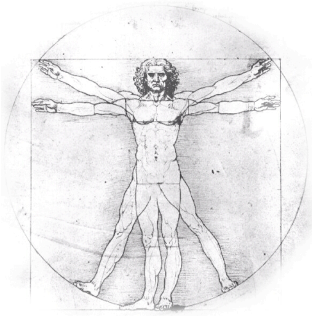
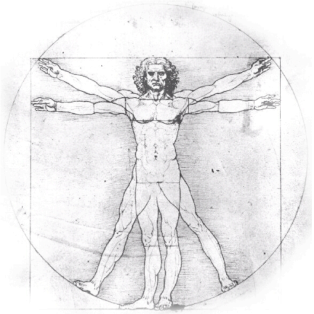
Electric Dipole Moments

neutron, atoms, molecules





Tim Chupp

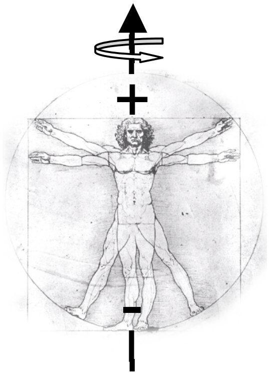
University of Michigan

NPSS @ NSCL: July 3, 2009

Definition: Electric Dipole Moment

Separation of Charge along **J: $\langle d\rangle = g_d\langle J\rangle$**

“violates” P and T symmetry

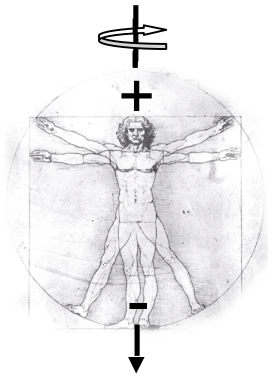


$$\vec{\mathbf{d}} = e\,\vec{\mathbf{r}}$$

$$\langle\vec{\mathbf{d}}\rangle = g_d\langle\vec{\mathbf{J}}\rangle$$

$$\langle\vec{\mathbf{r}}\rangle = \frac{g_d}{e}\langle\vec{\mathbf{J}}\rangle$$

if P or T is a symmetry, $g_d = -g_d$



$$\langle\vec{\mathbf{d}}\rangle = e\langle\vec{\mathbf{r}}\rangle = e\int \vec{r}\rho\ d^3r$$

Why is this so interesting? (Yes - it is.)

P-violation is well established

T- violation implies CP violation - also well established

Cosmological Baryon Asymmetry NOT accounted for in SM

requires CP violation

Parity:

Consider $H|\psi_E\rangle = E\,|\psi_E\rangle$

$|\psi_E{}^P\rangle = \mathbf{P}\,|\psi_E\rangle$

$\mathbf{P}\,H\,\mathbf{P}^{-1}\,|\psi_E{}^P\rangle = E\,|\psi_E{}^P\rangle$

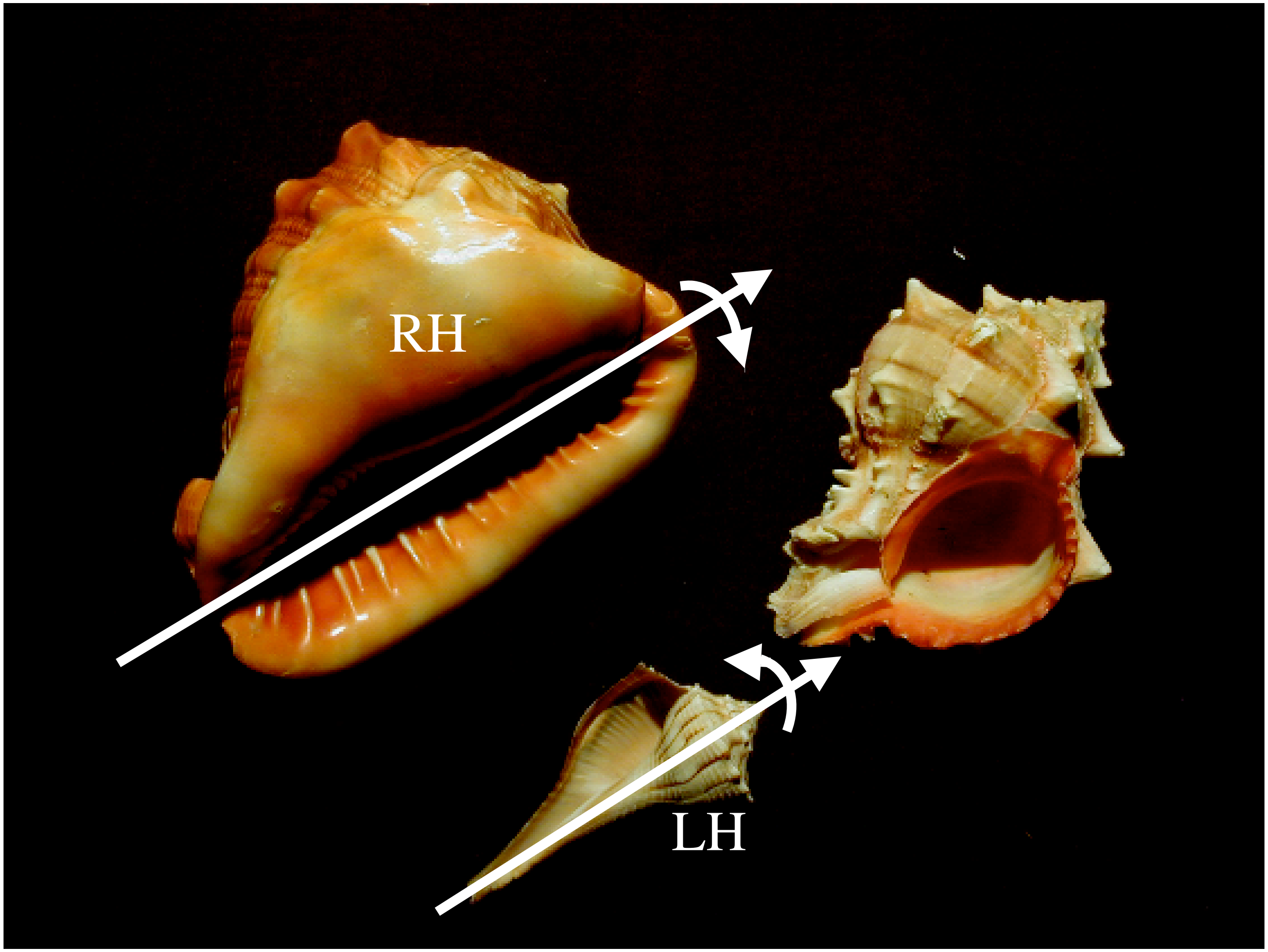
if $\mathbf{P}\,H\,\mathbf{P}^{-1} = H$ then $H|\psi_E{}^P\rangle = E\,|\psi_E{}^P\rangle$ (P-invariance)

i.e. $|\psi_E\rangle$ and $|\psi_E\rangle$ are degenerate or equivalent

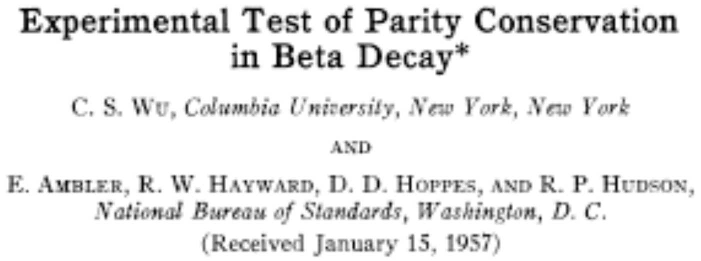
e.g. $H=p^2/2m+A\boldsymbol{\sigma}\bullet\mathbf{p}$: $\mathbf{P}\,H\,\mathbf{P}^{-1}= p^2/2m - A\boldsymbol{\sigma}\bullet\mathbf{p}$

Eigenstates/eigenenergies for H are not the same for H^P

Handedness - PARITY



Handedness - PARITY



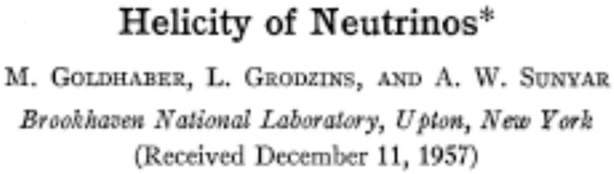
Experimental Test of Parity Conservation in Beta Decay*

C. S. Wu, *Columbia University, New York, New York*

AND

E. Ambler, R. W. Hayward, D. D. Hoppes, and R. P. Hudson, *National Bureau of Standards, Washington, D. C.*

(Received January 15, 1957)

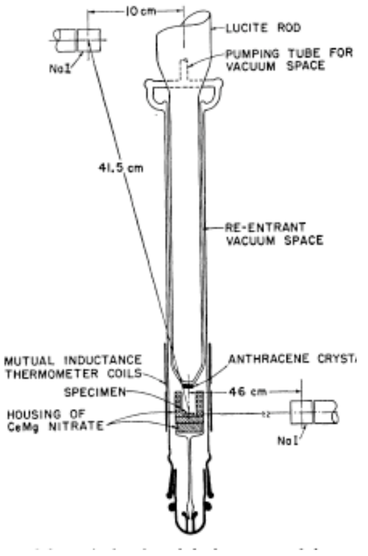


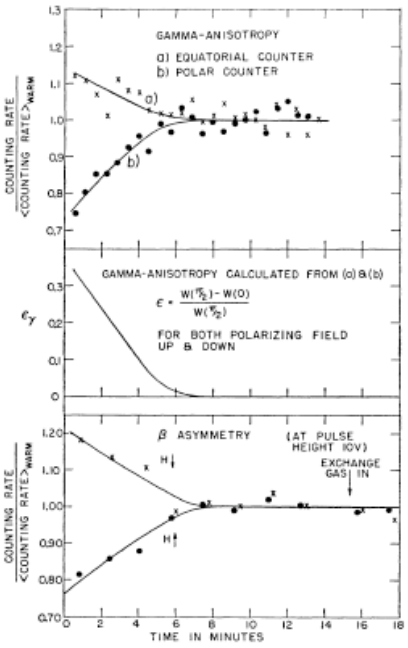
Helicity of Neutrinos*

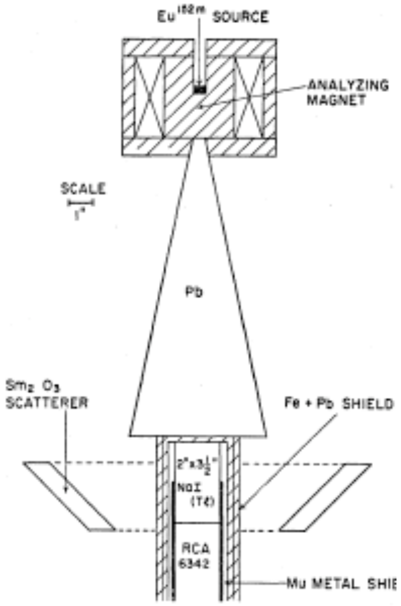
M. Goldhaber, L. Grodzins, and A. W. Sunyar

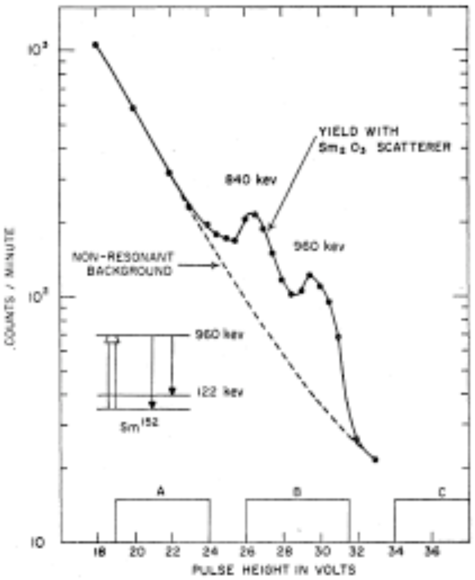
Brookhaven National Laboratory, Upton, New York

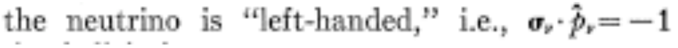
(Received December 11, 1957)











the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{\boldsymbol{p}}_\nu = -1$

CP Conservation

ν_L and $\bar{\nu}_R$

$(K_0 - \overline{K}_0)$, $(K_0 + \overline{K}_0)$ are CP eigenstates

CP Violation

$K_L \rightarrow \pi\,\pi\,\pi + \varepsilon\,\pi\pi$

$K_S \rightarrow \pi\,\pi + \varepsilon\,\pi\pi\pi$

Christenson, Fitch, Cronnin,Turaly, 1964(PRL13:138)

T Violation

$$\left\langle \frac{R\left(\overline{\mathrm{K}}^0_{t=0} \rightarrow \mathrm{e}^+\pi^-\nu_{t=\tau}\right) - R\left(\mathrm{K}^0_{t=0} \rightarrow \mathrm{e}^-\pi^+\bar{\nu}_{t=\tau}\right)}{R\left(\overline{\mathrm{K}}^0_{t=0} \rightarrow \mathrm{e}^+\pi^-\nu_{t=\tau}\right) + R\left(\mathrm{K}^0_{t=0} \rightarrow \mathrm{e}^-\pi^+\bar{\nu}_{t=\tau}\right)} \right\rangle = \left(6.6 \pm 1.3_{\mathrm{stat}} \pm 1.0_{\mathrm{syst}}\right) \times 10^{-3} \quad \text{(CPLear)}$$

Time reversal:

Consider $H|\psi_E\rangle = E\,|\psi_E\rangle$

$$|\psi_E^T\rangle = \mathbf{T}\,|\psi_E\rangle$$

$$\mathbf{T}\,H\,\mathbf{T}^{-1}\,|\psi_E^T\rangle = E\,|\psi_E^T\rangle$$

if $\mathbf{T}\,H\,\mathbf{T}^{-1} = H$ then $H|\psi_E^T\rangle = E\,|\psi_E^T\rangle$ (T-invariance)

i.e. $|\psi_E\rangle$ and $|\psi_E\rangle$ are degenerate or equivalent

Similarly for C, P:

T ~ motion reversal + complex conjugation

A note on relativistic QM of fermions

4-component Dirac spinor wavefunctions:

$$\begin{bmatrix} 1 \\ 0 \\ \boldsymbol{\sigma}\cdot\mathbf{p}c/(E+mc^2) \\ 0 \end{bmatrix} e^{-ip_\mu x^\mu} \quad \begin{bmatrix} 0 \\ 1 \\ 0 \\ \boldsymbol{\sigma}\cdot\mathbf{p}c/(E+mc^2) \end{bmatrix} e^{-ip_\mu x^\mu} \quad \begin{bmatrix} -\boldsymbol{\sigma}\cdot\mathbf{p}c/(E+mc^2) \\ 0 \\ 1 \\ 0 \end{bmatrix} e^{+ip_\mu x^\mu} \quad \begin{bmatrix} 0 \\ -\boldsymbol{\sigma}\cdot\mathbf{p}c/(E+mc^2) \\ 0 \\ 1 \end{bmatrix} e^{+ip_\mu x^\mu}$$

Operators applied to spinors are combinations of 16 linearly independent γ matrices called bilinear covariants: S,P,V,A,T

$$\gamma_0 = \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

$$\text{S: } I = \begin{bmatrix} 1&0&0&0 \\ 0&1&0&0 \\ 0&0&1&0 \\ 0&0&0&1 \end{bmatrix} \quad \text{P: } \gamma_5 = \begin{bmatrix} 0&0&1&0 \\ 0&0&0&1 \\ 1&0&0&0 \\ 0&1&0&0 \end{bmatrix} \quad \text{V: } \gamma_\mu \qquad \text{A: } \gamma_5\gamma_\mu \qquad \text{T: } 2\sigma_{\mu\nu} = i[\gamma_5, \gamma_\mu]$$

$$\gamma^i = \begin{bmatrix} 0 & \sigma_i \\ -\sigma_i & 0 \end{bmatrix}$$

Non-relativistic reductions of $\psi_f\Gamma\psi_i$:

S: $1 + \mathcal{O}(p^2/m^2)$ V: $[1 + \mathcal{O}(p^2/m^2), (\mathbf{p}_f + \mathbf{p}_i + i\boldsymbol{\sigma}\times(\mathbf{p}_f - \mathbf{p}_i))/(m+E)]$

P: $\boldsymbol{\sigma}\cdot(\mathbf{p}_f - \mathbf{p}_i)/2m$ A: $[\boldsymbol{\sigma}\cdot(\mathbf{p}_f + \mathbf{p}_i)/(m+E), \boldsymbol{\sigma}]$

T: $(\mathbf{p}_f - \mathbf{p}_i)/(m+E) + \boldsymbol{\sigma}\times(\mathbf{p}_f - \mathbf{p}_i)/(m+E)$

Note: under PARITY, V,P,T change sign, S,A do not change sign

CPT Theorem

Lorentz Invariance: all operators/Lagrangian made up of S,P,V,A,T

Non-relativistic reductions of $\psi_f\Gamma\psi_i$:

S: $1+\mathcal{O}(p^2/m^2)$ V: $[1+\mathcal{O}(p^2/m^2), (\mathbf{p}_f+\mathbf{p}_i+i\boldsymbol{\sigma}\mathrm{x}(\mathbf{p}_f-\mathbf{p}_i))/(m+E)]$

P: $\boldsymbol{\sigma}\cdot(\mathbf{p}_f-\mathbf{p}_i)/2m$ A: $[\boldsymbol{\sigma}\bullet(\mathbf{p}_f+\mathbf{p}_i)/(m+E), \boldsymbol{\sigma}]$

T: $(\mathbf{p}_f-\mathbf{p}_i)/(m+E) + \boldsymbol{\sigma}\ \mathrm{x}\ (\mathbf{p}_f-\mathbf{p}_i)/(m+E)$

	S	P	$V_0,\mathbf{V}$	$A_0.\mathbf{A}$	T
P	+	-	+,-	-,+	+
C	+	-	+,-	+,+	-
T	+	+	+,-	-,+	-
CPT	**+**	**+**	**+,+**	**+,+**	**+**

$$\mathbf{CPT\ L\ CPT^{-1} = L}$$

CP Violation in the SM

CKM Matrix

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta_{13}} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta_{13}} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta_{13}} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta_{13}} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta_{13}} & c_{23}c_{13} \end{pmatrix}$$

$$= \begin{pmatrix} 1-\lambda^2/2 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda & 1-\lambda^2/2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)$$

$\lambda = V_{us}$ (0.2257 ± 0.0010)

$A = 0.814 \pm 0.022$

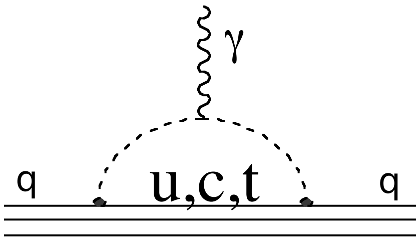
$\rho = 0.135 \pm 0.03$

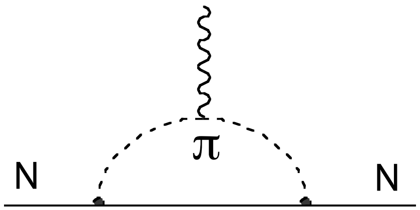
η: CP violating parameter (0.349 ± 0.017)

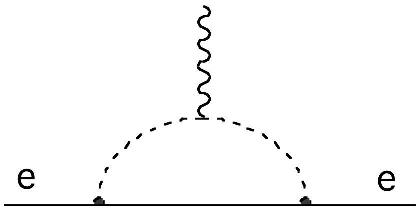
C. Amsler et al., Physics Letters B667, 1 (2008) section 11. THE CKM QUARK-MIXING MATRIX
Revised February 2008 by A. Ceccucci (CERN), Z. Ligeti (LBNL), and Y. Sakai (KEK).

Also: Strong Interaction (mediated by gluons) has CP violating parameter θ_{QCD}

CP Violation in the SM







CKM Phase introduces *i:*

$$(V_0,\mathbf{V}) \xrightarrow{T} (+V_0,-\mathbf{V})$$
$$(A_0,\mathbf{A}) \rightarrow (+A_0,-\mathbf{A})$$
$$i\delta(V_0,\mathbf{V}) \rightarrow i\delta(-V_0,+\mathbf{V})$$
$$i\delta(A_0,\mathbf{A}) \rightarrow i\delta(-A_0,+\mathbf{A})$$

Total amplitude changes

Any new degree of freedom
SUSY, L-R, Higgs,
introduces new amplitude
and phase.

