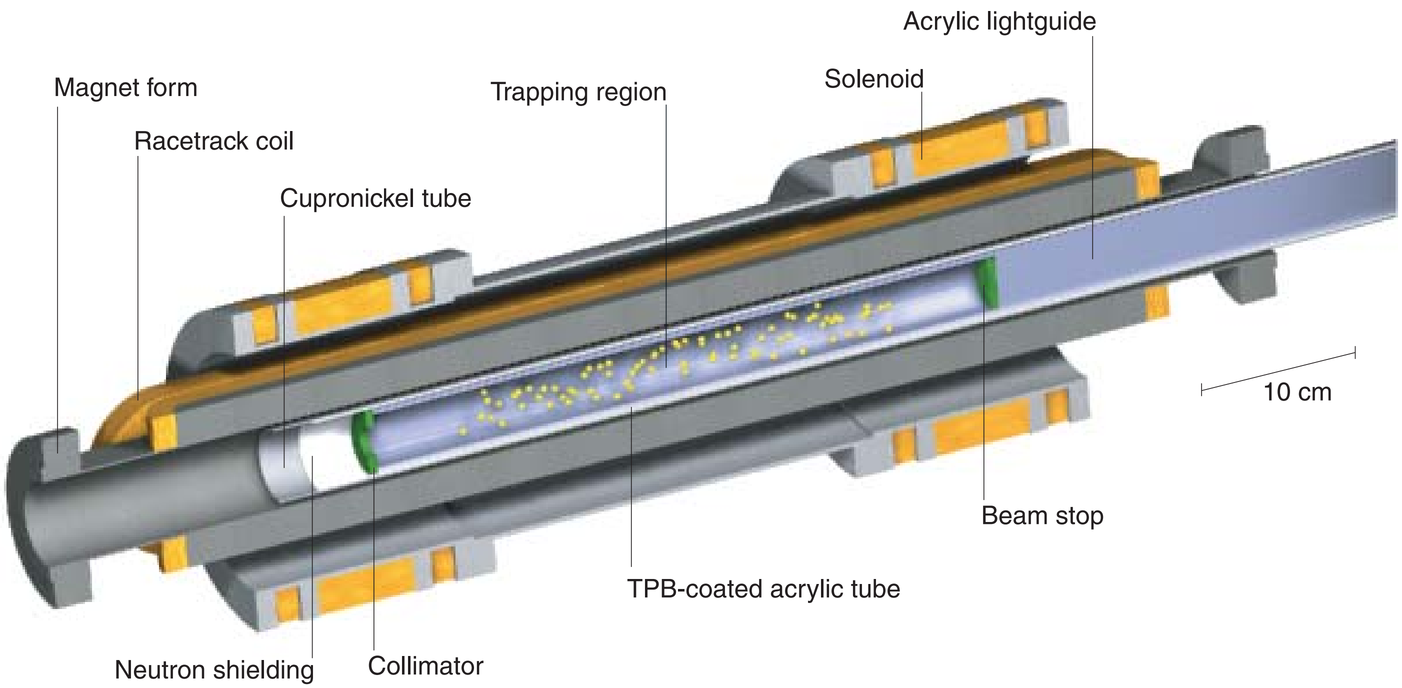


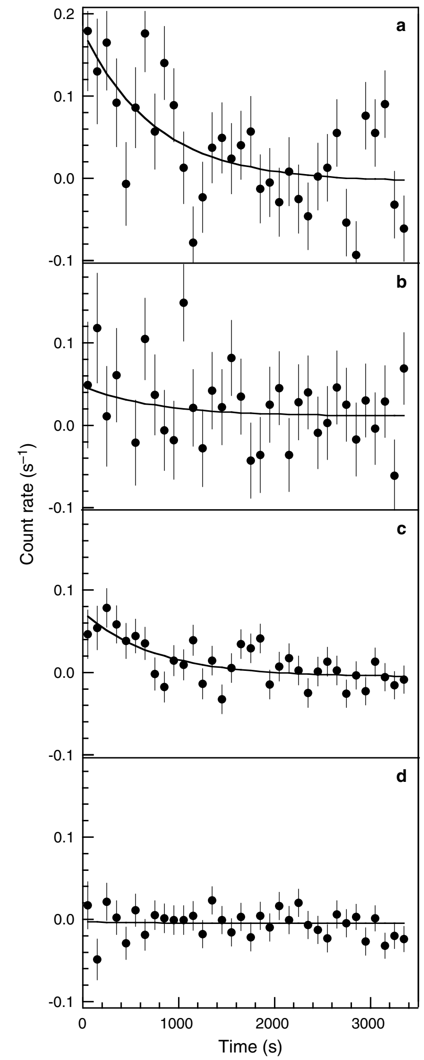
Incident cold neutron with momentum of 0.7 A^{-1} (1 mev) can excite a phonon in ^{4}He and become an UCN

UCN Production in Superfluid ^{4}He

Magnetic Trapping of UCN

(Nature 403 (2000) 62)





560 ± 160 UCNs trapped per cycle (observed)

480 ± 100 UCNs trapped per cycle (predicted)