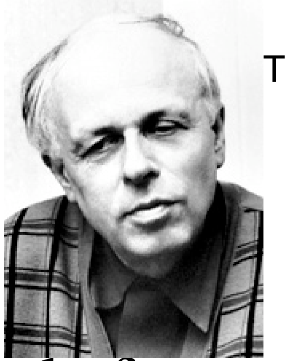
Baryon Asymmetry

Fact: There is more (few x10^{-10}) matter than antimatter

How? 1) Initial condition

2) Universe evolved from symmetric initial condition

A. Shakarov



The Nobel Peace Prize 1975

This is possible:

1) Non-equilibrium: universe expands faster than $B \leftrightarrow \overline{B}$

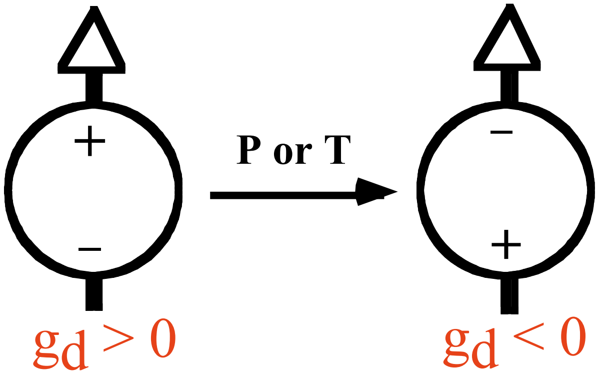
2) Baryon number violation: not observed by not forbidden

3) CP violation -

SM CP violation is not sufficient

Electric Dipole Moment

Separation of Charge along **J: d=**g_d**J**



A unique signal of new physics beyond SM - CKM
(almost - θ_{QCD} could be anything)

EDM Motivations

Undiscovered

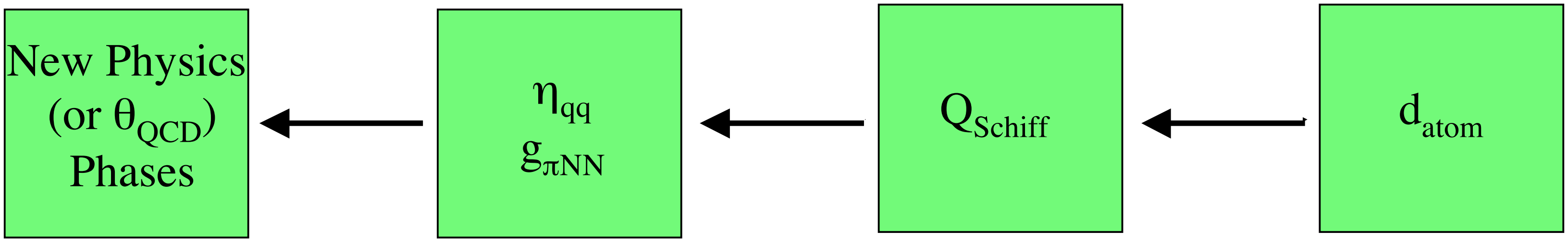
Study CP violation: mass scale

Signal of NEW PHYSICS (beyond SM - CKM)

Cosmological Baryon Asymmetry

EDMs and New Physics

CKM CP violation nearly vanishes



New Physics (or θ_{QCD}) Phases ← η_{qq} $g_{\pi NN}$ ← Q_{Schiff} ← d_{atom}

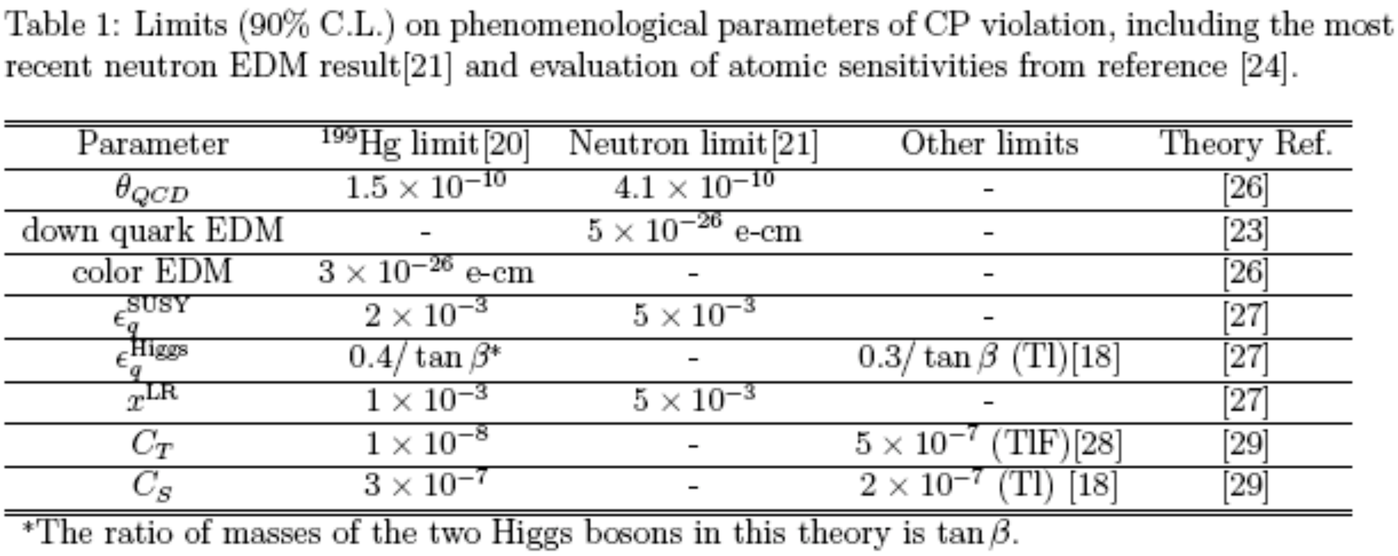


Table 1: Limits (90% C.L.) on phenomenological parameters of CP violation, including the most recent neutron EDM result[21] and evaluation of atomic sensitivities from reference [24].

Parameter	^{199}Hg limit[20]	Neutron limit[21]	Other limits	Theory Ref.
θ_{QCD}	1.5×10^{-10}	4.1×10^{-10}	-	[26]
down quark EDM	-	5×10^{-26} e-cm	-	[23]
color EDM	3×10^{-26} e-cm	-	-	[26]
$\epsilon_q^{\mathrm{SUSY}}$	2×10^{-3}	5×10^{-3}	-	[27]
$\epsilon_q^{\mathrm{Higgs}}$	$0.4/\tan\beta^*$	-	$0.3/\tan\beta$ (Tl)[18]	[27]
x^{LR}	1×10^{-3}	5×10^{-3}	-	[27]
C_T	1×10^{-8}	-	5×10^{-7} (TlF)[28]	[29]
C_S	3×10^{-7}	-	2×10^{-7} (Tl) [18]	[29]

*The ratio of masses of the two Higgs bosons in this theory is $\tan\beta$.

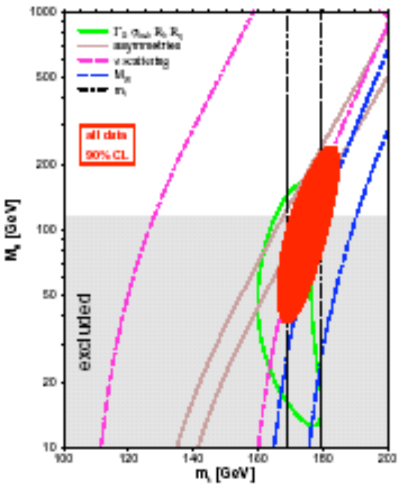
Physics Beyond the Standard Model

Why?

17 or more free parameters
Neutrino mixing (put in by hand - 7 more parameters)
CP violation and θ_{QCD}
CP violation and baryogenesis
Supersymmetry's beauty (more parameters!)
Quantum theory of gravity -- string theory
Do the data fit?
WHY NOT???

How?

Find superpartners, extra Higgs, etc. (LHC, NLC)
Overconstrain SM predicitions
Search for scalar, tensor interactions
Heavy Z, W_R, new generations, heavy neutrinos
Dark matter



Supersymmetry

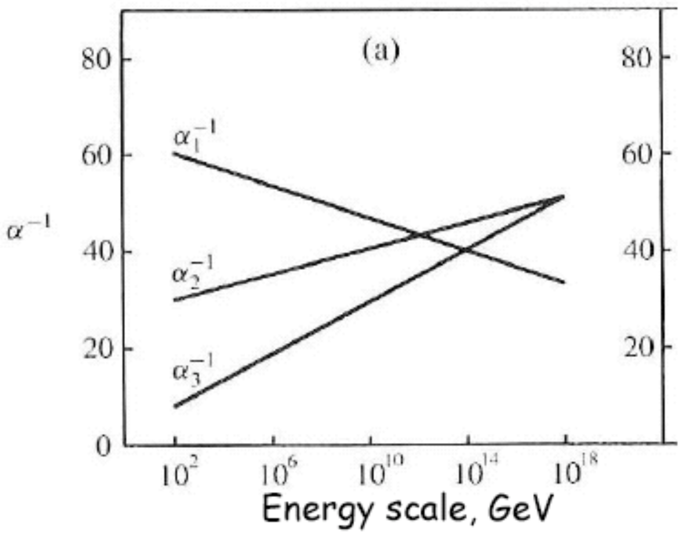
Is there a global symmetry conserving B or L?

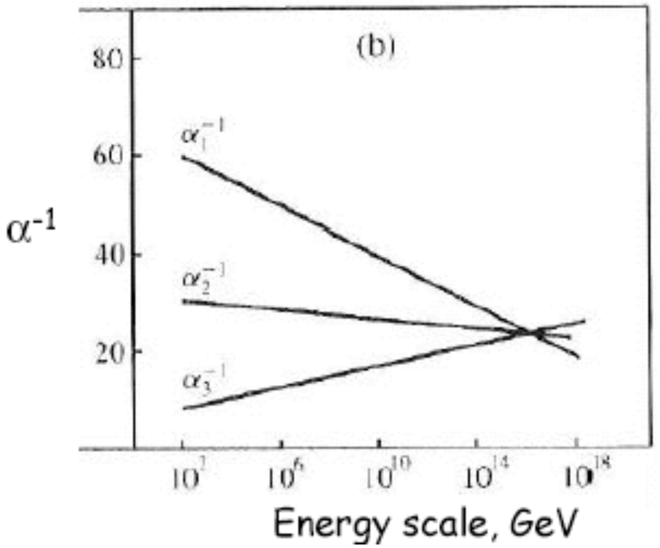
Supersymmetry conserves B-L

e.g. proton decay $p \rightarrow \pi^+ e^+$

Particles have superpartners

particle	sparticle
Quark	squark
Lepton	slepton
Boson	bosino

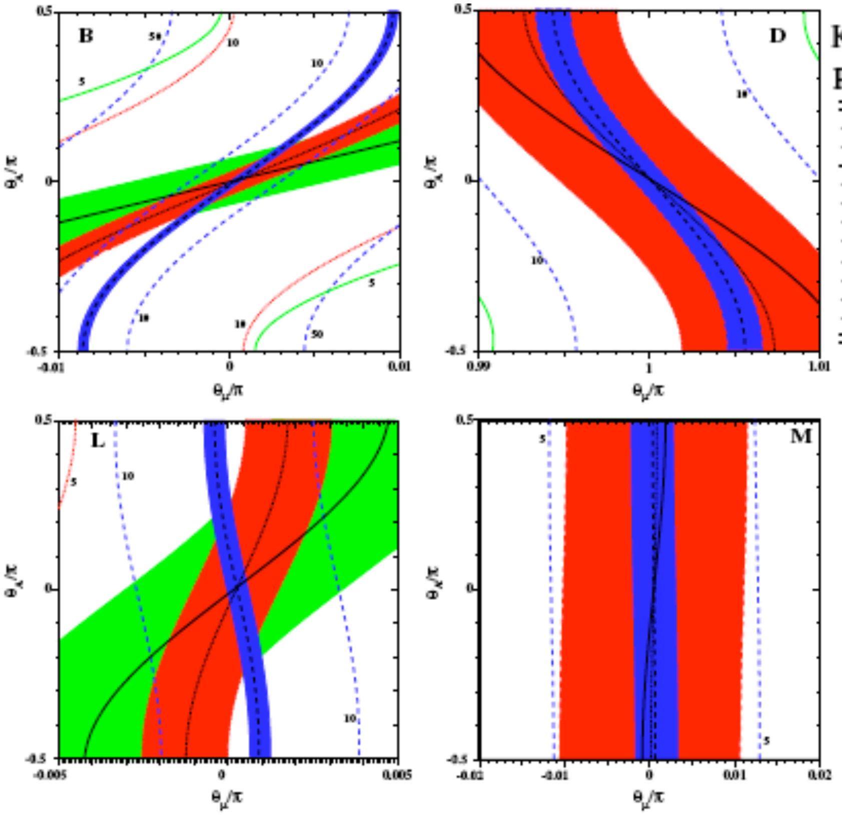




EDMs and New Physics

CKM CP violation nearly vanishes

New Physics (or θ_{QCD}) Phases → η_{qq} $g_{\pi NN}$ → Q_{Schiff} → d_{atom}



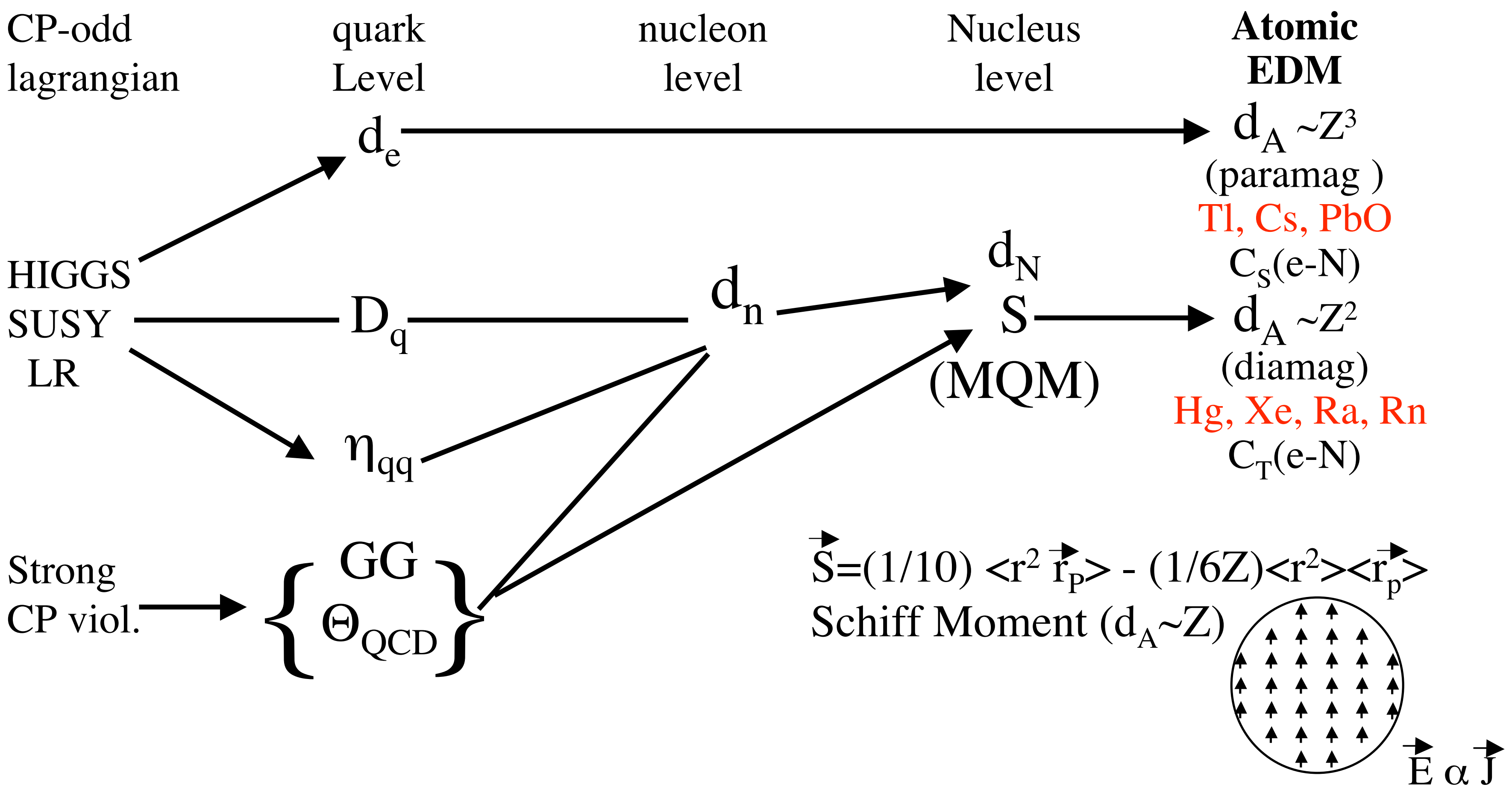
Keith A. Olive,[1] Maxim Pospelov,[2,3,4] Adam Ritz,[5] and Yudi Santoso[2,3]
PHYSICAL REVIEW D 72, 075001 (2005)

Benchmark point ($m_{1/2}$, m_0, $\tan\beta$)
B (250,75,10)
D (525 130 10)
L (450 355 50)
M (1500 1100,57)

- Neutron, electron and Schiff are complementary
- Even upper limits are important
- Need several systems to learn physics

Atomic EDMs

(Elementary Particle Interactions Polarize Atoms)



CP-odd lagrangian

quark Level

nucleon level

Nucleus level

Atomic EDM

HIGGS
SUSY
LR

Strong CP viol.

d_e

D_q

η_{qq}

$\left\{ \begin{matrix} GG \\ \Theta_{QCD} \end{matrix} \right\}$

d_n

d_N
S
(MQM)

$d_A \sim Z^3$
(paramag)
Tl, Cs, PbO
C_S(e-N)

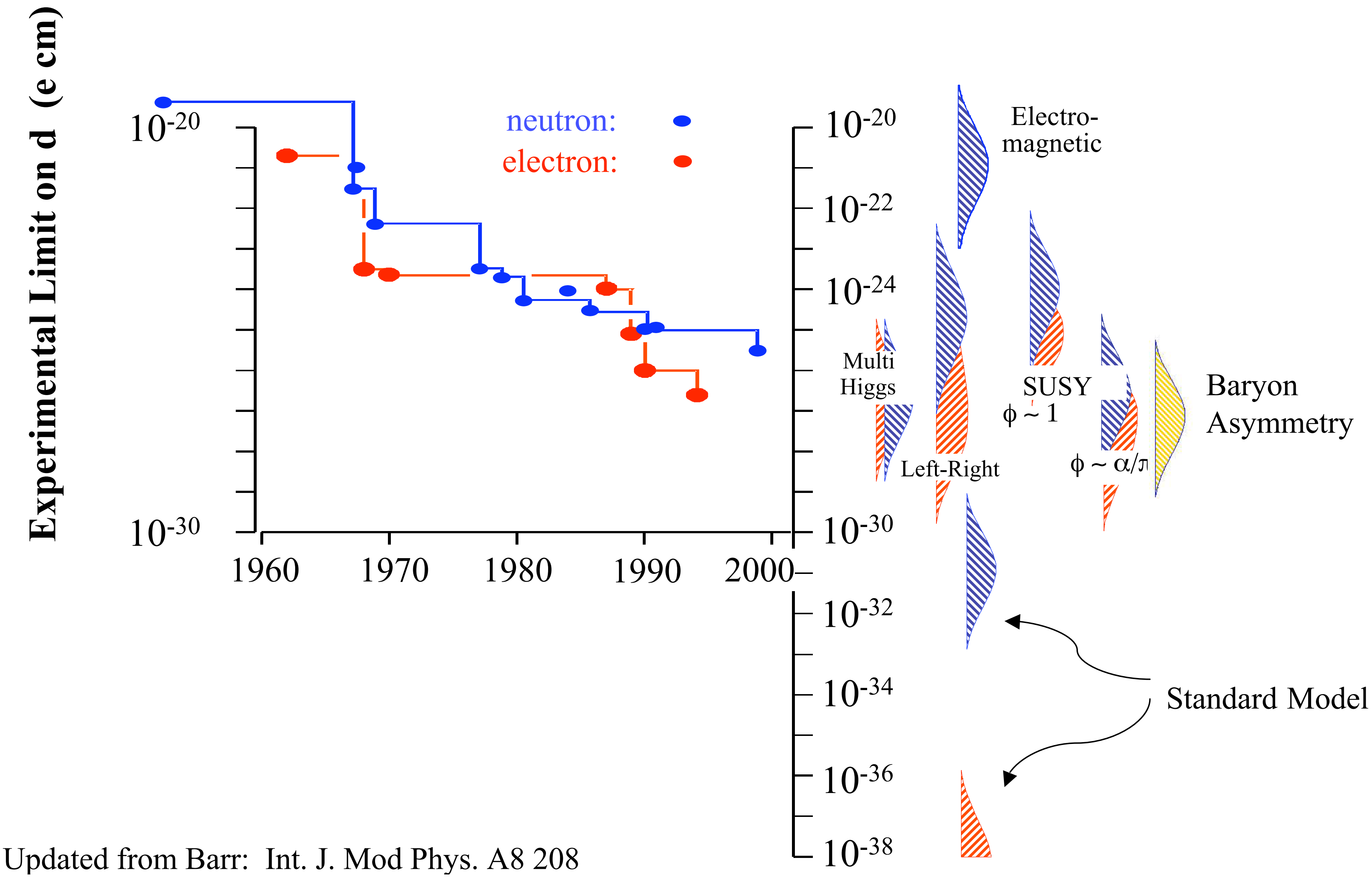
$d_A \sim Z^2$
(diamag)
Hg, Xe, Ra, Rn
C_T(e-N)

$\vec{S}=(1/10)\langle r^2\, \vec{r}_P\rangle - (1/6Z)\langle r^2\rangle\langle \vec{r}_p\rangle$

Schiff Moment (d_A~Z)