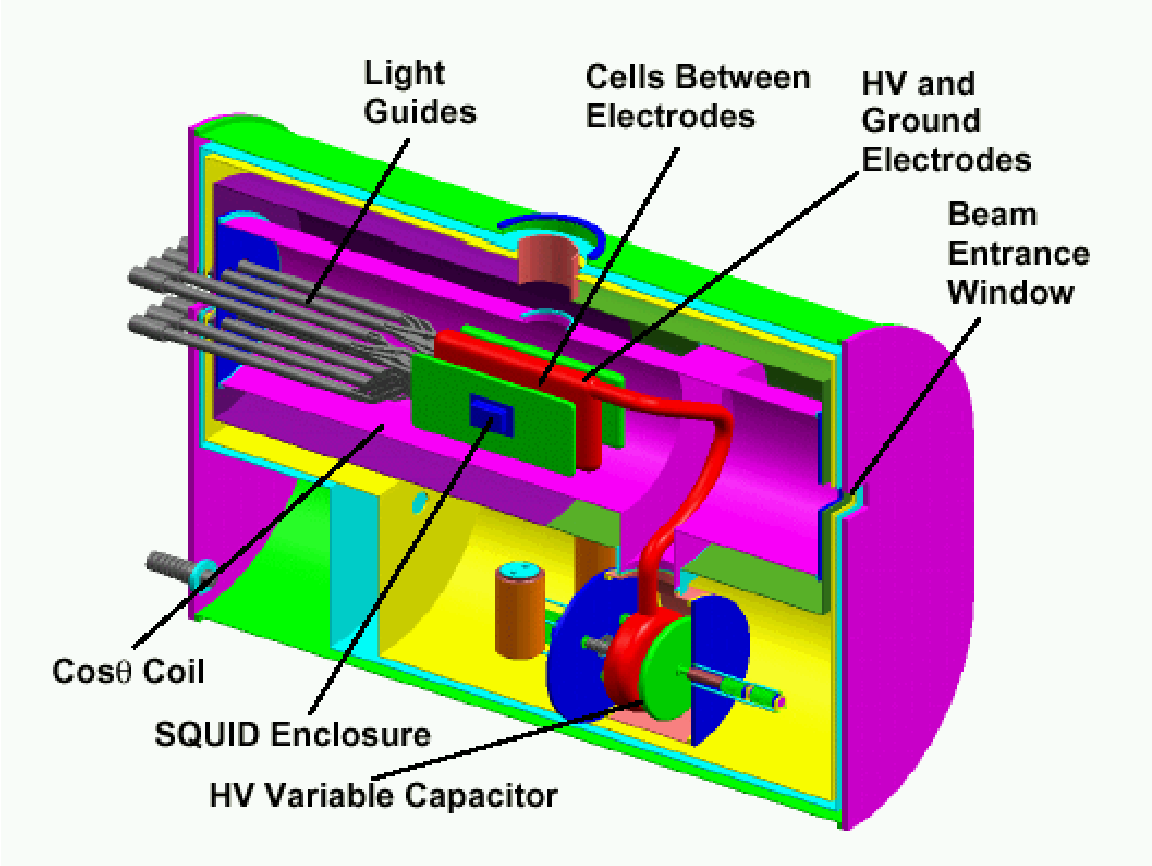
UCN Losses in Superfluid ^{4}He Bottle

- Neutron beta decay
- Wall absorption
- Upscattering in superfluid ^{4}He
  - Single-phonon upscattering rate ~ $e^{-1/KT}$
  - Multi-phonon upscattering rate ~ T^7
- n – ^{3}He absorption
  - Require purified ^{4}He with $^3He/^4He < 10^{-11}$

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

Total spin	σ_{abs} at v = 5m/sec
J = 0	~ 4.8 x 10^6 barns
J = 1	~ 0

A Preproposal by the UCN Collaboration



(Based on the idea originated by R. Golub and S. Lamoreaux in 1994)

Collaborating institutes:

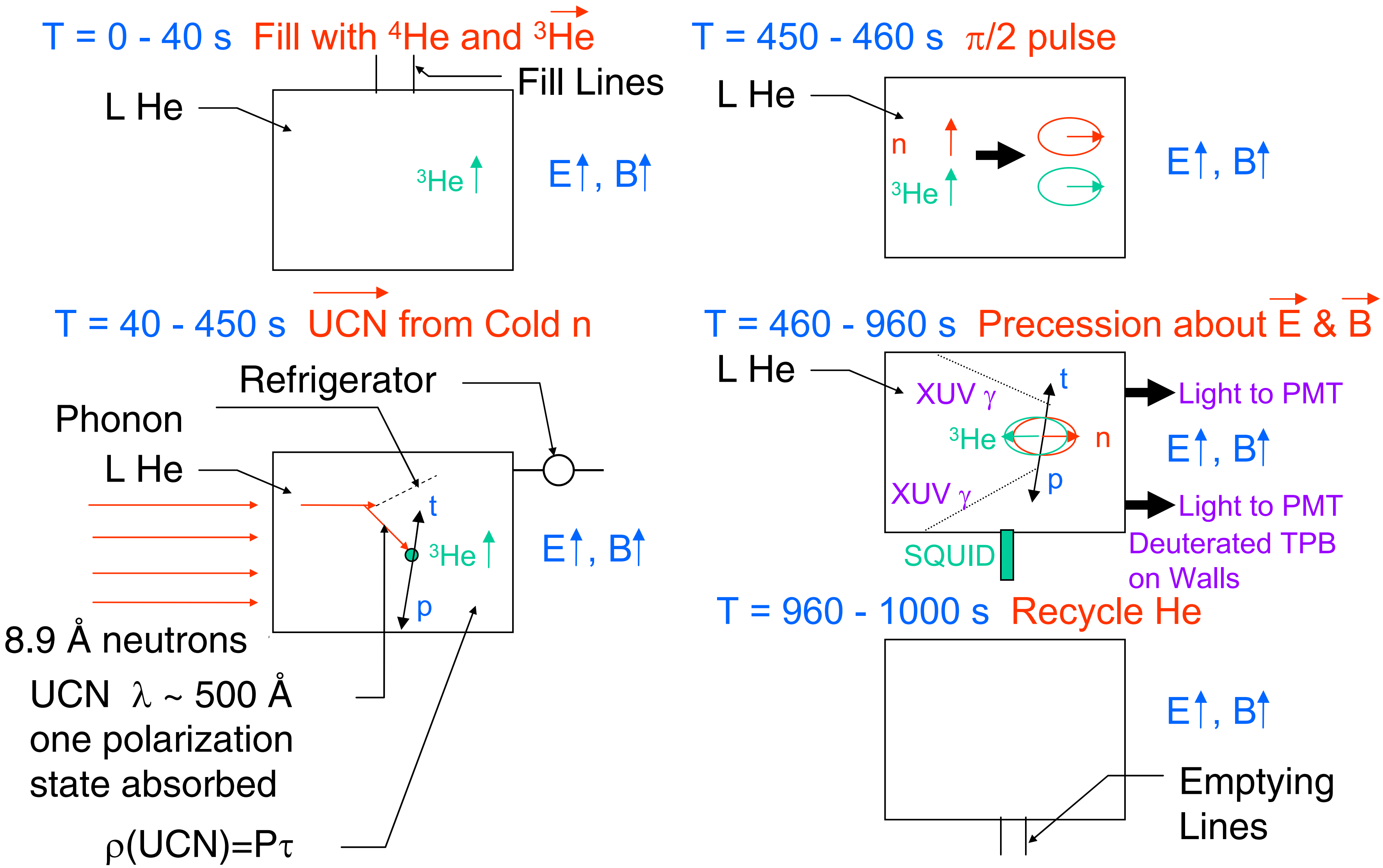
UC Berkeley, Caltech, Duke, Hahn-Meitner, Harvard, Hungarian Academy of Sciences, UIUC, ILL, Leiden, LANL, NIST, UNM, ORNL, Simon-Fraser

Neutron EDM Measurement Cycle

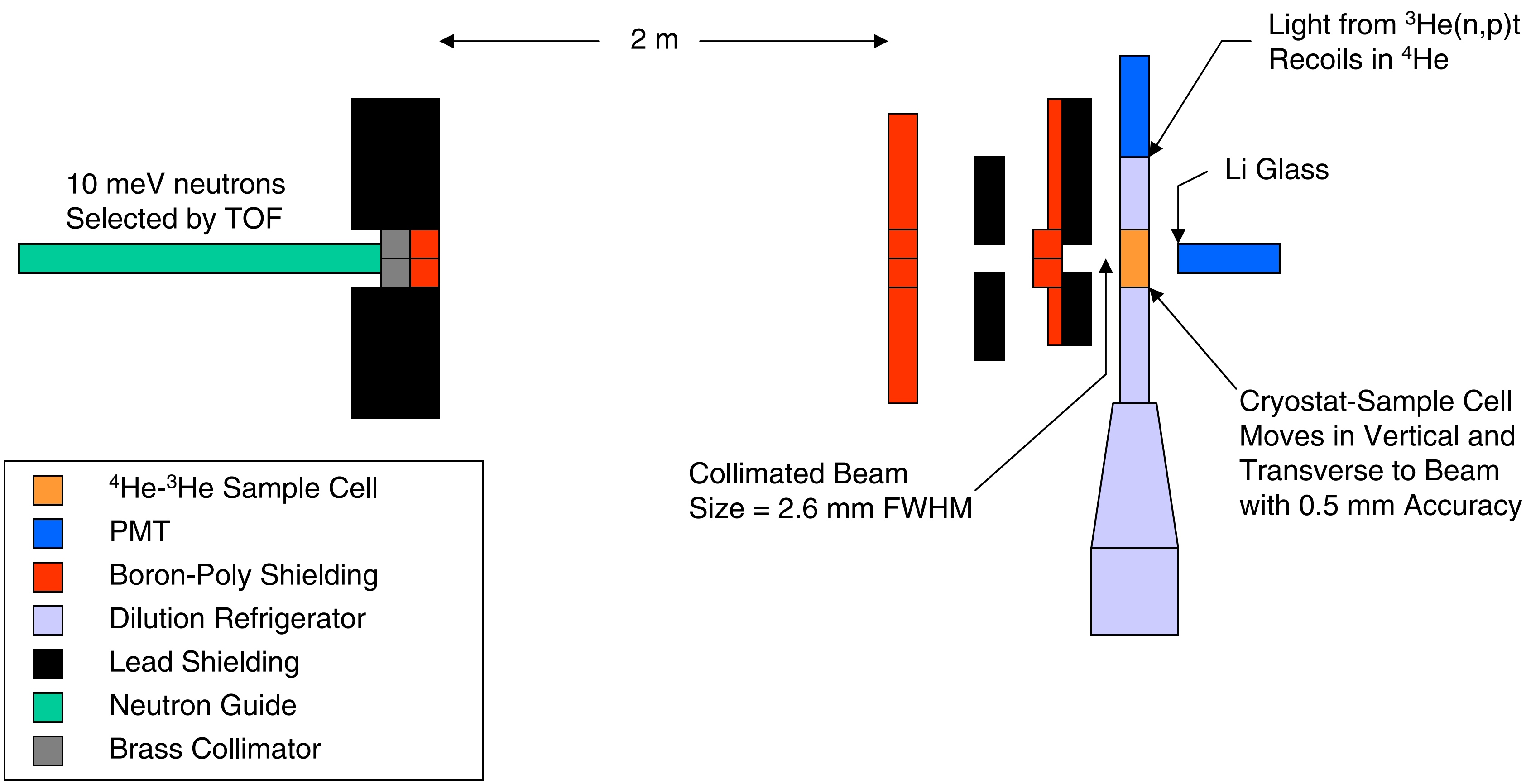
- Fill cells with superfluid ^{4}He containing polarized ^{3}He
- Produce polarized UCNs with polarized cold neutron beam
- Flip n and ^{3}He spin by 90^o using a π/2 RF coil
- Precess UCN and ^{3}He in a uniform B field (~1mG) and a strong E field (~50KV/cm). (ν(^{3}He) ~ 3.3 Hz, ν(n) ~ 3 Hz)
- Detect scintillation light from the reaction n + ^{3}He → p + t (and from other sources, including neutron beta decays)
- Empty the cells and change E field direction and repeat the measurement