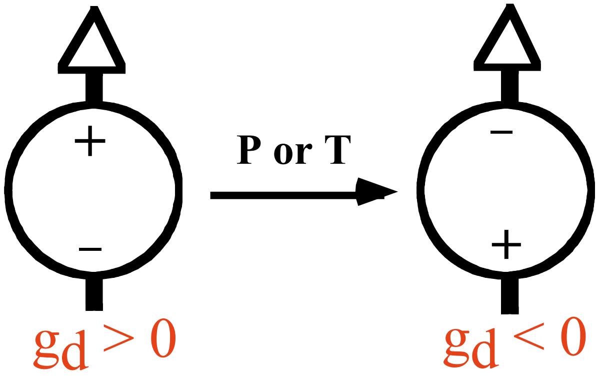
$\vec{E}\ \alpha\ \vec{J}$

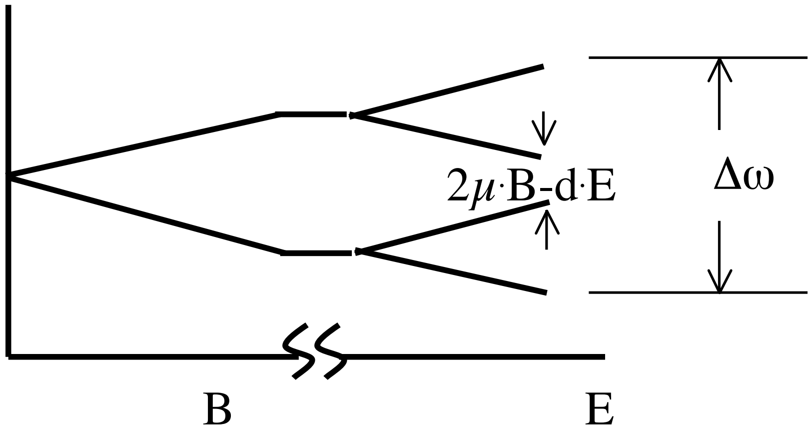
Sensitive Measurements: Neutron EDM



Updated from Barr: Int. J. Mod Phys. A8 208

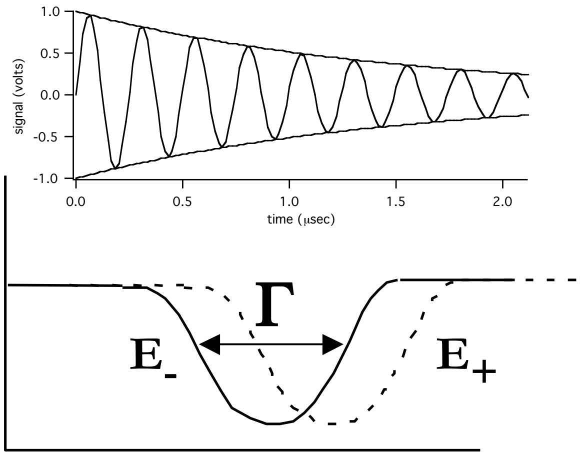
Measurements





Polarize RF pulse Measure Polarize RF pulse Measure …x50
E+ E- …E+ E- E0 E- E+E0

Collect →

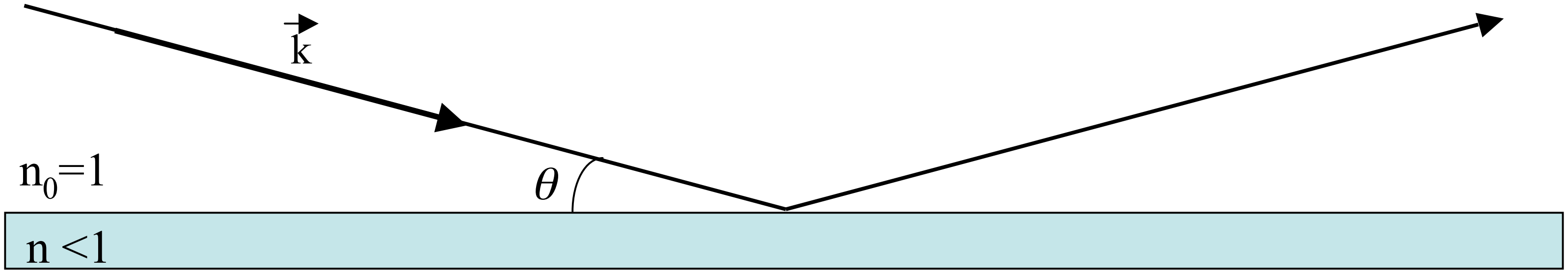


T_2
RF power
B homogeneity

$$\textbf{Precision: } (\sigma_d)^{-1} = 4E\Gamma^{-1}\,(S/N)$$

$$S/N = \sqrt{\mathcal{A}^2\, N_{Rn}}$$

Ultracold neutrons (UCN):



$$V = \frac{2\pi\hbar^2}{m} bN$$

N : number density of atoms

b : coherent scattering length

In case of different atoms i, use the weighted average $\langle n_i \cdot b_c \rangle$.

b is generally positive (reflection from edge of square well*) so n<1

*see Peshkin &Ringo, Am. J. Phys. **39**, 324 (1971)

neutrons are totally reflected, if $E_\perp < V$

$$E_\perp = \frac{1}{2} m v_\perp^2 = \frac{\hbar^2 k_\perp^2}{2m} = \frac{2\pi^2\hbar^2}{m\lambda_\perp^2}$$

$k_\perp = k\sin\theta$ and $\lambda_\perp = \lambda/\sin\theta$

$$\frac{2\pi^2\hbar^2}{m\lambda_\perp^2} < V \quad \text{or} \quad \sin\theta < \sqrt{\frac{mV}{2\pi^2\hbar^2}}\lambda \quad \Rightarrow \text{critical angle } \theta_C$$

For $\lambda^2 > \frac{1}{bN}$ Neutrons are reflected for all incident angles: UCN

Ultracold Neutron Energies are Very Low

The Fermi "Pseudo-Potential" the most advantageous materials is ~ 100 neV

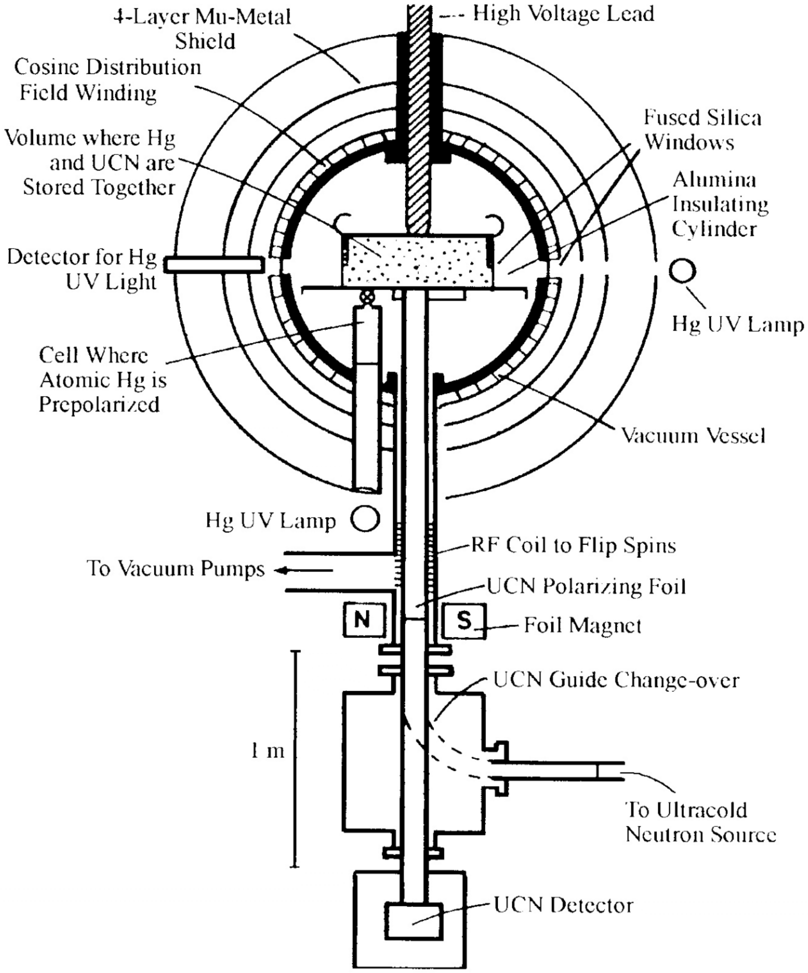
This corresponds to a:

Neutron Velocity	≈ 5 m/s
Neutron Wavelength	≈ 500 Å
Magnetic Moment Interaction	$\mu_n \cdot B \approx 100$ neV for $B \sim 1$Tesla
Gravitational Interaction	$m_n g h \approx 100$ neV for $h \sim 1$ m

Ultracold Neutron can be trapped in material, magnetic, or gravitational bottles

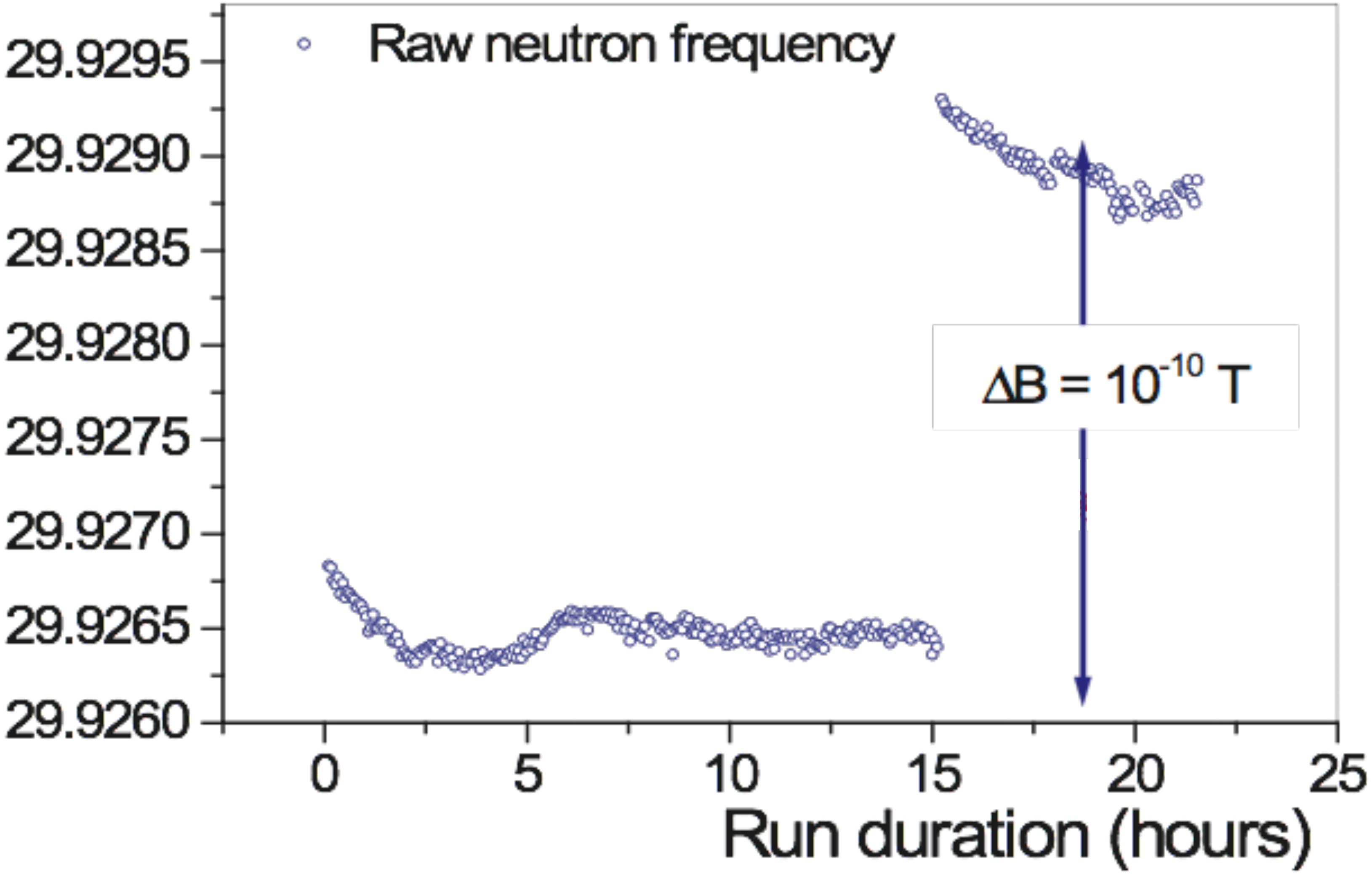
Current State of the Art – The ILL nEDM Experiment

- Provides the current best limit: $d_n < 3 \times 10^{-26}$ e•cm
- Characteristics:
  - – 1 UCN/cc
  - – 10 kV/cm
  - – 100 s neutron storage time
- Employs a ^{199}Hg **Co-magnetometer**



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

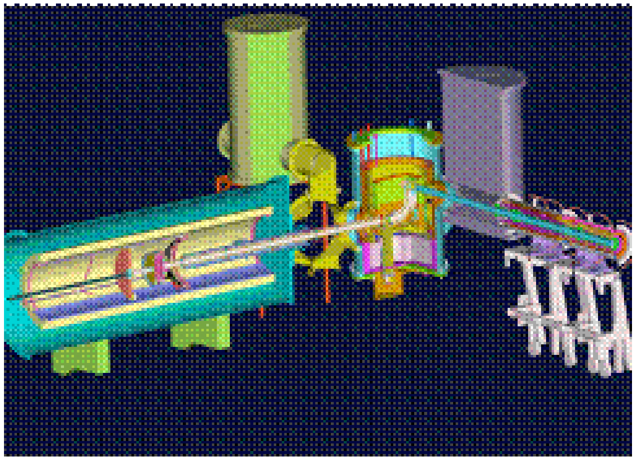
Key Systematic Check - ^{199}Hg Co-Magnetometer



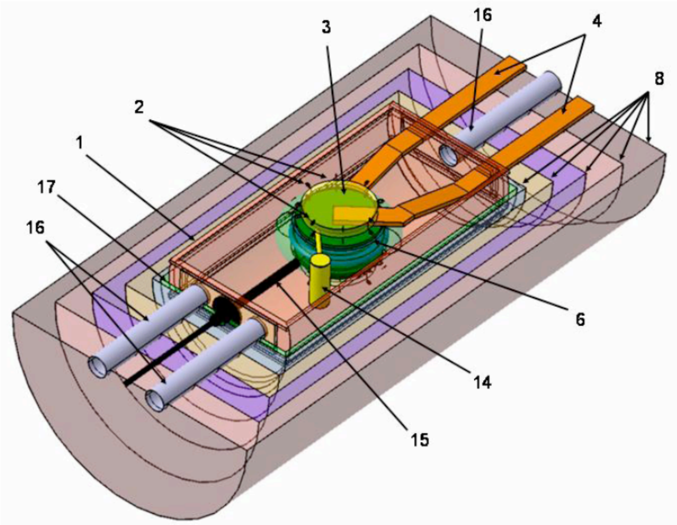
- "geometric phase" effect was found in this work

Current (future nEDM experiments

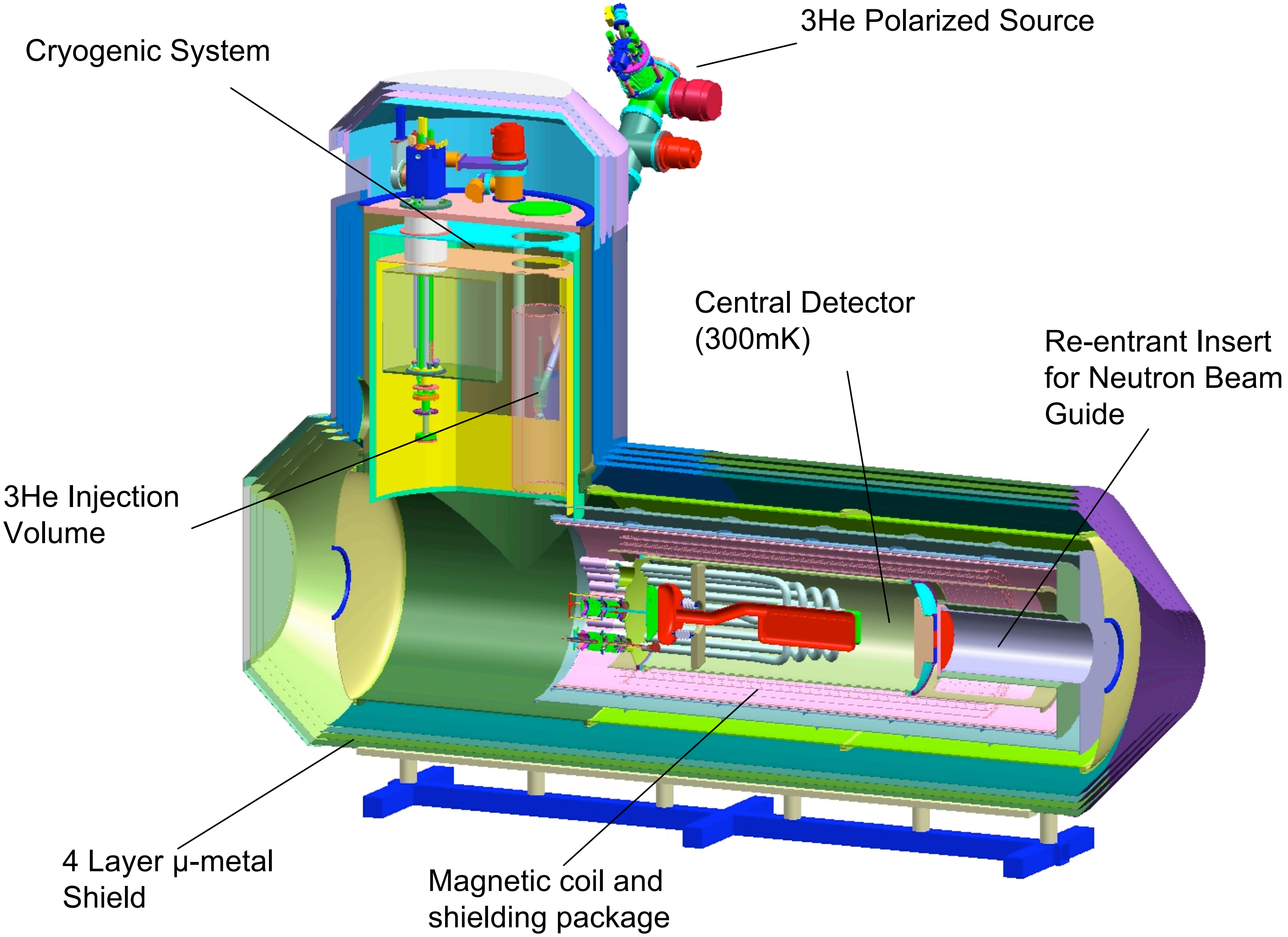
- ILL CryoEDM



- PSI OILL EDM, n2EDM



- SNS EDM


3He Polarized Source
Cryogenic System
Central Detector (300mK)
Re-entrant Insert for Neutron Beam Guide
3He Injection Volume
4 Layer μ-metal Shield
Magnetic coil and shielding package

The Neutron Electric Dipole Moment at the SNS

"nEDM"

Goal of new experiment:

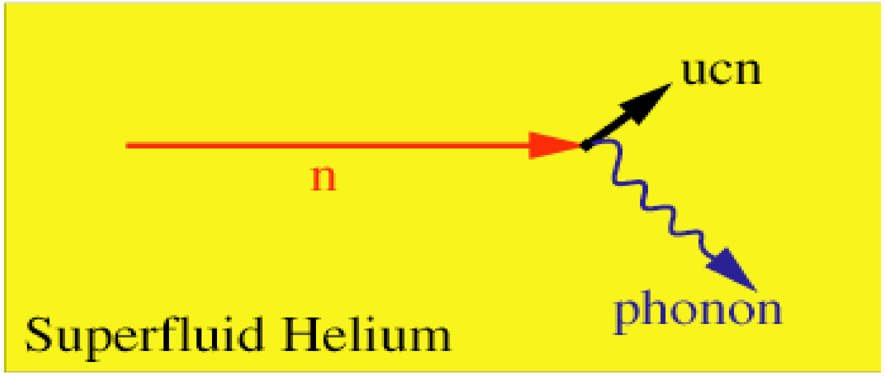
E - 50 kV/cm (x5)
T - 500 s (x5)
N - 100 s (x100)

$$\sigma_{edm} \propto \frac{1}{2ET\sqrt{N_n}}$$

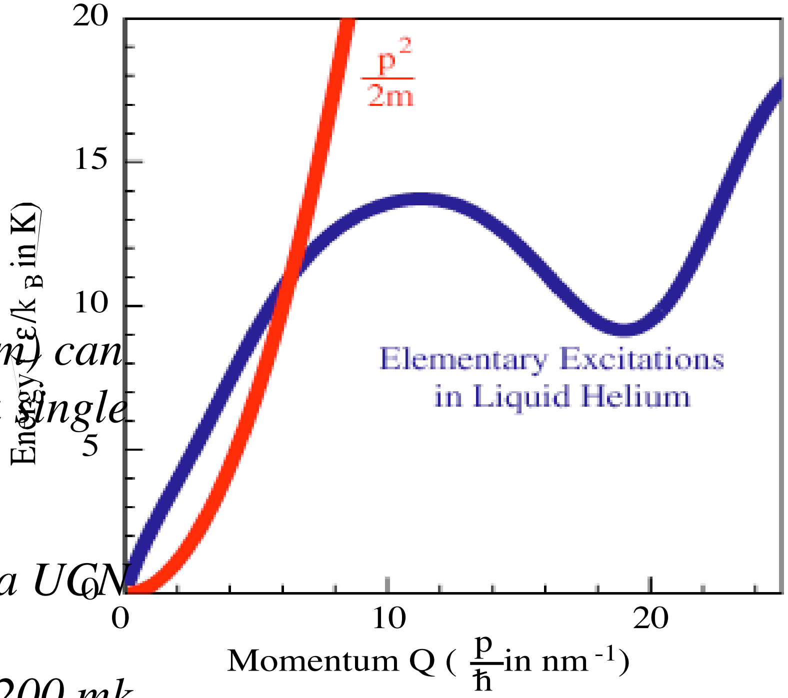
How?