$$\phi(t) = Ne^{-\Gamma_{tot}t}\{\frac{1}{\tau_\beta} + \frac{1}{\tau_3}[1 - P_3P_n\cos(\omega_r t + \phi)]\}$$

EXPERIMENT CYCLE

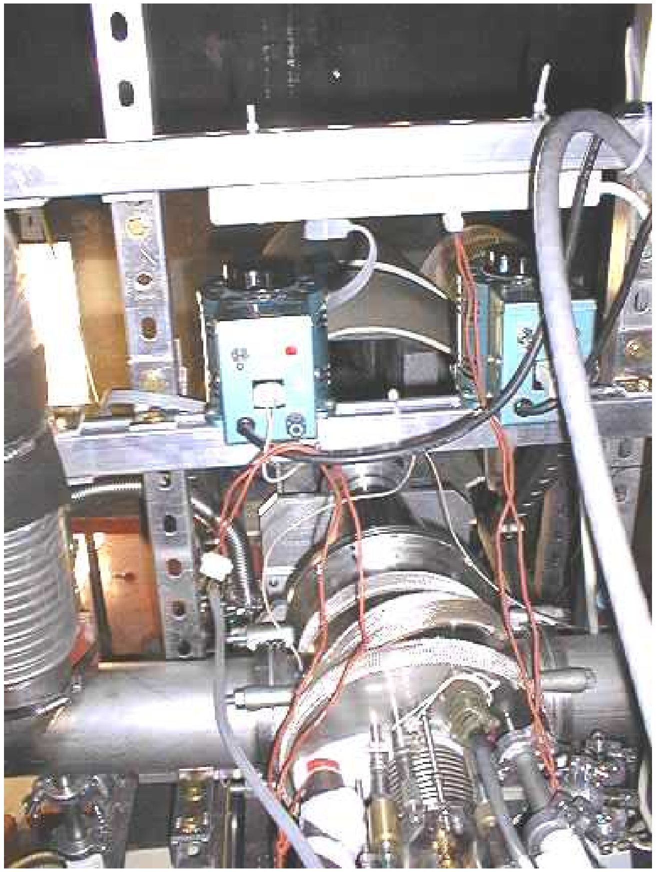


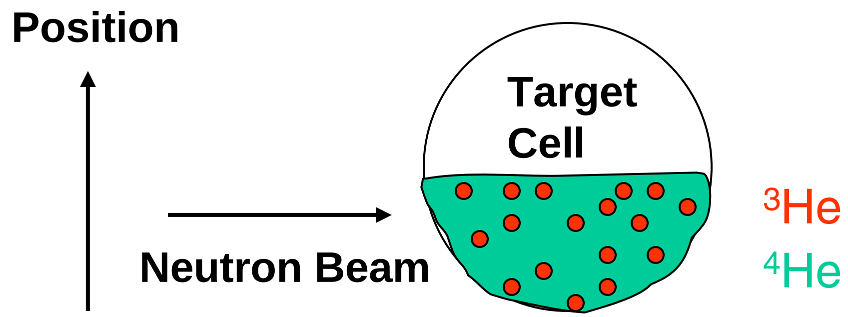
EXPERIMENTAL LAYOUT
LANSCE FP 11a