Superfluid Helium

Production of Ultra Cold Neutrons in Superfluid Helium



Golub and Pendlebury (1977)



- *Neutrons of energy $E \approx 0.95$ meV (11 k or 0.89 nm) can scatter in liquid helium to near rest by emission of a single phonon.*

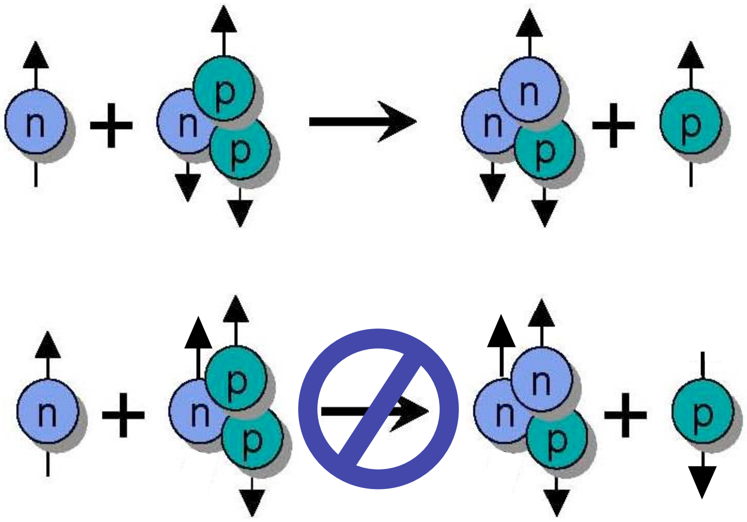
- *Upscattering by absorption of an 11 K phonon is a UCN loss mechanism. But population of 11 K phonons is suppressed by a large Boltzman Factor: $\sim e^{-11/T}$ T~200 mk*

- *The only nuclear interaction between neutrons with $E < 20$ MeV is elastic scattering;* *__NO nuclear capture of low energy neutrons on ^{4}He__*

Dope with Polarized ^{3}He

$$n + {}^3He \rightarrow {}^3H + p$$

In one spin state ONLY



$\sigma_{J=0}$ = 5300 barn at v_0=2200 m/s

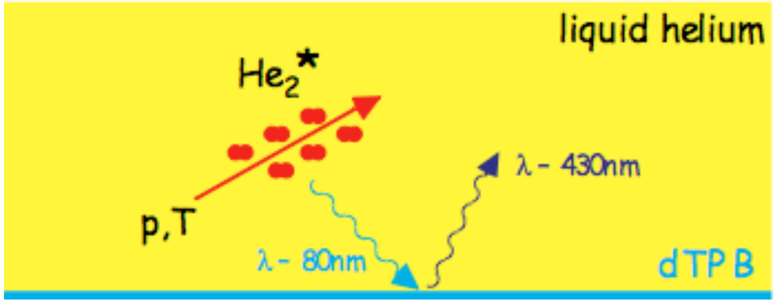
$\sigma_{J=1} \approx 0$

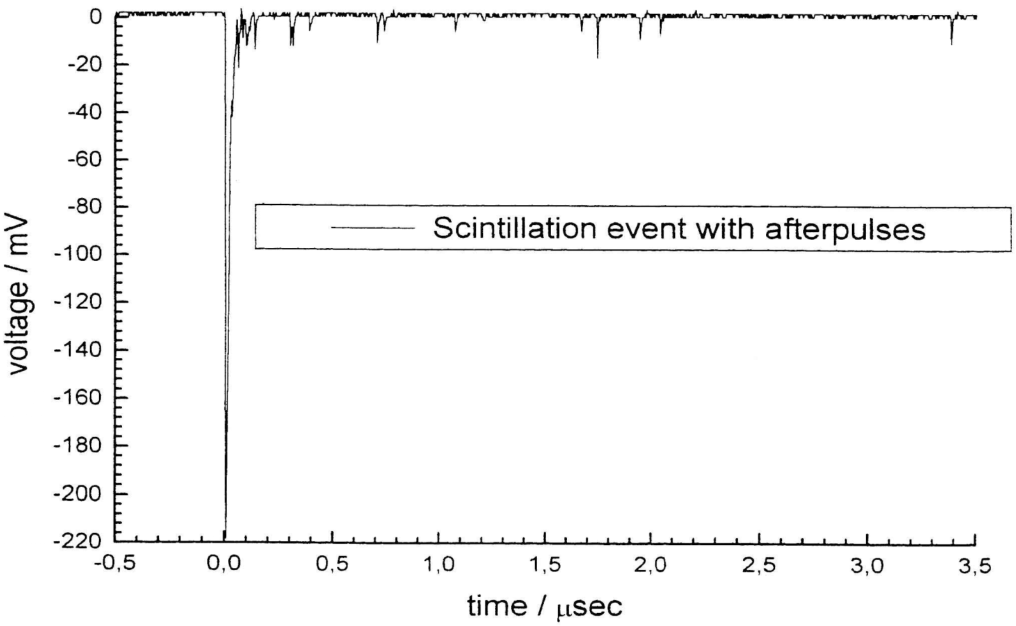
NO capture in the triplet state

Liquid Helium is a scintillator

- Recoiling charged particle creates an ionization track in the helium.
- Helium ions form excited He_2^* molecules(ns time scale) in both singlet and triplet states.
- He_2^* singlet molecules decay, producing a large prompt
- (< 20 ns) emission of extreme ultraviolet (EUV) light.
- EUV light (80 nm) converted to blue using the deuterated organic fluor dTPB (tetraphenyl butadiene).

$$n + {}^3He \rightarrow p + T$$





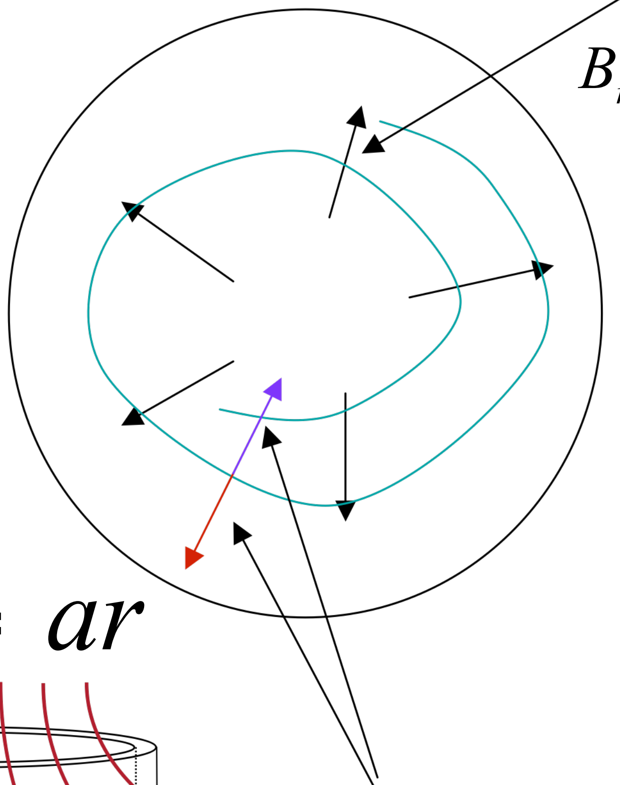
Gravitational Shift

- Due to difference in the effective temperature of the UCN and ^{3}He atoms, there can be a displacement between the centers-of-gravity; this places a constraint on systematic magnetic field gradients

$$\Delta h = \frac{m_n g h^2}{3kT}$$

- This is 1.5 mm for UCN, for h = 10 cm and T = 5 mK
  - Systematic magnetic gradient (e.g., gradient correlated with the high voltage) must be less than 10 pG/cm for 10^{-28} e cm
  - 1 nA leakage (1/4 loop) gives a possible systematic of
  - 5×10^{-29} e cm

Gradient Interference with Exv field



Radial gradient

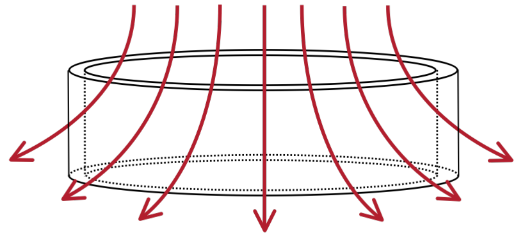
$$B_{rot} = \sqrt{(B_0 - \omega_r / \gamma)^2 + (aR - \omega_r RE / c)^2}$$

$$B \approx B_0 - \frac{aR^2 \omega_r E / c}{B_0 - \omega_r / \gamma}$$

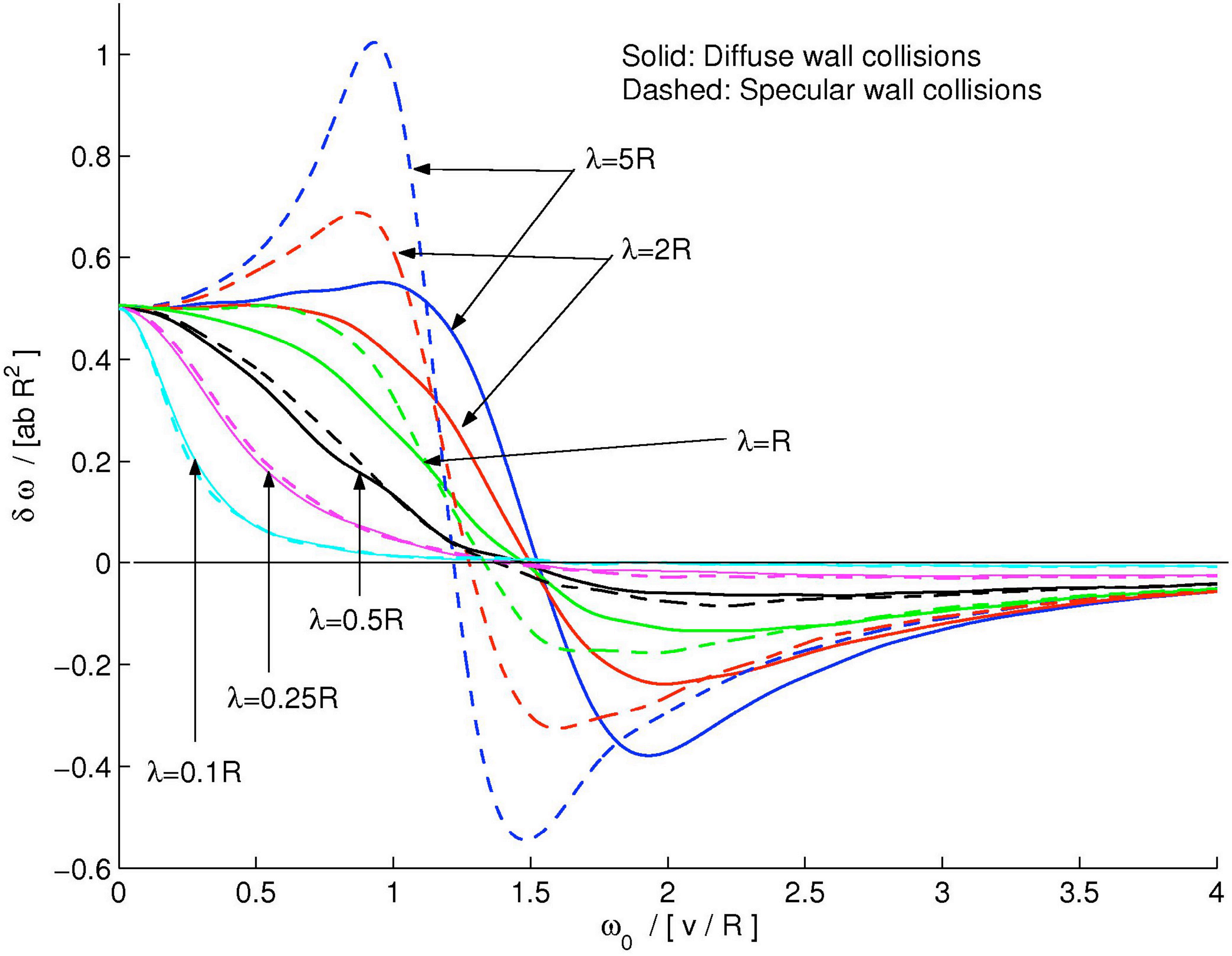
$$\delta\omega = \frac{\gamma^2 aR^2 E}{c}$$

v × E field
Changes sign with direction

$$B_r = ar$$



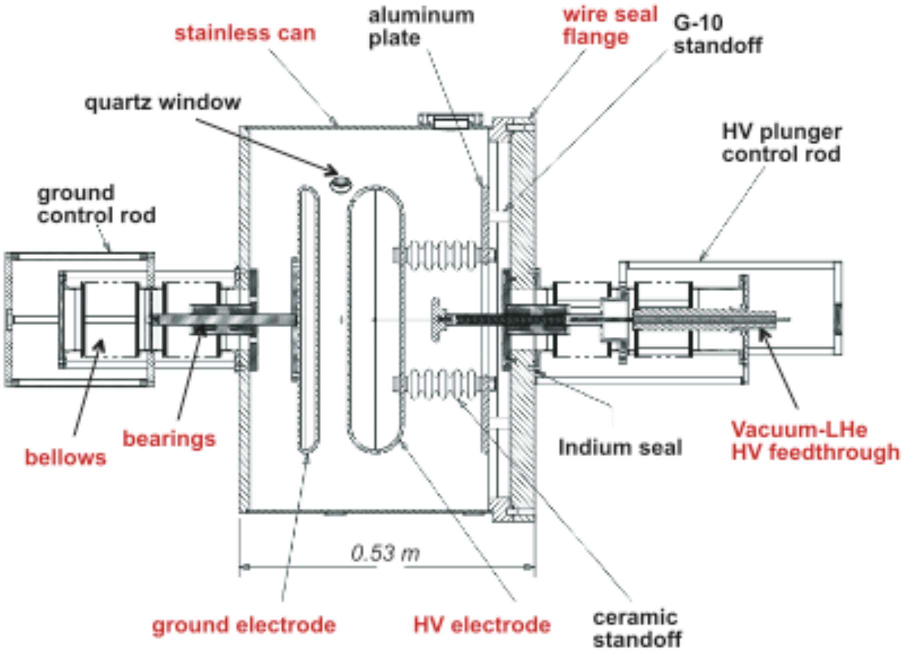
Vary temperature

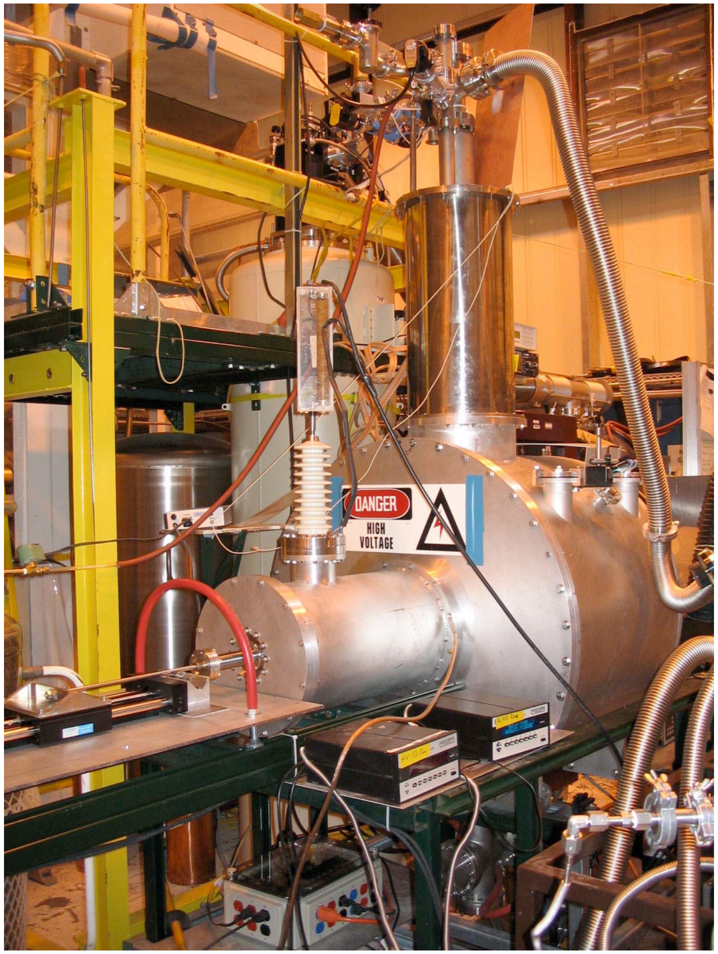


High Voltage Capacitor System

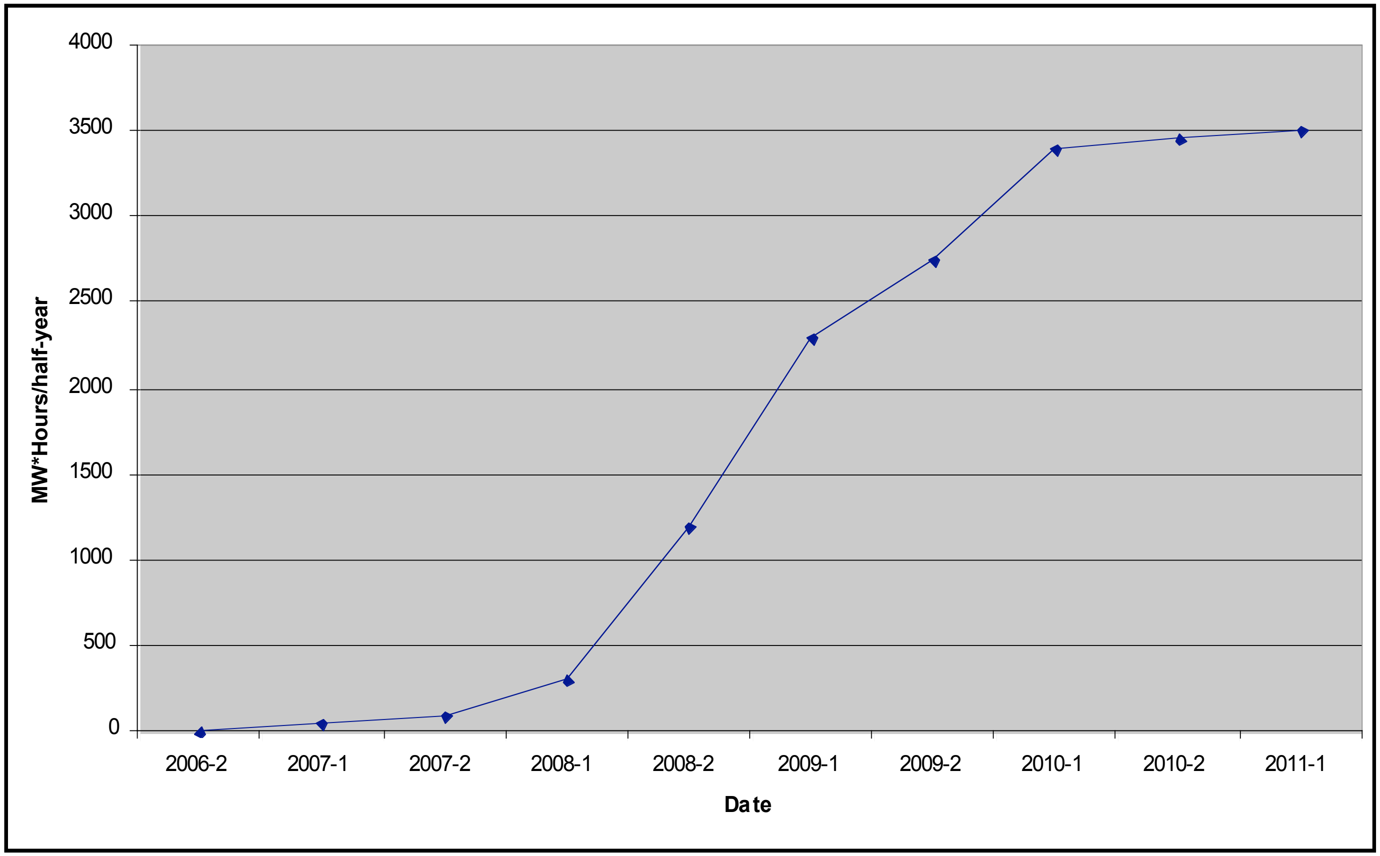
d = 0.5 5 cm
HV = 50 500 kV

$q = CV$





Proposed SNS Operational Ramp-Up



Source: SNS Project

November operations – 60 kw @ 15 Hz

Summary

- nEDM is in the early stages of constructing an apparatus to measure the neutron EDM.
- DOE & NSF are committed to this project.
- We expect to begin installation in 2009.
- Our goal is to either measure the magnitude of the neutron EDM or to lower the current experimental limit by two orders of magnitude.

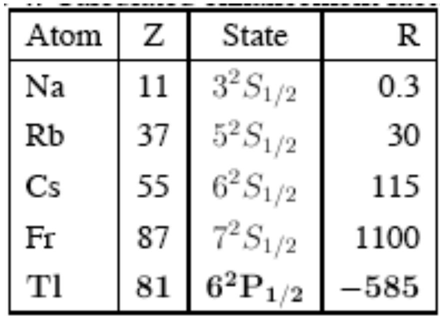
Paramagnetic Atoms

$\vec{E}_{ext}$ polarizes atom: $0 = \Sigma\vec{F} = e\vec{E}_{int} - \vec{\nabla}(\vec{\mu}\cdot\vec{B})$

$$-\vec{v}\times\vec{E} = \frac{Ze^2}{mr^2}\vec{r}\times\vec{p}$$

$$E_{int} \sim \alpha^2 Z^3 E_{ext}$$

$$E_{int} > E_{ext} \text{ for } Z>27$$



Atom	Z	State	R
Na	11	$3^2S_{1/2}$	0.3
Rb	37	$5^2S_{1/2}$	30
Cs	55	$6^2S_{1/2}$	115
Fr	87	$7^2S_{1/2}$	1100
Tl	81	$6^2P_{1/2}$	−585

But: Scalar e-N interactions also contribute:

$d_{Tl} = -585d_e - kC_s$ (k ~ 1-100 - A. Ritz et al.)

For $C_s=0$: $d_e<2\text{x}10^{-27}$e-cm; for $C_s\neq 0$ $d_e< \sim 10^{-25}$ e-cm

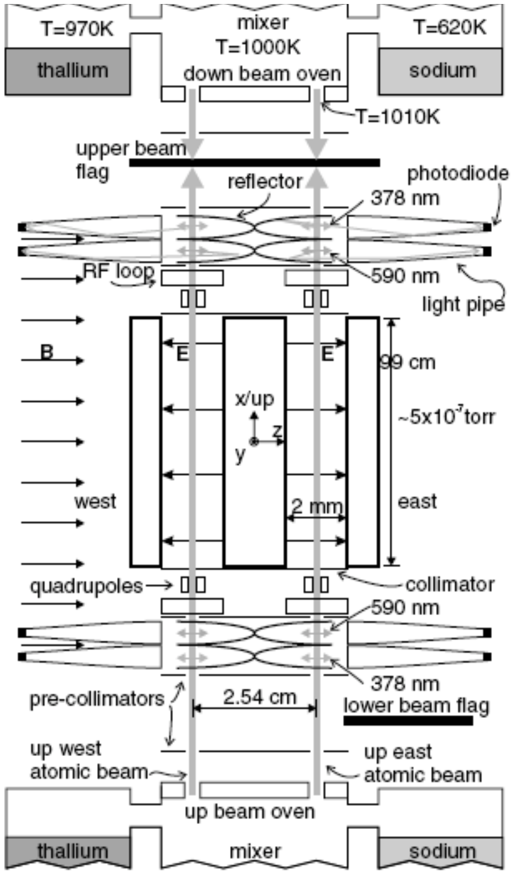
$d_{Tl}<9\text{x}10^{-25}$ e-cm $\quad$ $d_{Cs}<120\text{x}10^{-25}$ e-cm

Thallium/Sodium (comagnetometer)

$$h\omega = 2(d \cdot E + \mu \cdot B)$$

$\frac{\mu_0}{2r}\frac{V}{R}$, vxE, …

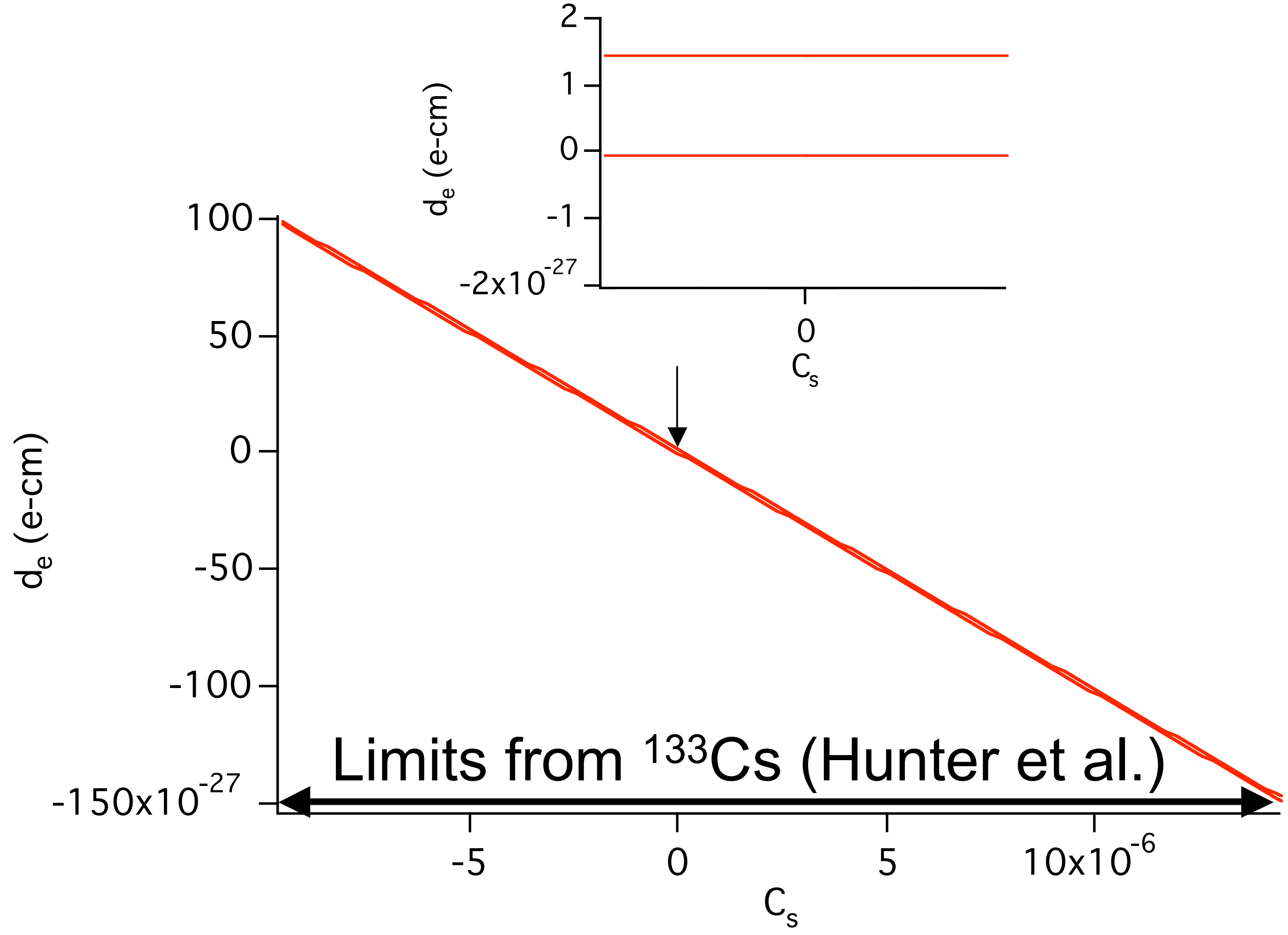
Leakage current



Use $Z^{2,3}$ to pick a second species

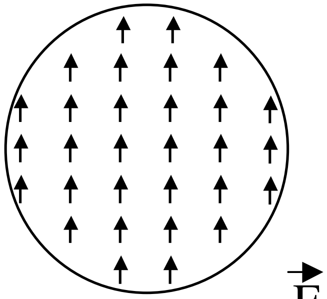
Also: Berry’s phase, vxE…

Electron EDM



Diamagnetic Atoms: J=0 (^{199}Hg, Noble gases)

Atomic electrons probe nuclear distribution of EDM:

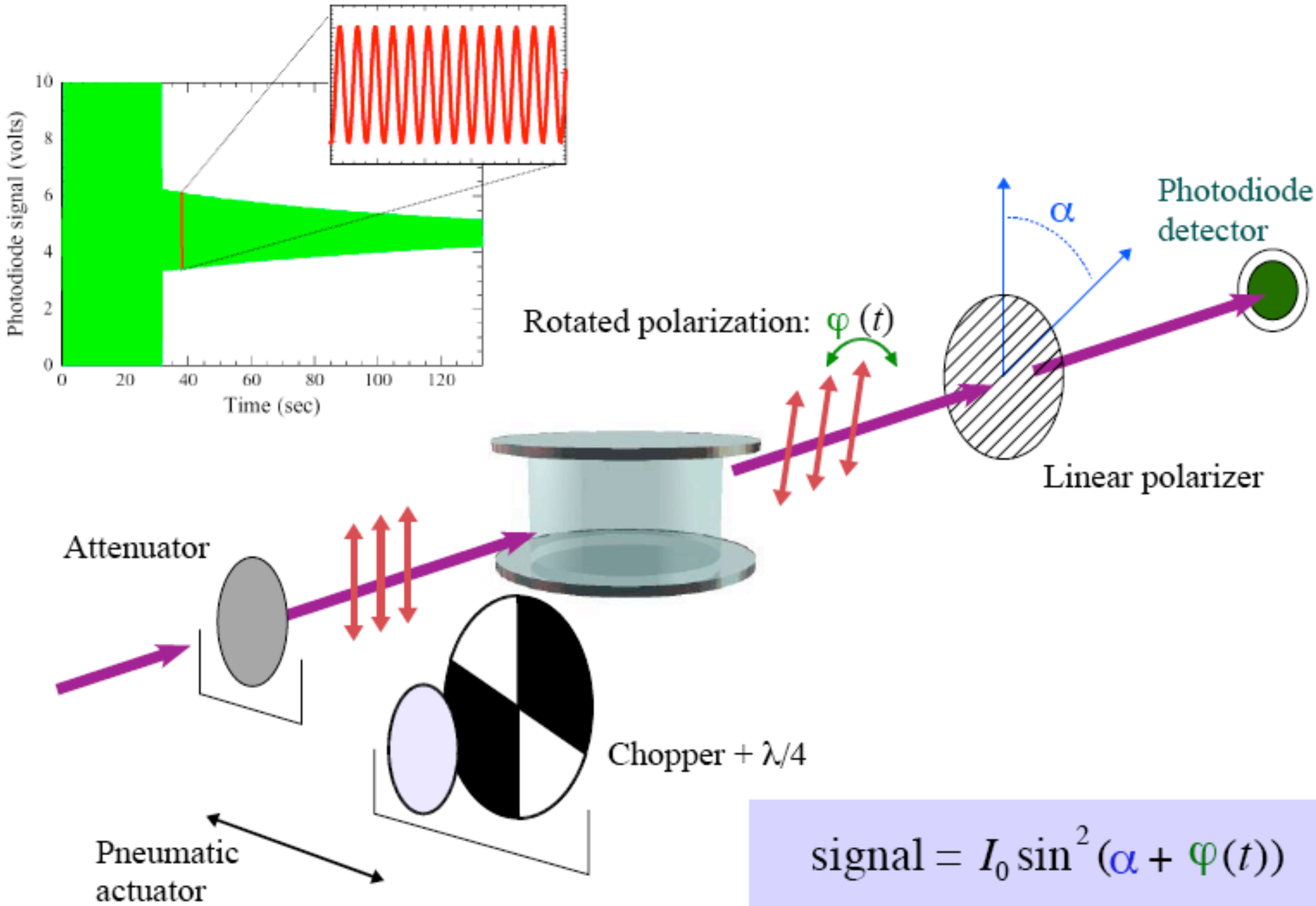


$\vec{E}\ \alpha\ \vec{J}$

$$\vec{S}=(1/10)\ \langle r^2\ \vec{r}_P\rangle - (1/6Z)\langle r^2\rangle\langle \vec{r}_p\rangle$$

$\sim Z^2$ or Z^3

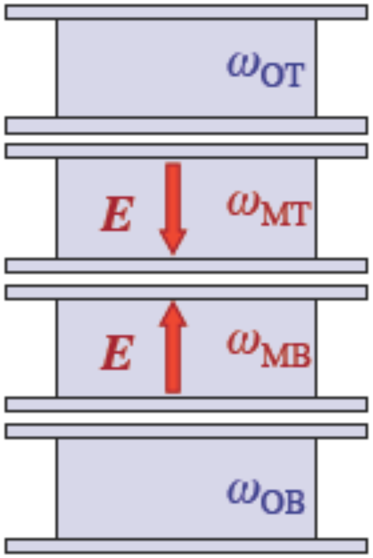
Seattle ^{199}Hg Experiment

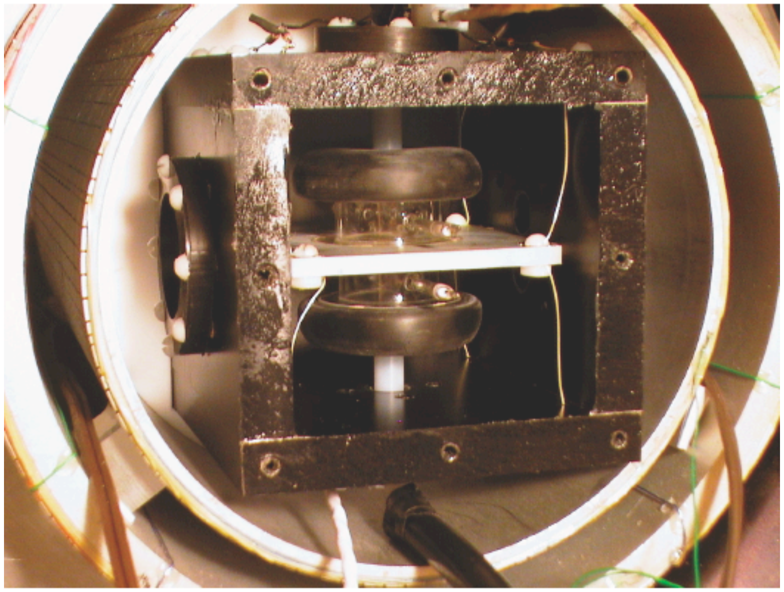


$$\text{signal} = I_0 \sin^2(\alpha + \varphi(t))$$

$$\varphi(t) = A e^{-t/T_2} \sin(\omega t + p)$$

Seattle ^{199}Hg Experiment





(EDM combo): $(\omega_{MT} - \omega_{MB}) - \frac{1}{3}(\omega_{OT} - \omega_{OB})$

- cancels up to 2nd order gradient noise
- same EDM sensitivity as middle cell difference

(LeakTest combo): $(\omega_{MT} + \omega_{MB}) - (\omega_{OT} + \omega_{OB})$

- cancels linear gradient noise
- gives zero for a true EDM
- sensitive to magnetic systematics

Seattle ^{199}Hg Experiment

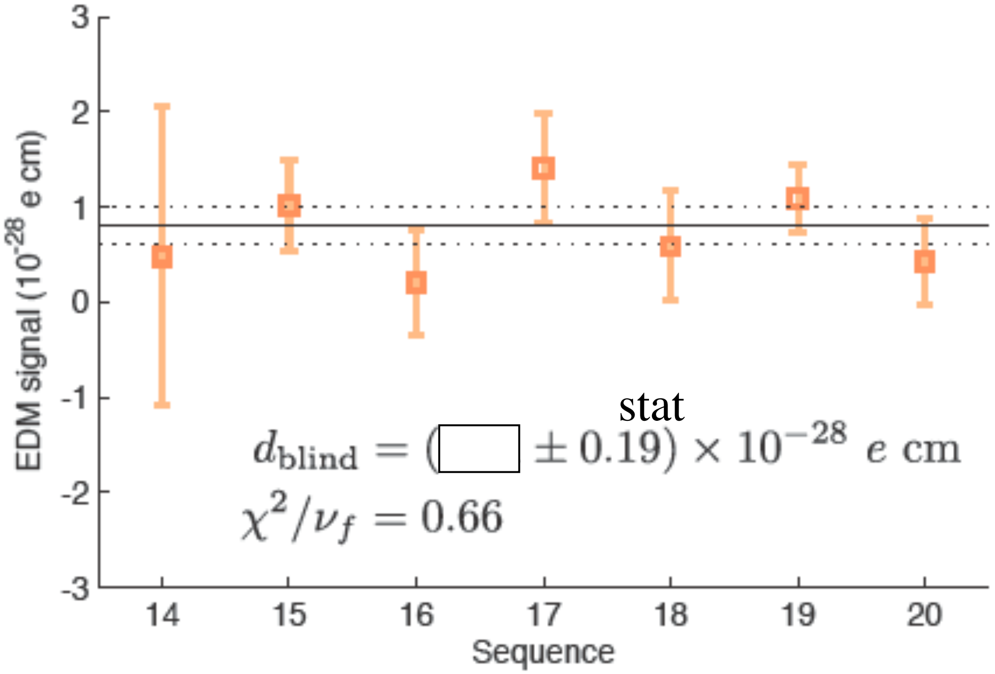
2001: $d(^{199}\text{Hg}) = [-10.6 \pm 4.9_{\text{stat.}} \pm 4.0_{\text{syst.}}] \times 10^{-29}\ e\ \text{cm}$

$d_{\text{Hg}} < 2.1\text{x}10^{-28}$ e-cm (95% c.l.)

2009-: $d(^{199}\text{Hg}) = [0.49 \pm 1.29 \pm 0.76] \text{ x } 10^{-29}\ e\ \text{cm}$

$d_{\text{Hg}} < 3.1\text{x}10^{-29}$ e-cm (95% c.l.)

BLIND ANALYSIS (3X MORE DATA)



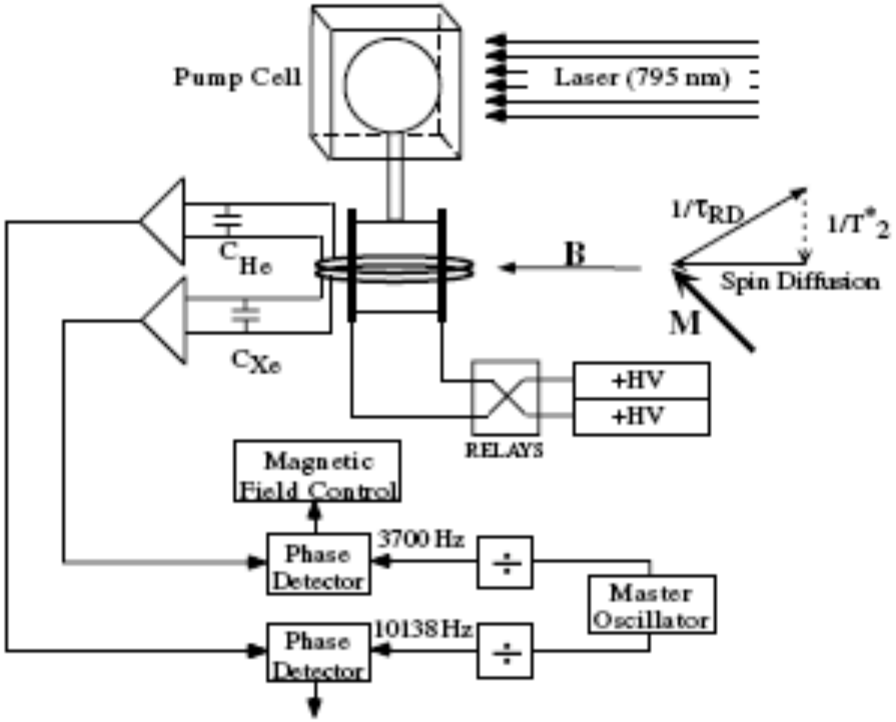
stat

$$d_{\text{blind}} = (\boxed{} \pm 0.19) \times 10^{-28}\ e\ \text{cm}$$

$$\chi^2/\nu_f = 0.66$$

d_{Hg} + R(1)*2x10^{-28}

Two species maser measurement: ^{129}Xe/^{3}He



NUMBER 1 PHYSICAL REVIEW LETTERS 1 JANUARY 2001

Atomic Electric Dipole Moment Measurement Using Spin Exchange Pumped Masers of ^{129}Xe and ^{3}He

M. A. Rosenberry* and T. E. Chupp
University of Michigan, Ann Arbor, Michigan 48109
(Received 1 August 2000)

We have measured the T-odd permanent electric dipole moment of ^{129}Xe with spin exchange pumped masers and a ^{3}He comagnetometer. The comagnetometer provides a direct measure of several systematic effects that may limit electric dipole moment sensitivity, and we have directly measured the effects of changes in leakage current that result when the applied electric field is changed. Our result, $d(^{129}\mathrm{Xe}) = 0.7 \pm 3.3(\mathrm{stat}) \pm 0.1(\mathrm{syst}) \times 10^{-27} e$ cm, is a fourfold improvement in sensitivity.

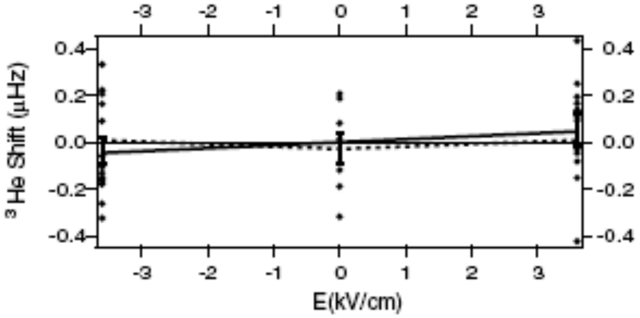
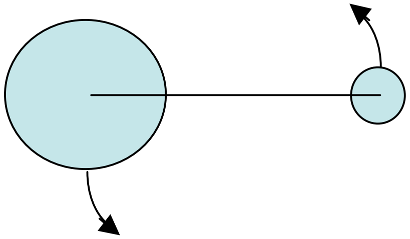


FIG. 2. Corrected ^{3}He beat frequencies for a single run plotted

This has 10-100x more sensitivity possible.

Molecular EDMs

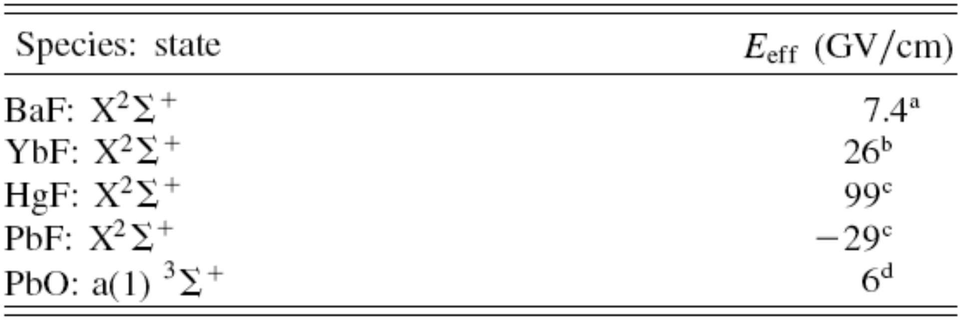


Intrinsic dipole moment along symmetry axis $\langle\vec{d}\rangle=0$.