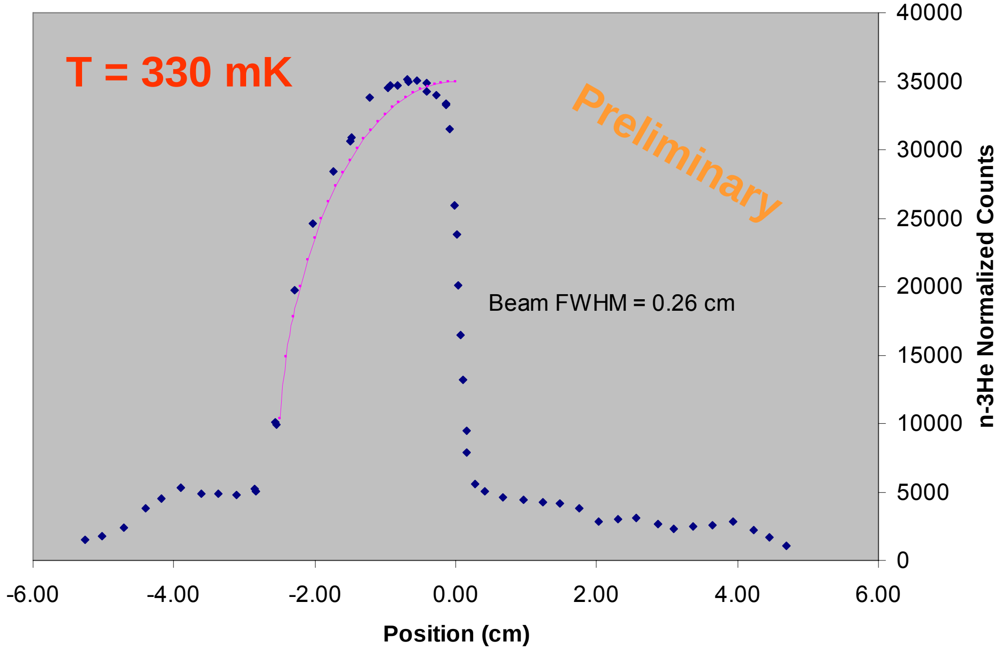


^{3}He Distributions in Superfluid ^{4}He

Dilution Refrigerator at LANSCE Flight Path 11a

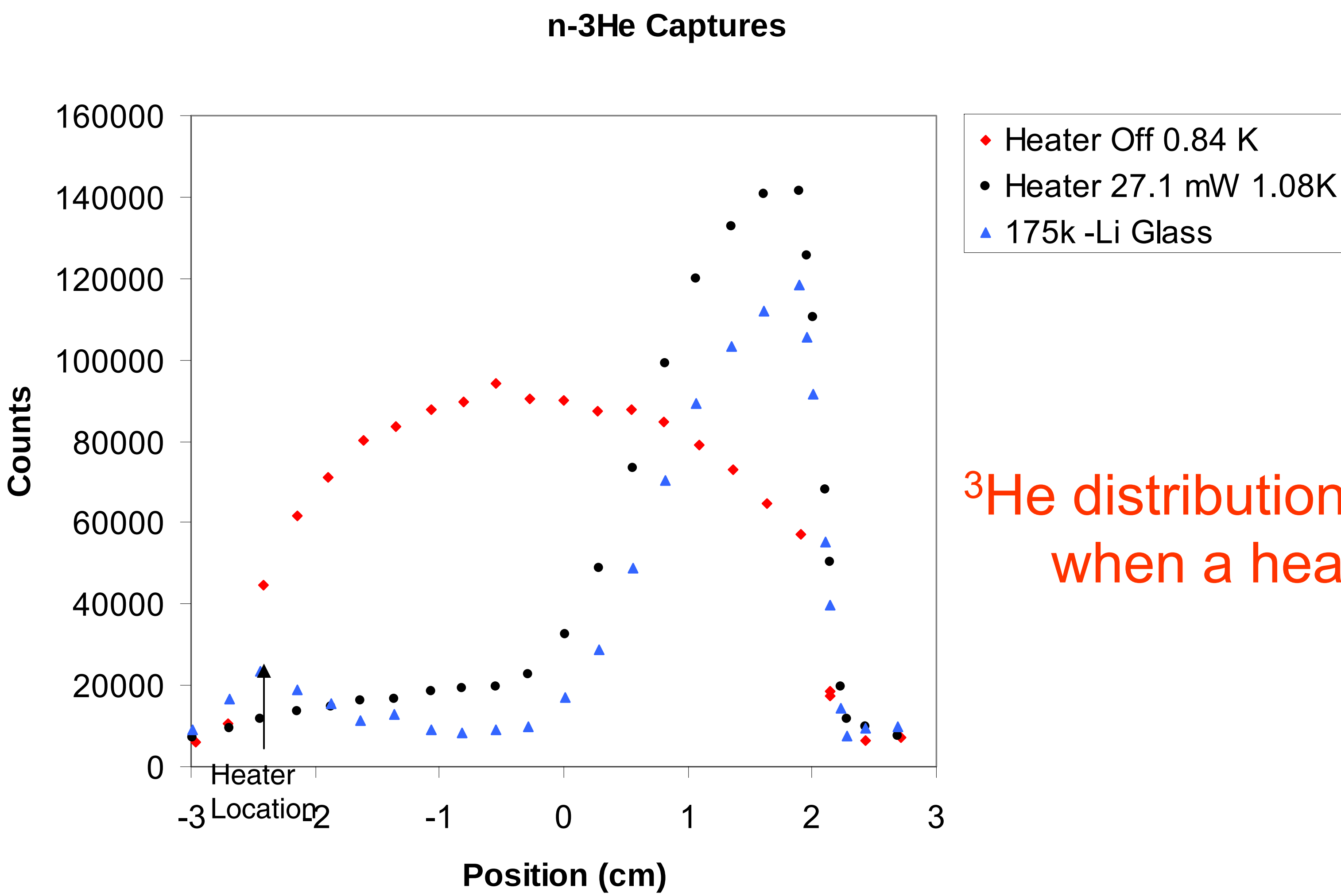






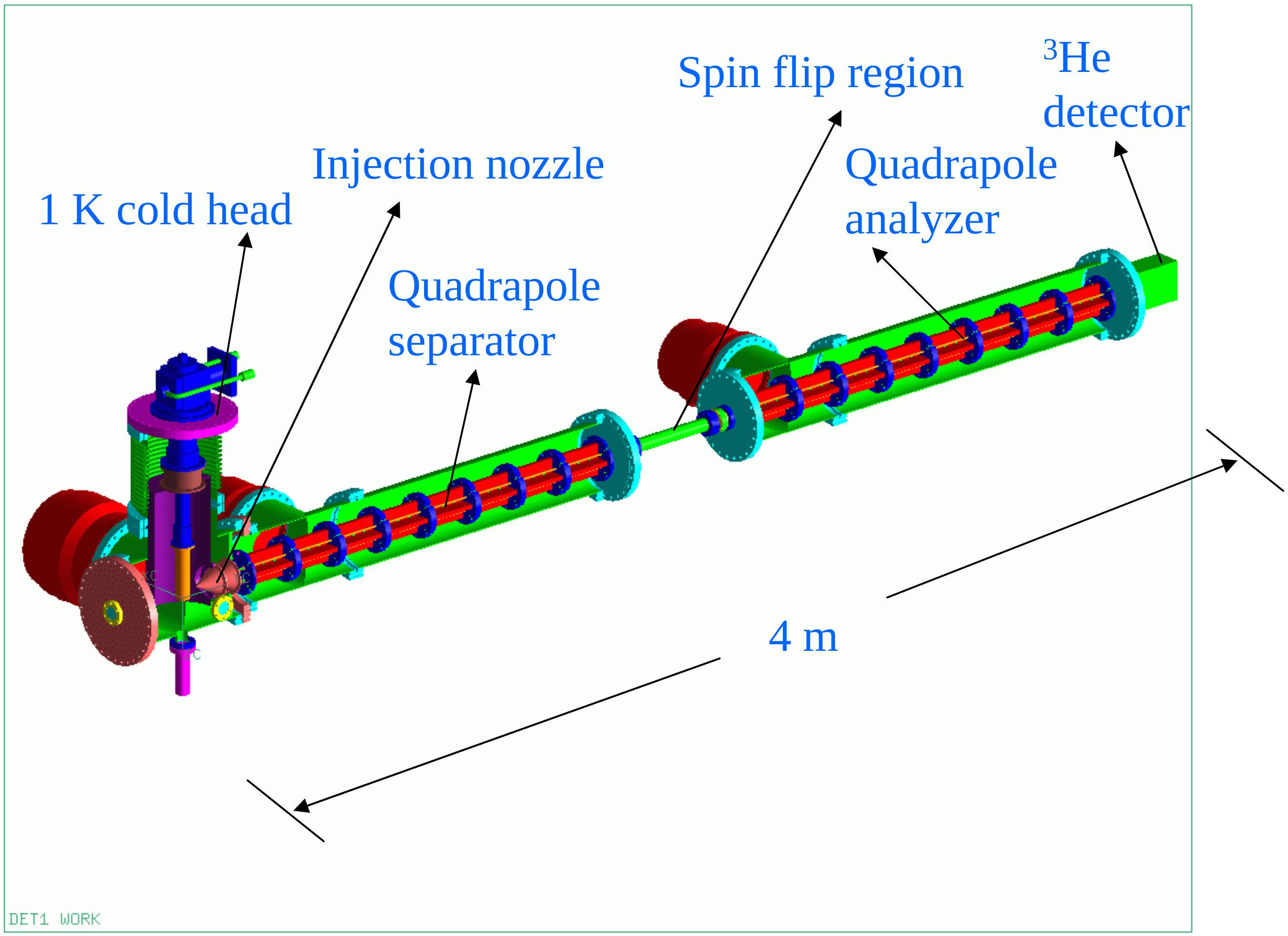
Physica B329-333, 236 (2003)

HEAT EFFECTS



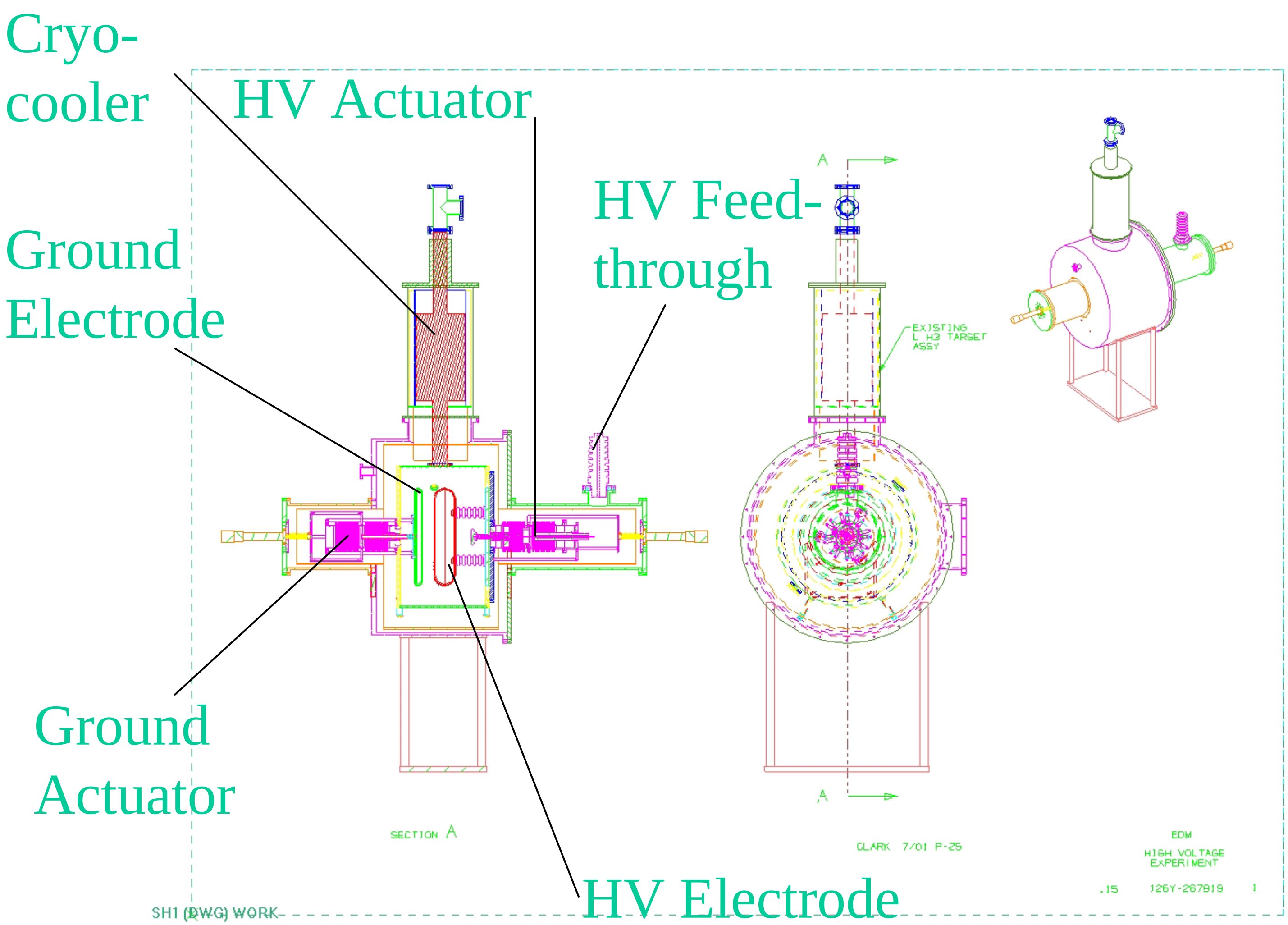
^{3}He distribution is modified when a heater is on

POLARIZED ^{3}He SOURCE



Being constructed and tested at Los Alamos

Electric Field Test



Voltage amplification / Variable capacitor / Moveable HV contact

What motivates searches for B Violation?

- Baryon asymmetry of the universe (BAU) requires B violation if it is not present in the initial conditions
- *Sakharov (1967), Kuzmin (1970)*
- In Standard Model baryon number is not conserved
- (at the non-perturbative level) *'t Hooft (1976)* **...**
- Idea of Unification of particles and their interactions predict various mechanisms for B violation
- *Pati & Salam (1973): quark – lepton unification, Left - Right symmetry, Georgi & Glashow (1974): SU(5) - unification of forces* **...**
- New low quantum gravity scale models: *N. Arkani-Hamed, S. Dimopoulos, G. Dvali (1998)* **...**

Conservation or violation of (B–L) is an essential issue

Conservation of angular momentum in N disappearance

->$\Delta B = \pm \Delta L$ or $|\Delta(B-L)| = 0, 2$

<u>In Standard Model</u> and in GUTS which lead to proton decay, $\Delta(B-L) = 0$

What about $|\Delta(B-L)| = 2$?

n ↔ $\bar{n}$ transitions — "too crazy"?

But neutral meson $|q\bar{q}\rangle$ states oscillate -

K^0, B^0 ⟷ (2nd order weak interactions) ⟷ $\bar{K}^0, \bar{B}^0$

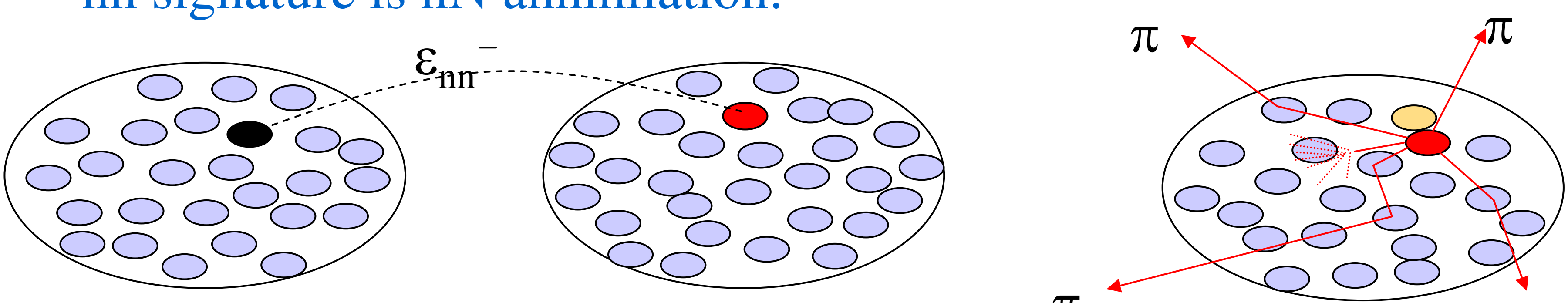
And neutral fermions can oscillate too -

ν_μ ⟷ (ΔL) ⟷ ν_τ

So why not -

n ⟷ ($\Delta[B-L]$) ⟷ $\bar{n}$?