Apply E: Polarizes d ǁ E ($U \sim E^2$). (just 100 V/cm)

Apply B: splits $m_{j:}$ $\hbar\omega=-2\mu\bullet B\left(1\pm\frac{g_d}{g_\mu}\frac{E}{B}\right)$

i.e. search for $\vec{d}$ along $\vec{J}$

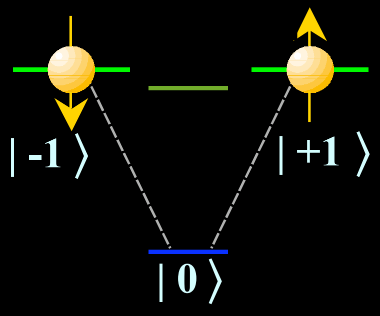


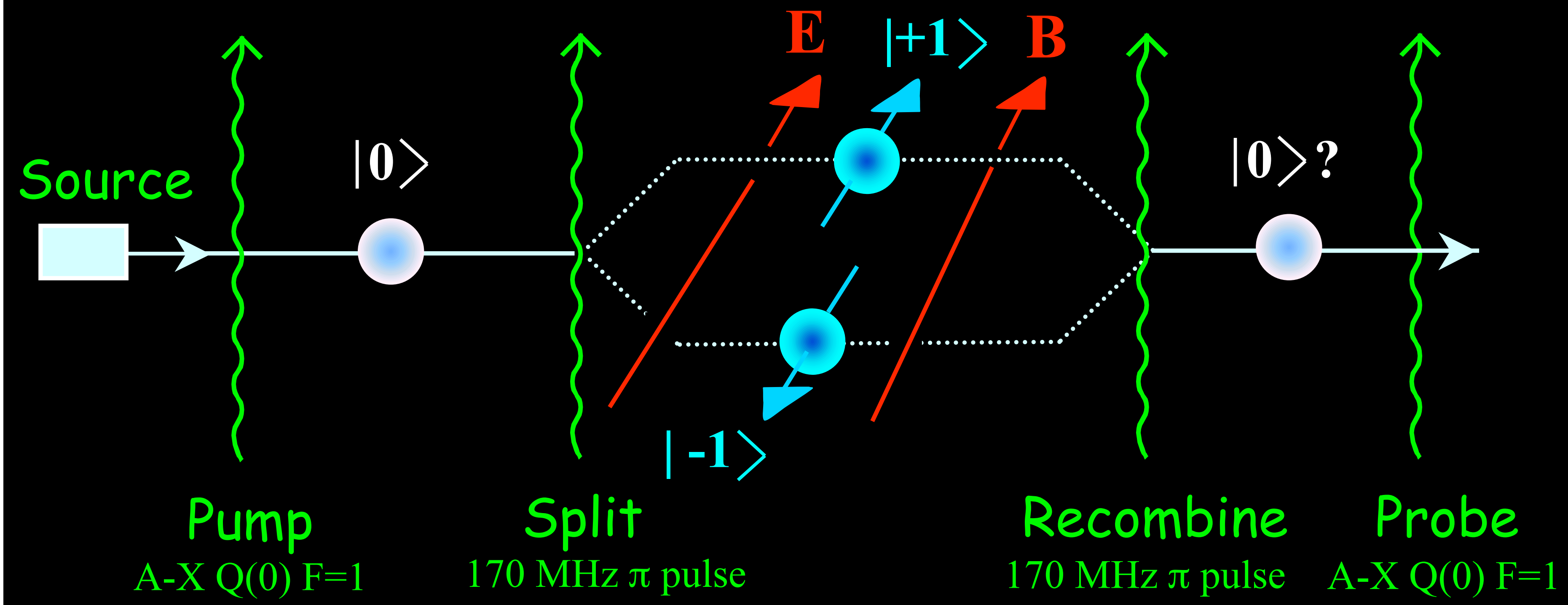
Species: state	E_{eff} (GV/cm)
BaF: $X^2\Sigma^+$	7.4[a]
YbF: $X^2\Sigma^+$	26[b]
HgF: $X^2\Sigma^+$	99[c]
PbF: $X^2\Sigma^+$	−29[c]
PbO: a(1) $^3\Sigma^+$	6[d]

TlF: J=0; unpaired proton (Ramsey, Sandars/Hinds, Hinds/Cho)
Paramagnetic molecules: d_e (YbF; PbO, WC…)

E. Hinds et al.

Interferometer to measure $2d_e\eta E$

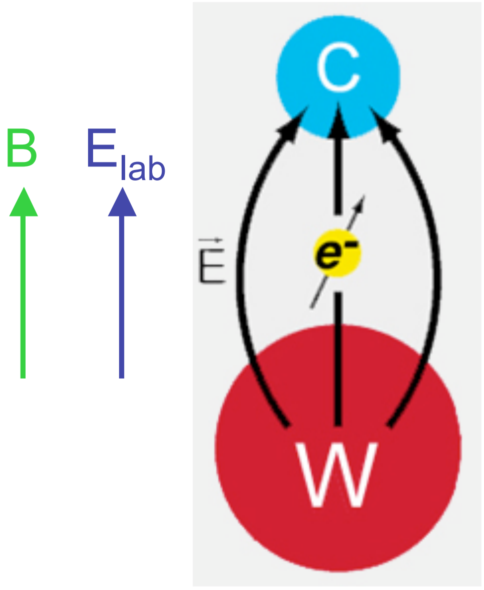


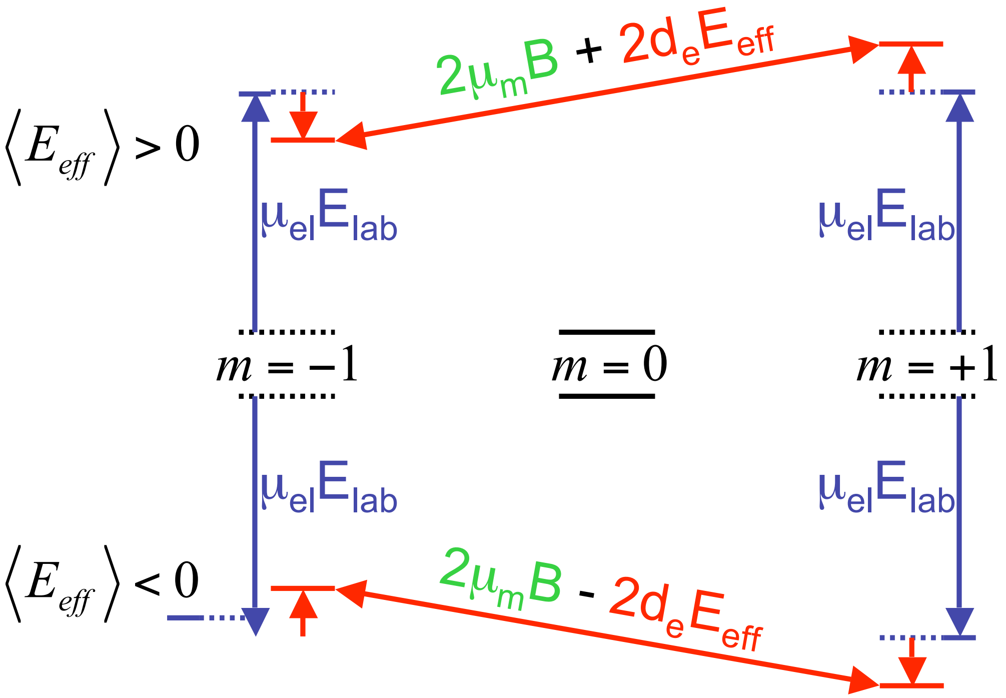


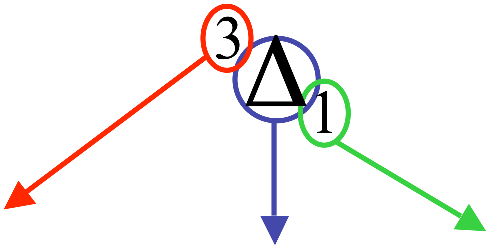
Phase difference = $2\,(\mu B + d_e\eta E)T/\hbar$

$d_e=(-0.2\pm3.2)\mathrm{x}10^{-26}$ e-cm (2002 PRL89 p 023003)

Co-magnetometers in Molecular Systems
(from Aaron Leanhardt - U. Michigan)







$^3\Delta_1$

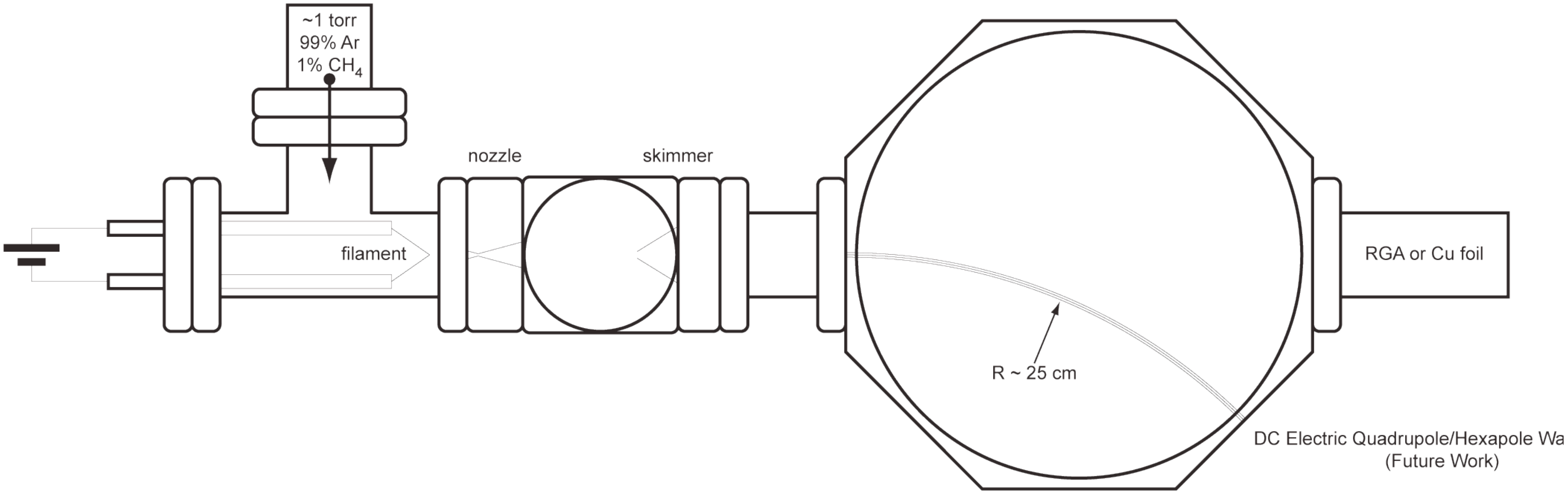
spin: $\Sigma = \pm 1$

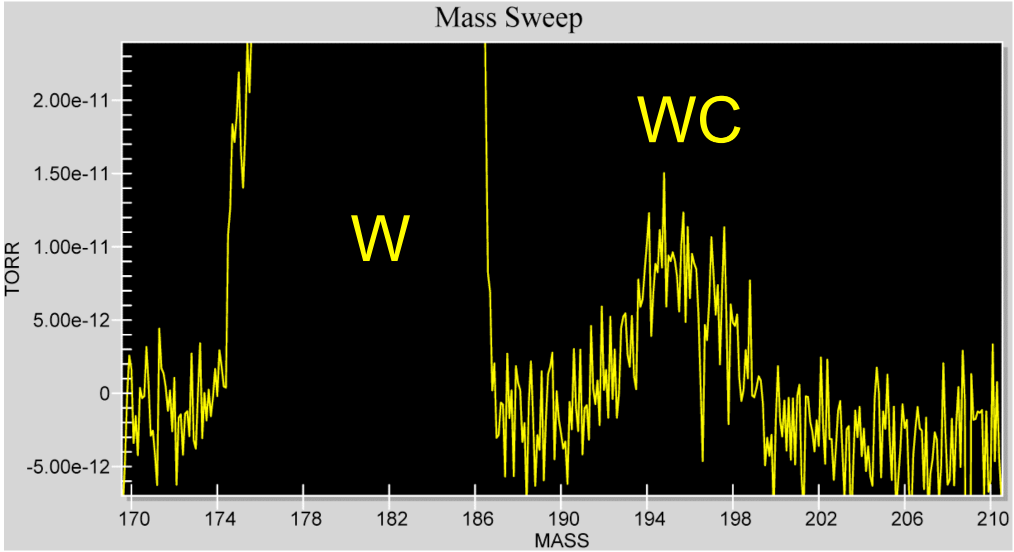
orbital: $\Lambda = \pm 2$

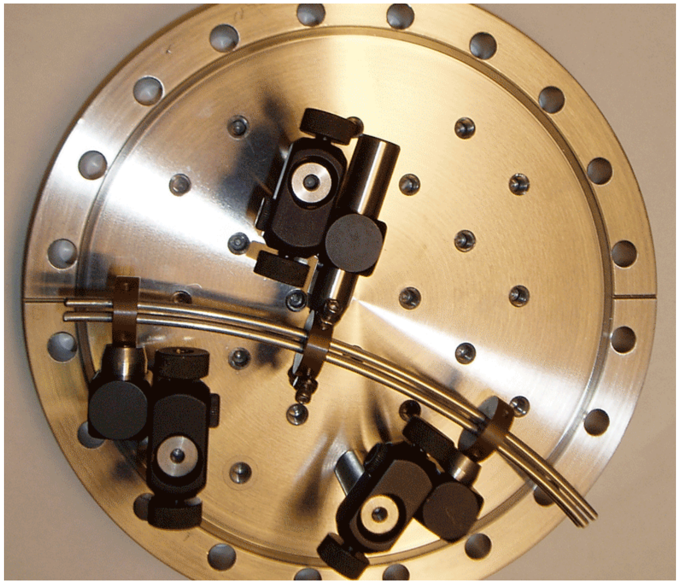
spin + orbital: $\Omega = \Lambda + \Sigma = \pm 1$

Note: Vary magnitude of E_{lab}: Fully mixed states of opposite parity and E_{eff} nominally ***independent*** of $E_{lab,}$ i.e. hω does not depend on |E|.

WC Experiment: Aaron Leanhardt - U. Michigan







Also: cold Th0 by deMille, Doyle, Gabrielse (Yale/Harvard)

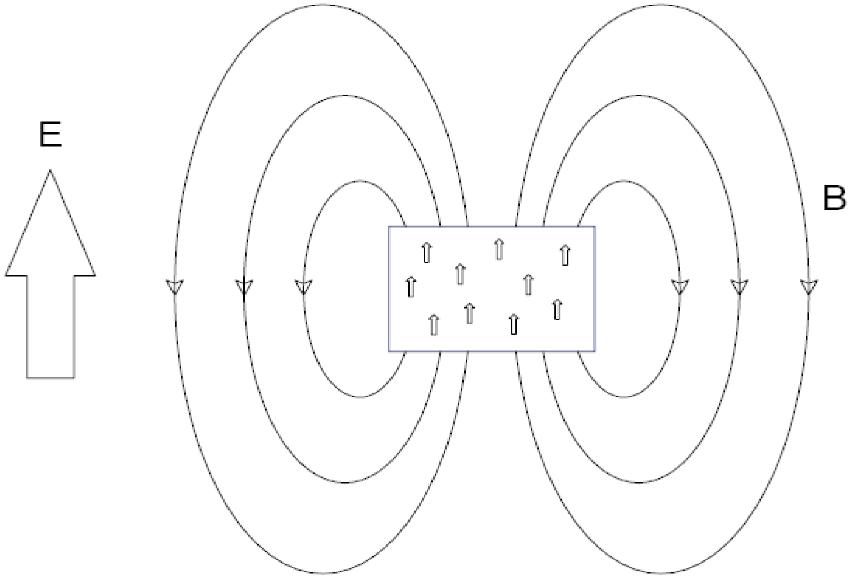
EDM Experiments in Solids

Basic Idea: Electric field polarizes e, Atom

→ garnet PbTi

Produces Large M

Detect with magnetometer



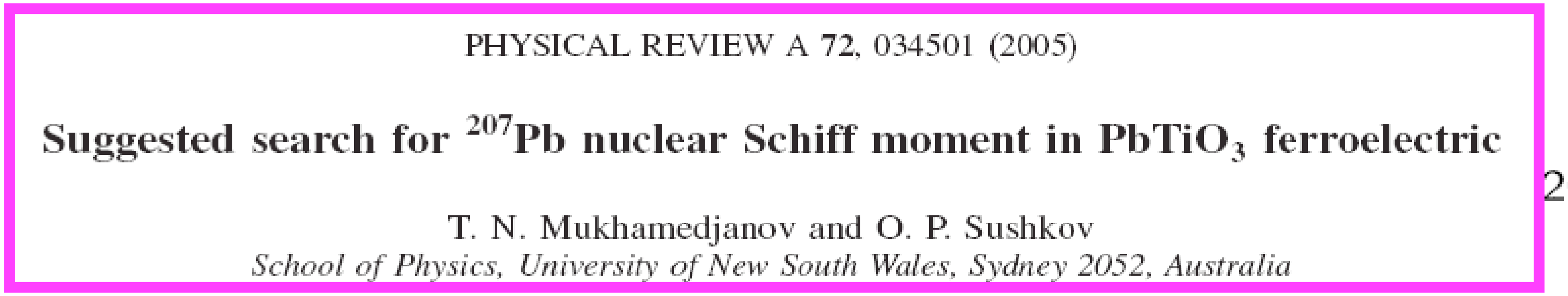
$$B \approx N\mu \frac{dE}{kT_S}$$

is measured by a magnetometer

(F. L. Shapiro, Usp. Phys. Nauk (1968))

Thanks to D. Budker

Where does the improvement come from?



PHYSICAL REVIEW A **72**, 034501 (2005)

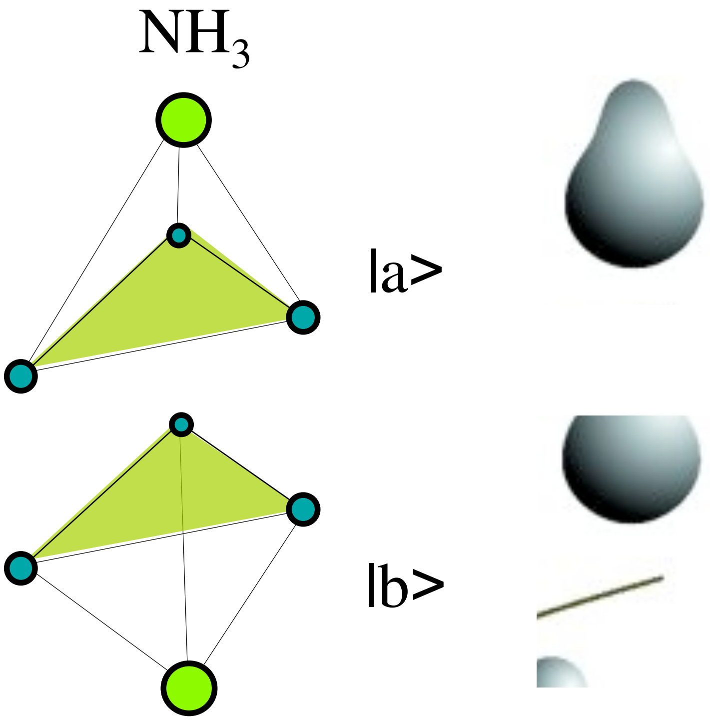
Suggested search for ^{207}Pb nuclear Schiff moment in $PbTiO_3$ ferroelectric

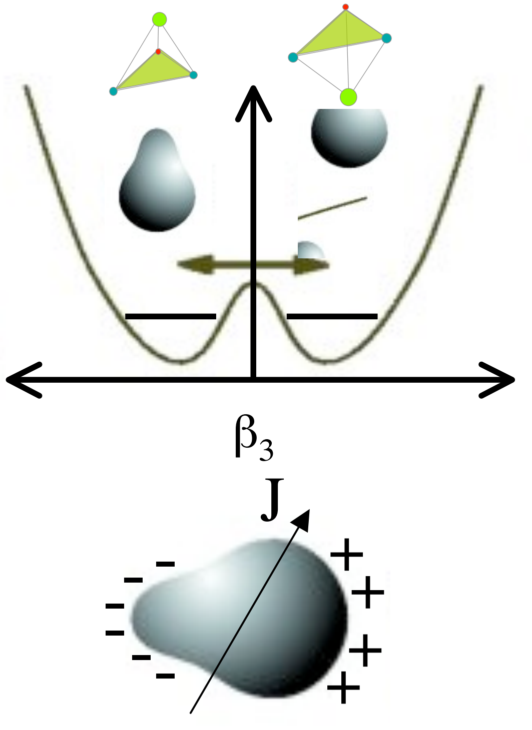
T. N. Mukhamedjanov and O. P. Sushkov
School of Physics, University of New South Wales, Sydney 2052, Australia

- $PbTiO_3$ is a ferroelectric crystal ⟶ large effective electric field: $E_{\text{int}} \approx 10^8$ V/cm
- A solid-state experiment ⟶ large number of atoms: $N \approx 10^{22}$ cm^{-3}
- Nuclear de-magnetization cooling to reach nuclear spin temperature: $T_s \approx 10^{-4}$ K
- Other schemes (optical pumping?) may give even lower nuclear spin temperature: $T_s \approx 10^{-8}$ K

Octupole Enhancements

(see Feynman vol 3.)





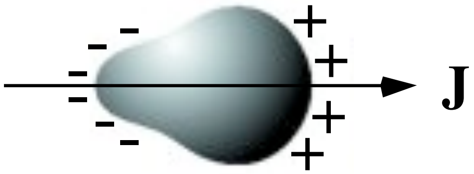
$$|\psi_\pm\rangle = \frac{1}{\sqrt{2}}\left(|a\rangle \pm |b\rangle \right)$$

$$S \sim \frac{\langle + | \eta r^3 \cos\theta | - \rangle}{E_+ - E_-} \sim \frac{\eta \beta_2 \beta^2_3 Z A^{2/3} r_0{}^3}{E_+ - E_-}$$

Nuclei with Octupole Deformation/Vibration

(Haxton & Henley; Auerbach, Flambaum, Spevak; Engel et al., Hayes & Friar, etc.)

$$S \sim \frac{\langle + | \eta r^3 \cos\theta | - \rangle}{E_+ - E_-} \sim \frac{\eta \beta_2 \beta_3^2 Z A^{2/3} r_0^3}{E_+ - E_-}$$



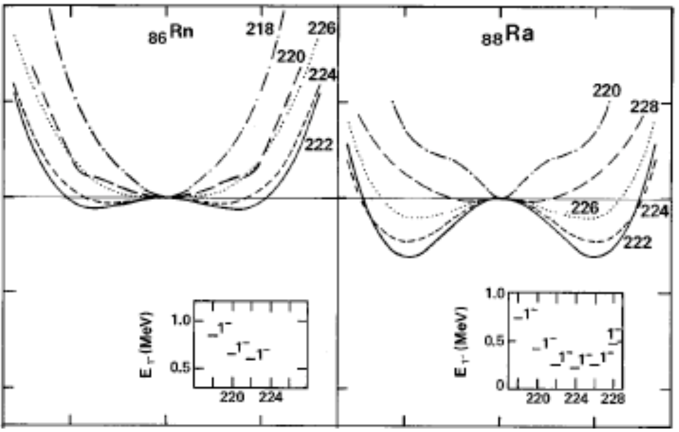
$$\eta_{qq} = 3.75 \times 10^{-4}$$

	^{223}Rn	^{223}Ra	^{225}Ra	^{223}Fr	^{129}Xe	^{199}Hg
$t_{1/2}$	23.2 m	11.4 d	14.9 d	22 m		
I	7/2	3/2	1/2	3/2	1/2	1/2
ΔE th (keV)	37*	170	47	75		
ΔE exp (keV)	-	50.2	55.2	160.5		
$10^{11} S$ (e-fm^3)	375	150	115	185	0.6	-0.75
$10^{28} d_A$ (e-cm)	1250	1250	940	1050	0.3	2.1

Ref: Dzuba PRA66, 012111 (2002) - Uncertainties of 50%

*Based on Woods-Saxon Potential

† Nilsson Potential Prediction is 137 keV



NOTES:
Ocutpole Enhancements
Engel et al. agree with Flambaum et al.
Even octupole vibrations enhance **S** (Engel, Flambaum& Zelevinsky)

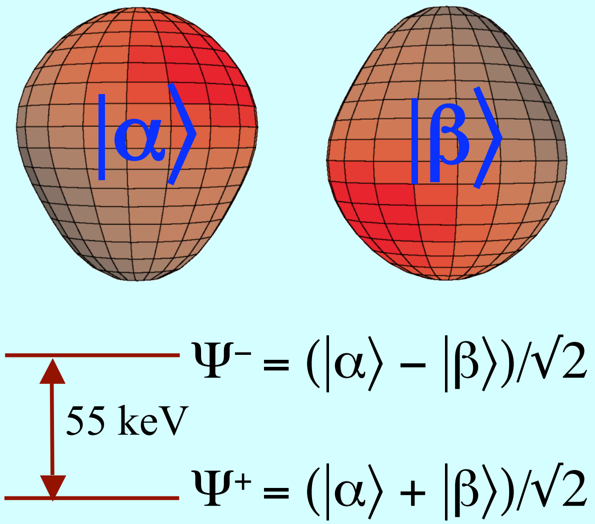
Enhanced EDM of ^{225}Ra

Enhancement mechanisms:

- Large intrinsic Schiff moment due to octupole deformation;
- Closely spaced parity doublet;
- Relativistic atomic structure.