$n\bar{n}$ signature is $\bar{n}N$ annihilation:



Nucleus A → $A^* + \bar{n}$

$\bar{n}N$ → pions

What Mass Scale is probed?

in the lowest order the n-nbar transition should involve a 6-quark operator with the amplitude suppressed by $\sim m^{-5}$:

- Observable transition rates would correspond to the mass scale m **~ 100** TeV
- Anything happening at this scale?

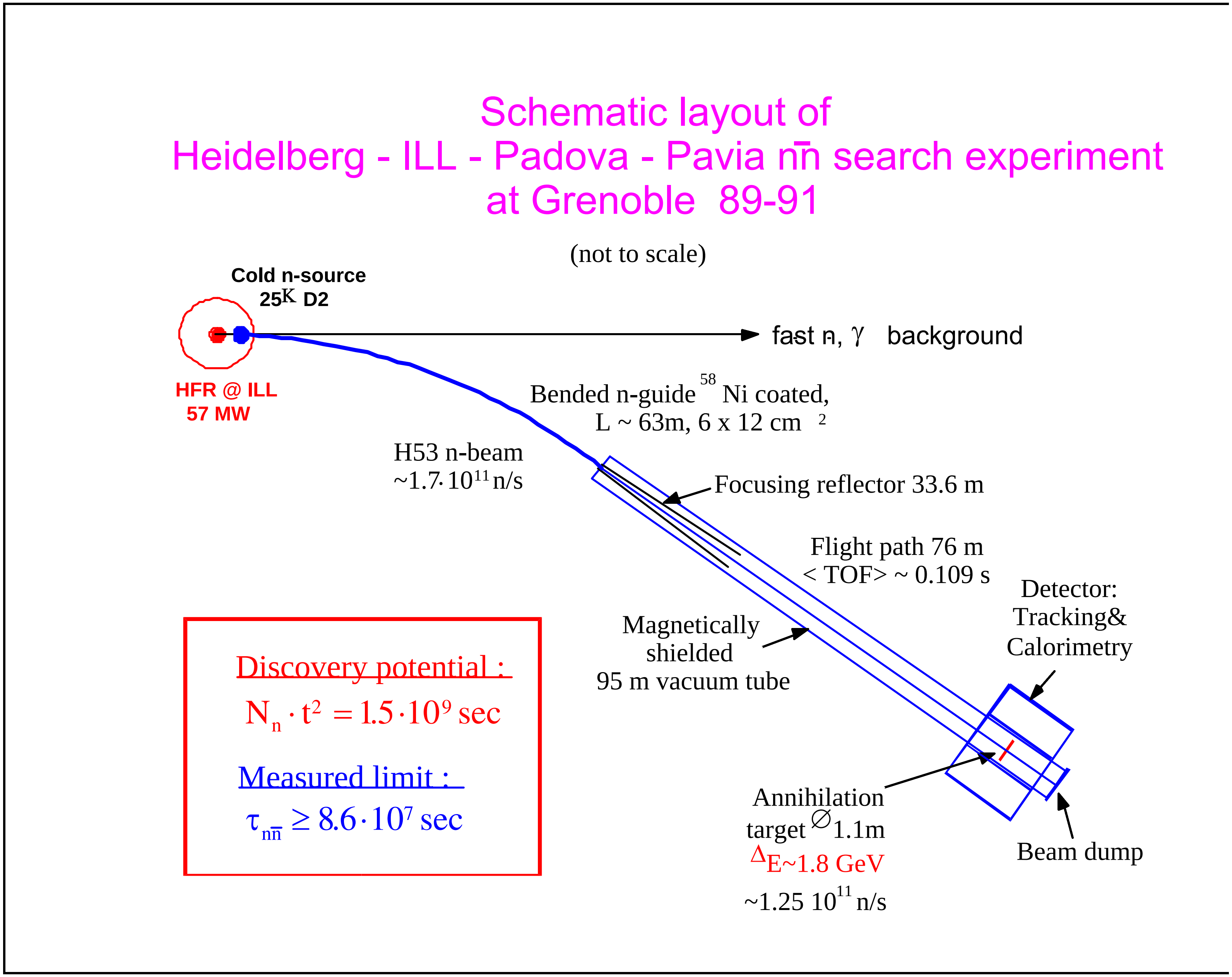
New Ideas for n-nbar Oscillations

- G. Dvali and G. Gabadadze, “Non-conservation of global charges in the brane universe and baryogenesis”, Physics Letters B 460 (1999) 47-57

- K. S. Babu and R. N. Mohapathra. “Observable neutron-antineutron oscillations in seesaw models of neutrino mass, Physics Letters B 518, (2001) 269-275

- S. Nussinov and R. Shrock, “N-nbar Oscillations in models with large extra dimensions” Phys. Rev. Lett. 88, (2002) 171601

Last Experiment at ILL



Typical detector for the "neutrons in the bottle experiment"