Haxton & Henley (1983)
Auerbach, Flambaum & Spevak (1996)
Engel, Friar & Hayes (2000)

Parity doublet



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

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

Enhancement Factor: EDM (^{225}Ra) / EDM (^{199}Hg)

Skyrme Model	Isoscalar	Isovector	Isotensor
SkM*	1500	900	1500
SkO’	450	240	600

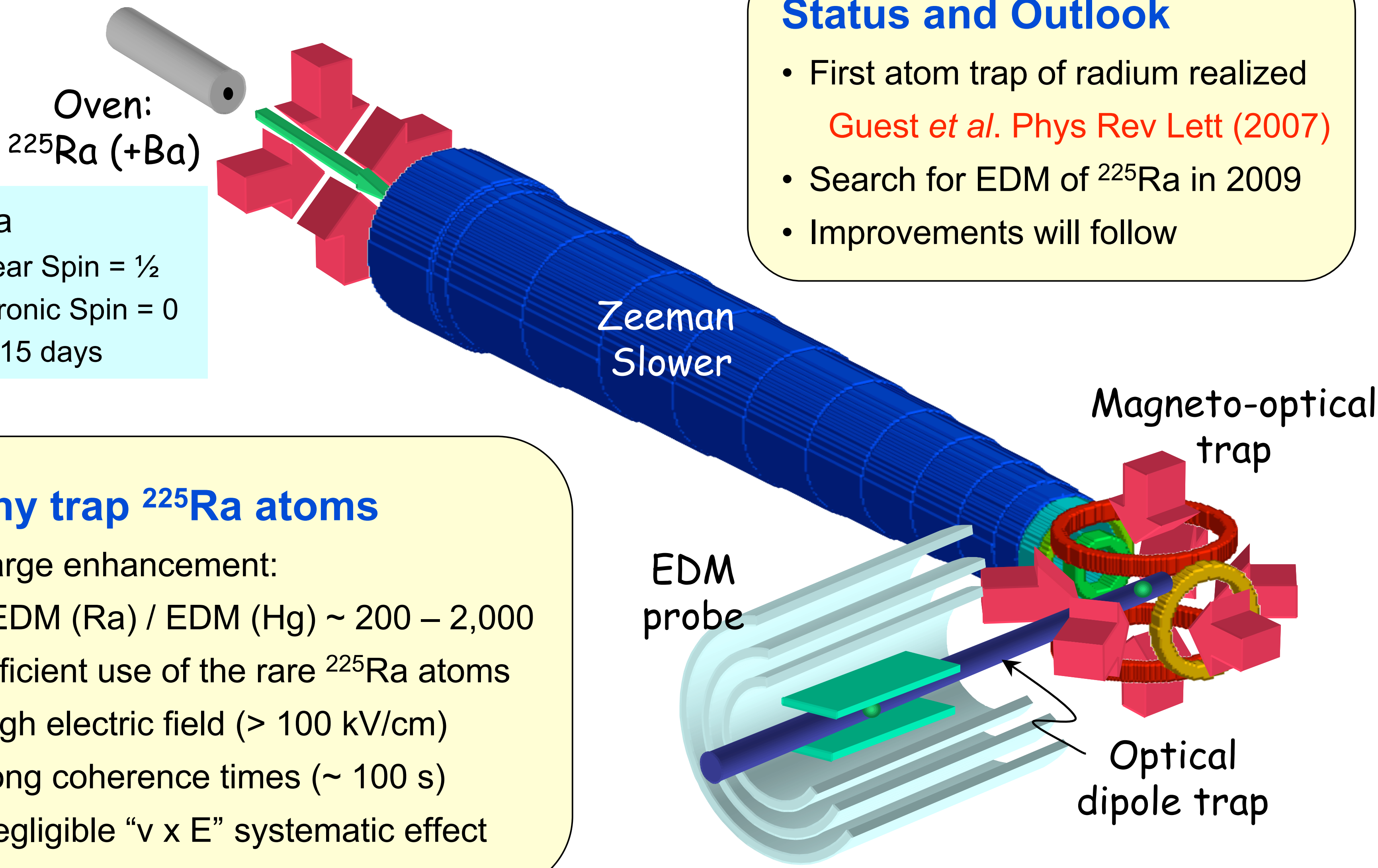
Schiff moment of ^{199}Hg, de Jesus & Engel, PRC (2005)
Schiff moment of ^{225}Ra, Dobaczewski & Engel, PRL (2005)

Search for EDM of ^{225}Ra at Argonne
(Z.T. Lu et al.)

Status and Outlook

- First atom trap of radium realized

  Guest *et al*. Phys Rev Lett (2007)
- Search for EDM of ^{225}Ra in 2009
- Improvements will follow



^{225}Ra

Nuclear Spin = ½

Electronic Spin = 0

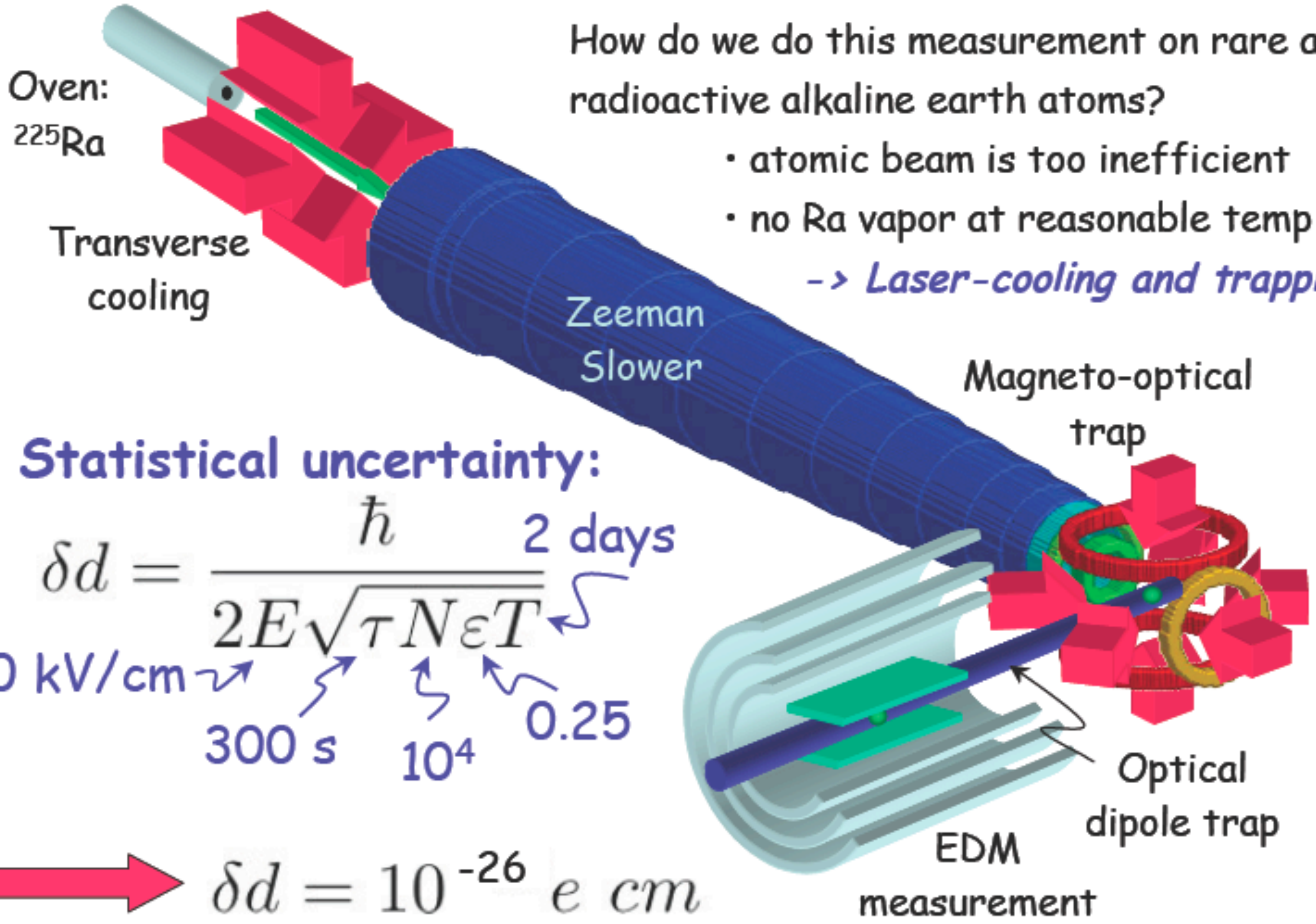
$t_{1/2}$ = 15 days

Why trap ^{225}Ra atoms

- Large enhancement:

  EDM (Ra) / EDM (Hg) ~ 200 – 2,000
- Efficient use of the rare ^{225}Ra atoms
- High electric field (> 100 kV/cm)
- Long coherence times (~ 100 s)
- Negligible “v x E” systematic effect

EDM measurement on Ra-225



How do we do this measurement on rare and radioactive alkaline earth atoms?

- atomic beam is too inefficient
- no Ra vapor at reasonable temp

-> Laser-cooling and trapping

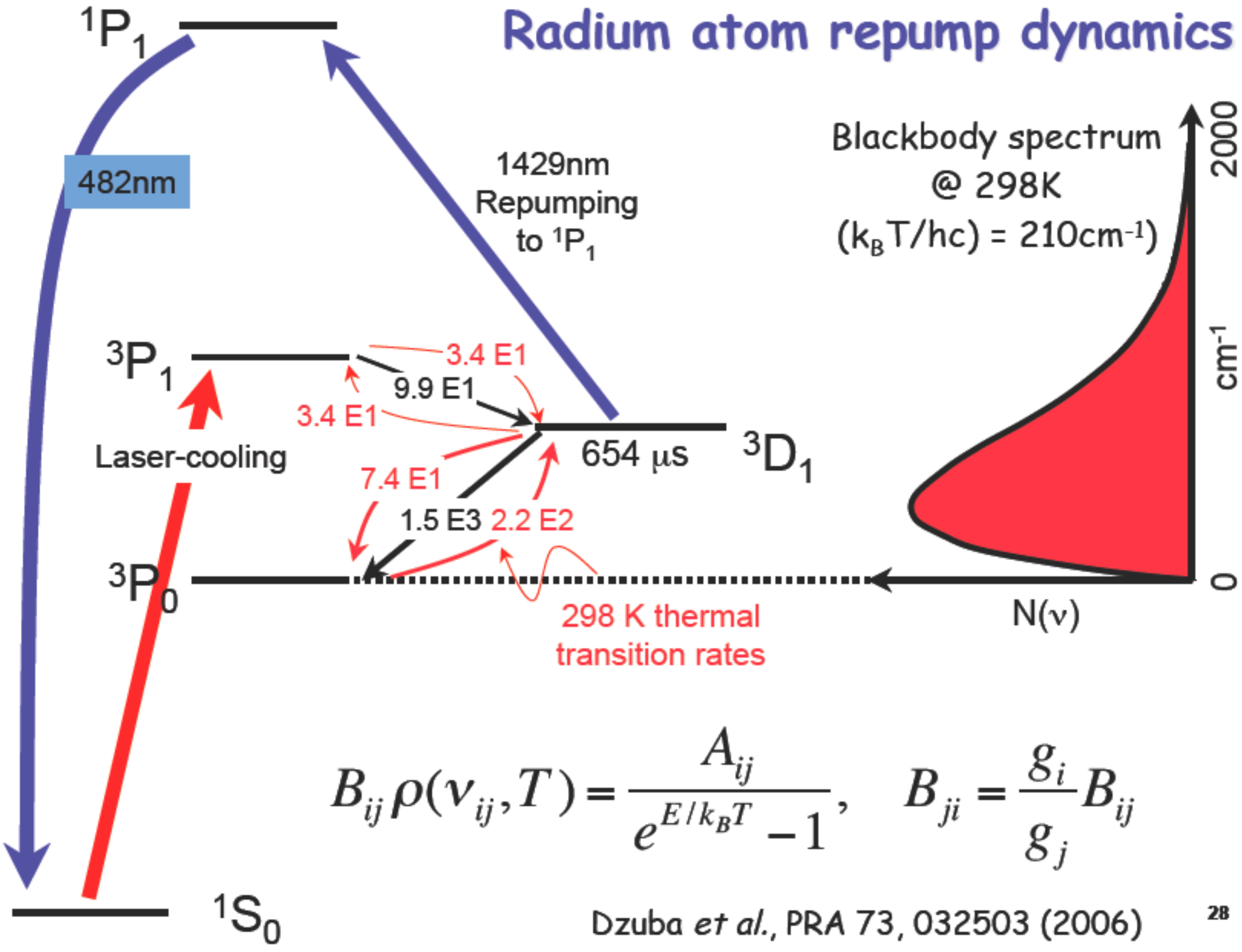
Statistical uncertainty:

$$\delta d = \frac{\hbar}{2\underset{100\ \text{kV/cm}}{E}\sqrt{\underset{300\ \text{s}}{\tau}\,\underset{10^4}{N}\,\underset{0.25}{\varepsilon}\,\overset{2\ \text{days}}{T}}}$$

$$\Rightarrow \delta d = 10^{-26}\ e\ cm$$

With enhancement competitive with Hg-199

Radium atom repump dynamics



$$B_{ij}\rho(\nu_{ij},T) = \frac{A_{ij}}{e^{E/k_BT}-1}, \quad B_{ji} = \frac{g_i}{g_j}B_{ij}$$

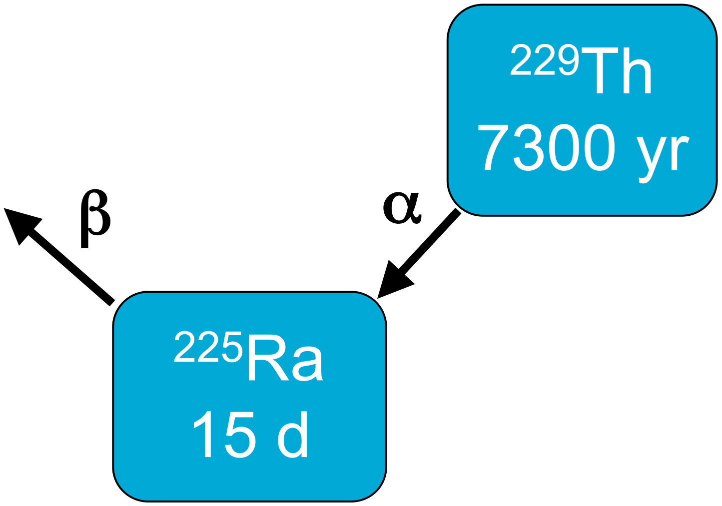
Dzuba *et al.*, PRA 73, 032503 (2006)

Search for ^{225}Ra EDM at FRIB

Present scheme

- 1 mCi ^{229}Th source

→ 4 x 10^7 s^{-1} ^{225}Ra



^{229}Th

7300 yr

α

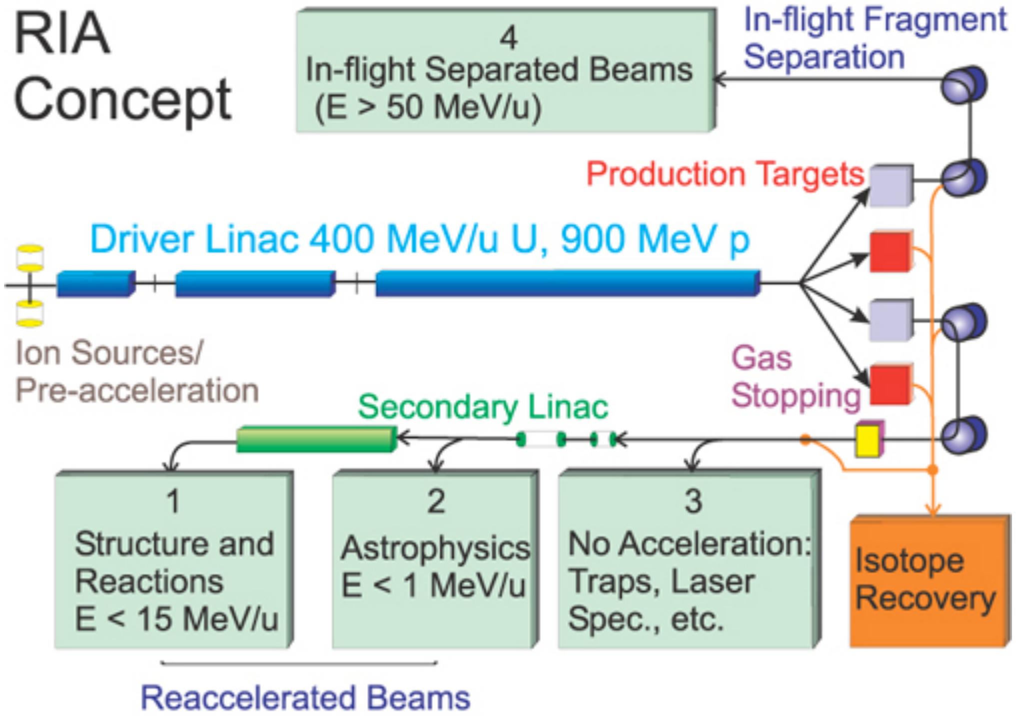
β

^{225}Ra

15 d

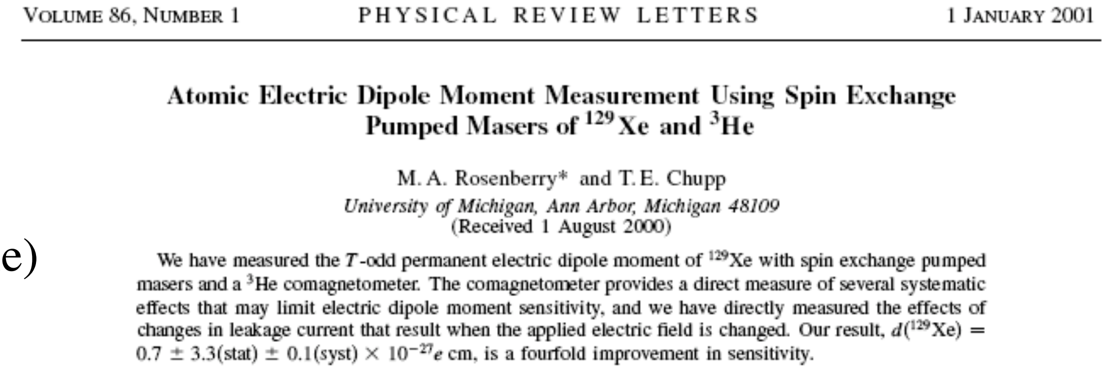
Facility for Rare Isotope Beam

- FRIB yield: 1 x 10^{12} s^{-1} ^{225}Ra



Why $^{223/221}$Rn?

- Octupole enhancement.
- Long(er) half-life
- EDM measurement in cells (see ^{129}Xe)
- Co-magnometer measurement



VOLUME 86, NUMBER 1 PHYSICAL REVIEW LETTERS 1 JANUARY 2001

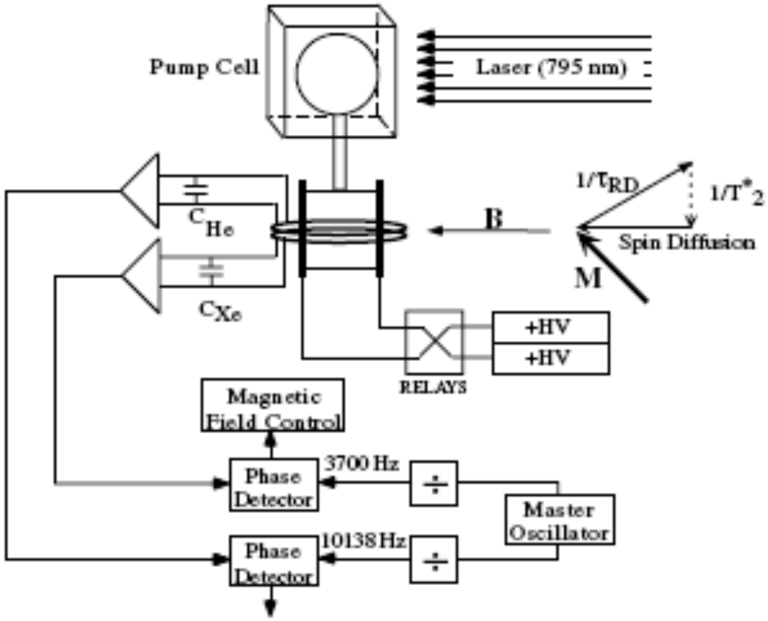
Atomic Electric Dipole Moment Measurement Using Spin Exchange Pumped Masers of ^{129}Xe and ^{3}He

M. A. Rosenberry* and T. E. Chupp

University of Michigan, Ann Arbor, Michigan 48109

(Received 1 August 2000)

We have measured the T-odd permanent electric dipole moment of ^{129}Xe with spin exchange pumped masers and a ^{3}He comagnetometer. The comagnetometer provides a direct measure of several systematic effects that may limit electric dipole moment sensitivity, and we have directly measured the effects of changes in leakage current that result when the applied electric field is changed. Our result, $d(^{129}\text{Xe}) = 0.7 \pm 3.3(\text{stat}) \pm 0.1(\text{syst}) \times 10^{-27} e$ cm, is a fourfold improvement in sensitivity.



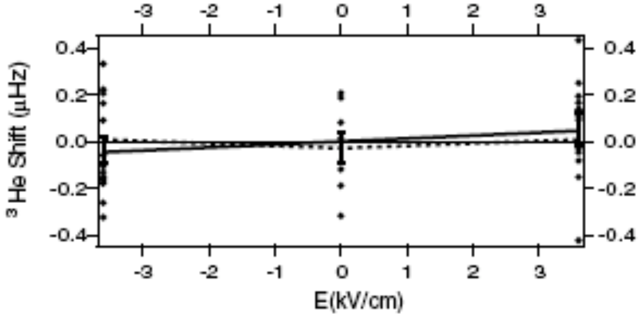
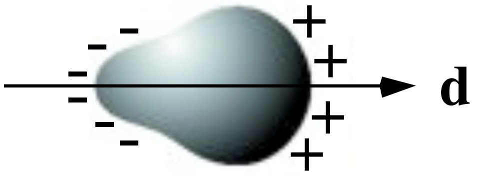


FIG. 2. Corrected ^{3}He beat frequencies for a single run plotted

Radon Isotopes

(Haxton & Henley; Auerbach, Flambaum, Spevak; Engel et al., Hayes & Friar, etc.)

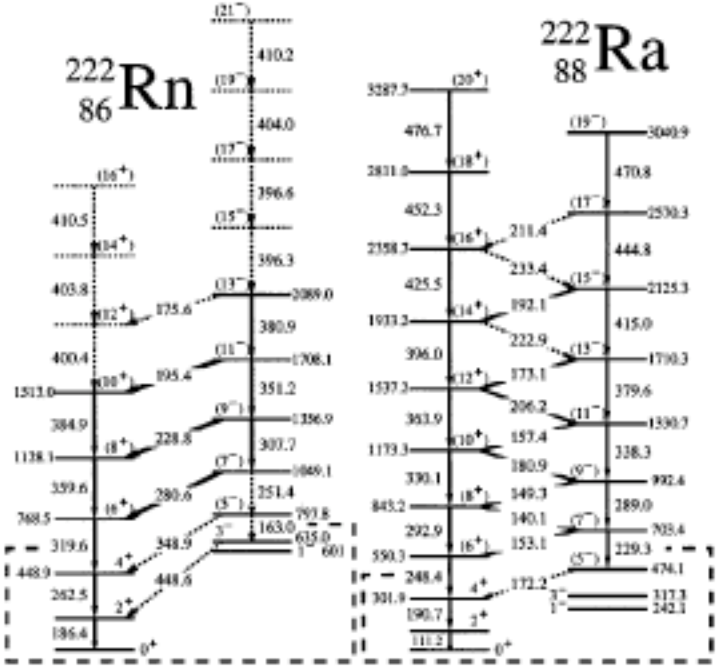
$$S \sim \frac{\langle + | \eta r^3 \cos\theta | - \rangle}{E_+ - E_-} \sim \frac{\eta \beta_2 \beta_3^2 Z A^{2/3} r_0^3}{E_+ - E_-}$$

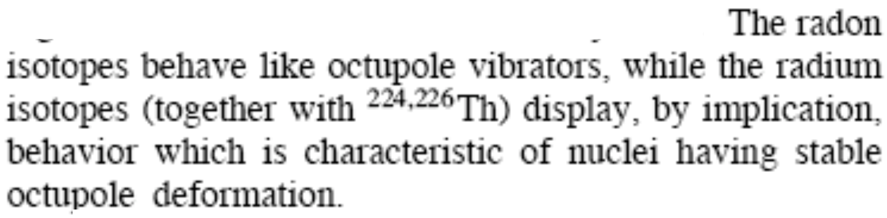


VOLUME 78, NUMBER 15 PHYSICAL REVIEW LETTERS 14 APRIL 1997

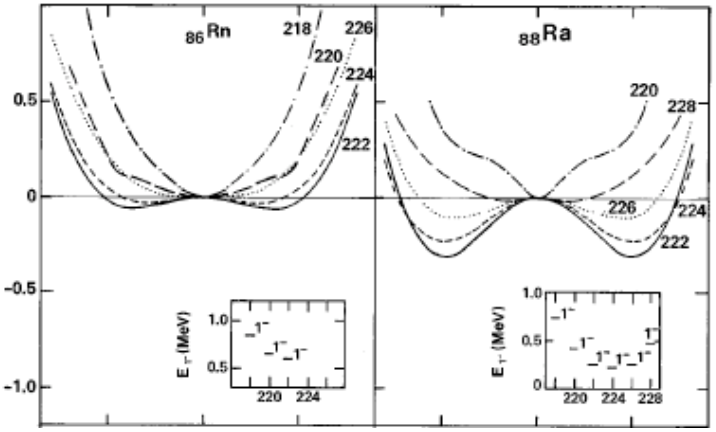
Observation of Octupole Structures in Radon and Radium Isotopes and Their Contrasting Behavior at High Spin

J. F. C. Cocks,[1] P. A. Butler,[1] K. J. Cann,[1] P. T. Greenlees,[1] G. D. Jones,[1] S. Asztalos,[2] P. Bhattacharyya,[3] R. Broda,[4] R. M. Clark,[2] M. A. Deleplanque,[2] R. M. Diamond,[2] P. Fallon,[2] B. Fornal,[4] P. M. Jones,[5] R. Julin,[5] T. Lauritsen,[6] I. Y. Lee,[2] A. O. Macchiavelli,[2] R. W. MacLeod,[2] J. F. Smith,[7] F. S. Stephens,[2] and C. T. Zhang[3]





The radon isotopes behave like octupole vibrators, while the radium isotopes (together with ^{224,226}Th) display, by implication, behavior which is characteristic of nuclei having stable octupole deformation.

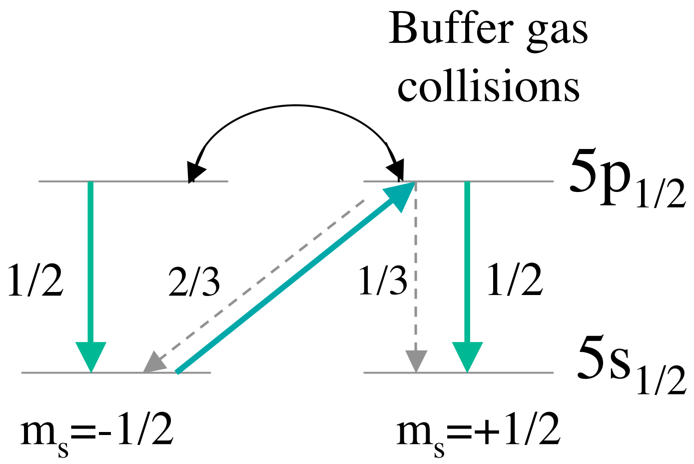


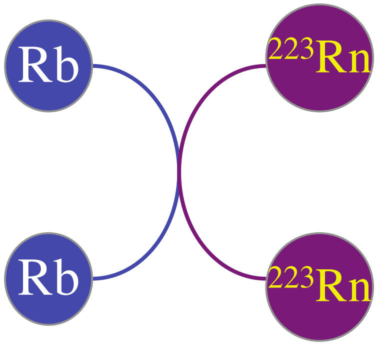
βdecay Studies of Rn Structure
8 π @ TRIUMF (fall 2009)

- Very high-level density in the odd-A Rn isotopes within the β decay Q-value window
- Many/most of the transitions will be highly converted.
- Long chain of radioactive daughters requires flexible collect, count, move, cycles.
- In this environment a γ-ray or electron singles spectrum is of little use in establishing structure/(i.e. a decay scheme).
- High statistics β: γ-γ, γ-e, e-e are required
- The 8π Spectrometer at ISAC is certainly the world's best facility for such studies.
- Timeline Issues: At beams at ISAC – 2010 (2008?) + 1 year for analysis (meets start of RadonEDM)

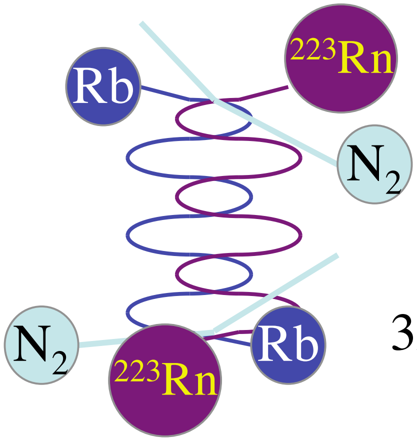
Spin-Exchange Optical Pumping

- Optically pump the Rb with circularly polarized laser light.
- Spin-exchange collisions transfer the polarization to the radon nuclei.





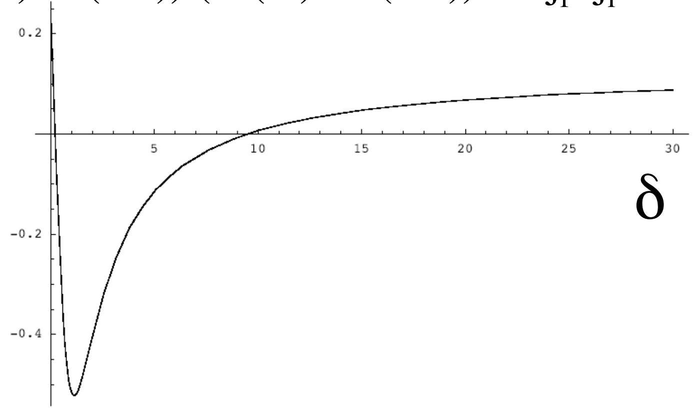
Binary Collision:
$\tau \sim 10^{-12}$ sec.



van Der Waals
Molecule:
τ is dependent on
3rd body (N_2) pressure.

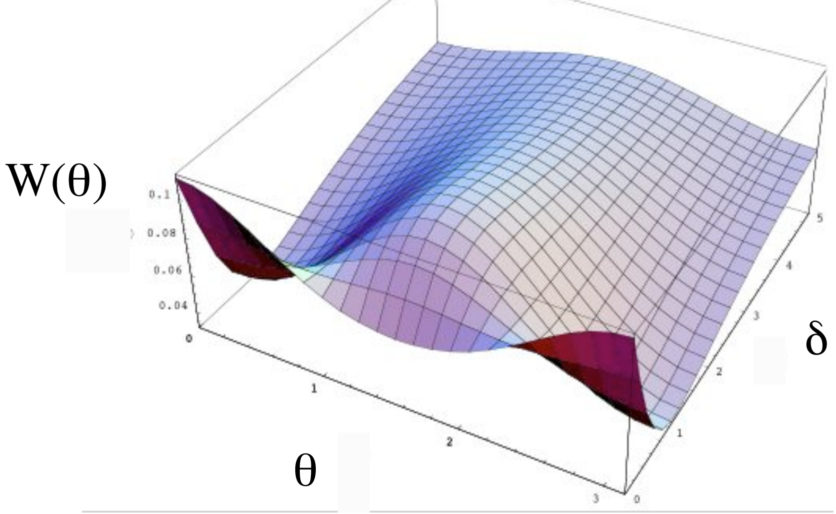
Gamma Ray Anisotropies

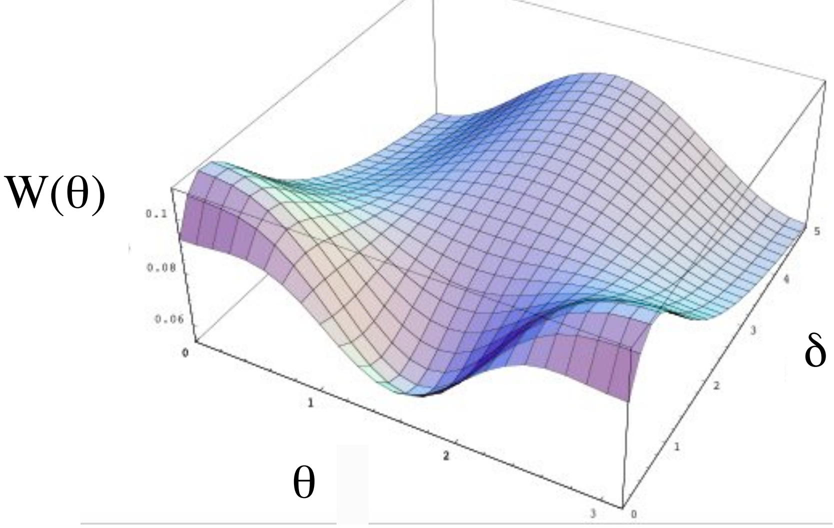
- Polarized nuclei emit gamma rays with calculable directional distributions.

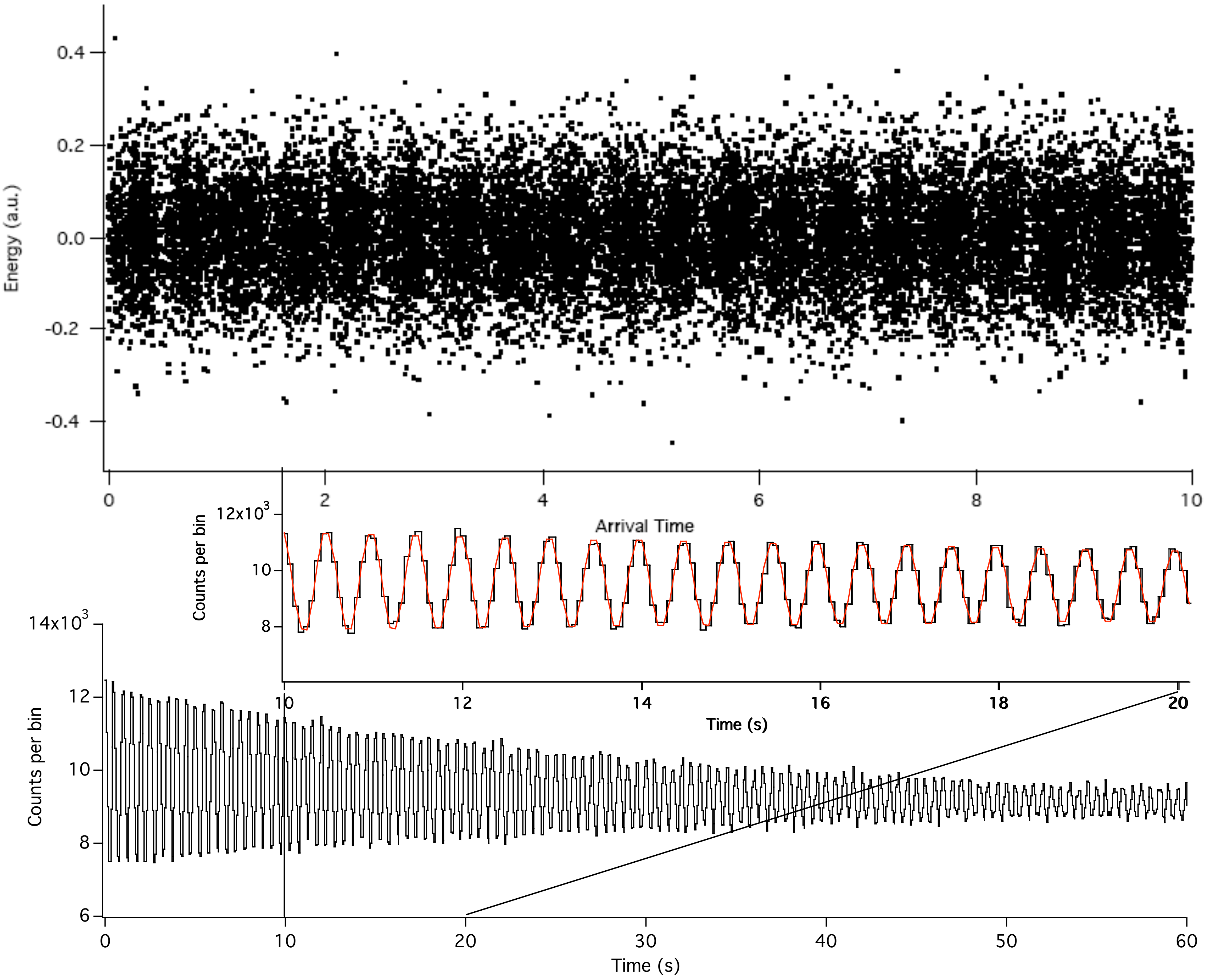

(W(0°)-W(90°))/(W(0°)+W(90°)) for $j_f=j_i+1$

$j_f=j_i-1$ pure dipole transition

$$W(\theta)=\frac{1}{4\pi}\left\{1+\frac{3}{2j_i(2j_i-1)}\left[\sum_{m_i} m_i^2 a_{m_i}-\frac{1}{3}j_i(j_i+1)\right]P_2(\cos\theta)\right\}$$


$j_f=j_i+1$


$j_f=j_i$


Energy (a.u.)
0.4
0.2
0.0
-0.2
-0.4
0
2
4
6
8
10
Arrival Time
Counts per bin
12x10^3
10
8
10
12
14
16
18
20
Time (s)
Counts per bin
14x10^3
12
10
8
6
0
10
20
30
40
50
60
Time (s)

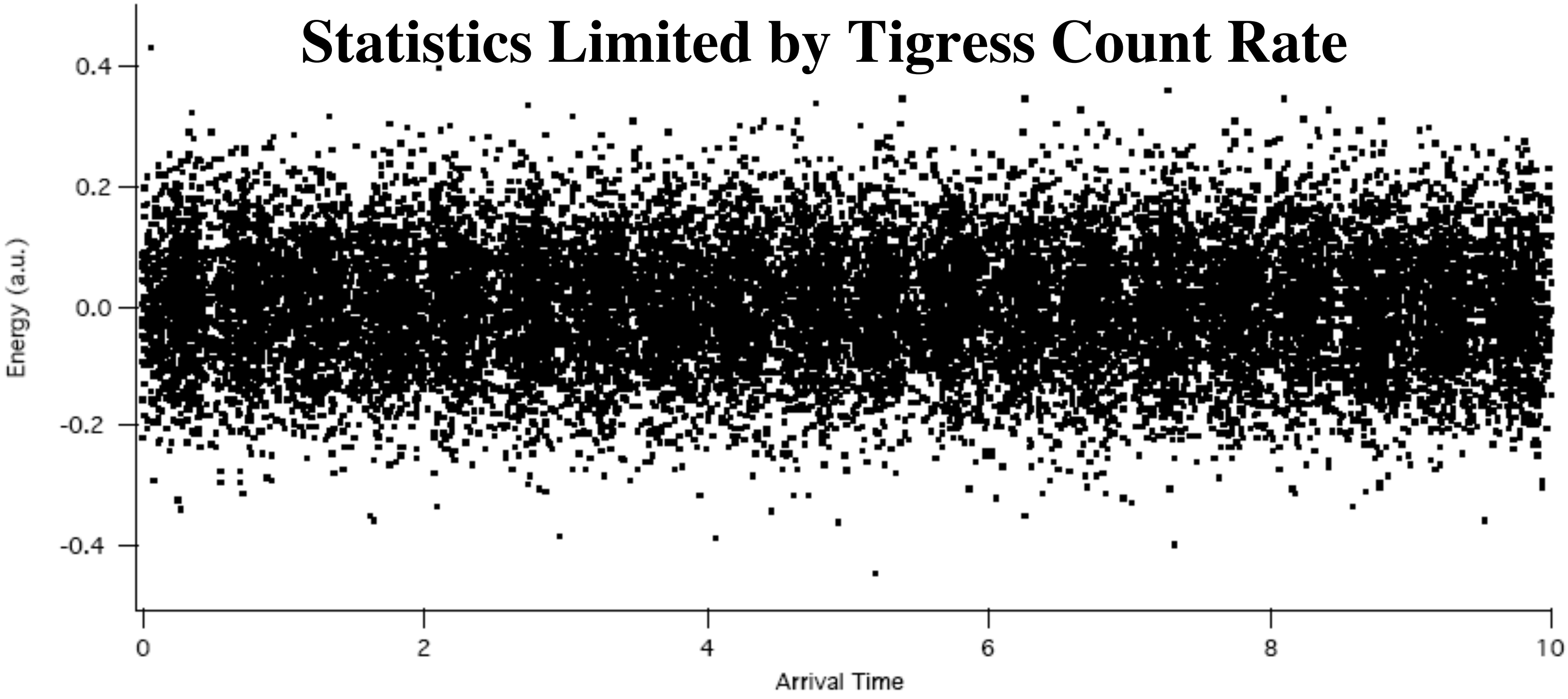
Gamma Anisotropy (A=0.2 *0.1*)
T_2 = 30 s E=5 kV/cm

	Gamma Anisotropy
Count Rate (s^{-1})	1.2×10^5
A	0.2
Background	0.01
Total N (100 Days)	1×10^{12}
σ_{d_A} (e-cm)	1×10^{-26}

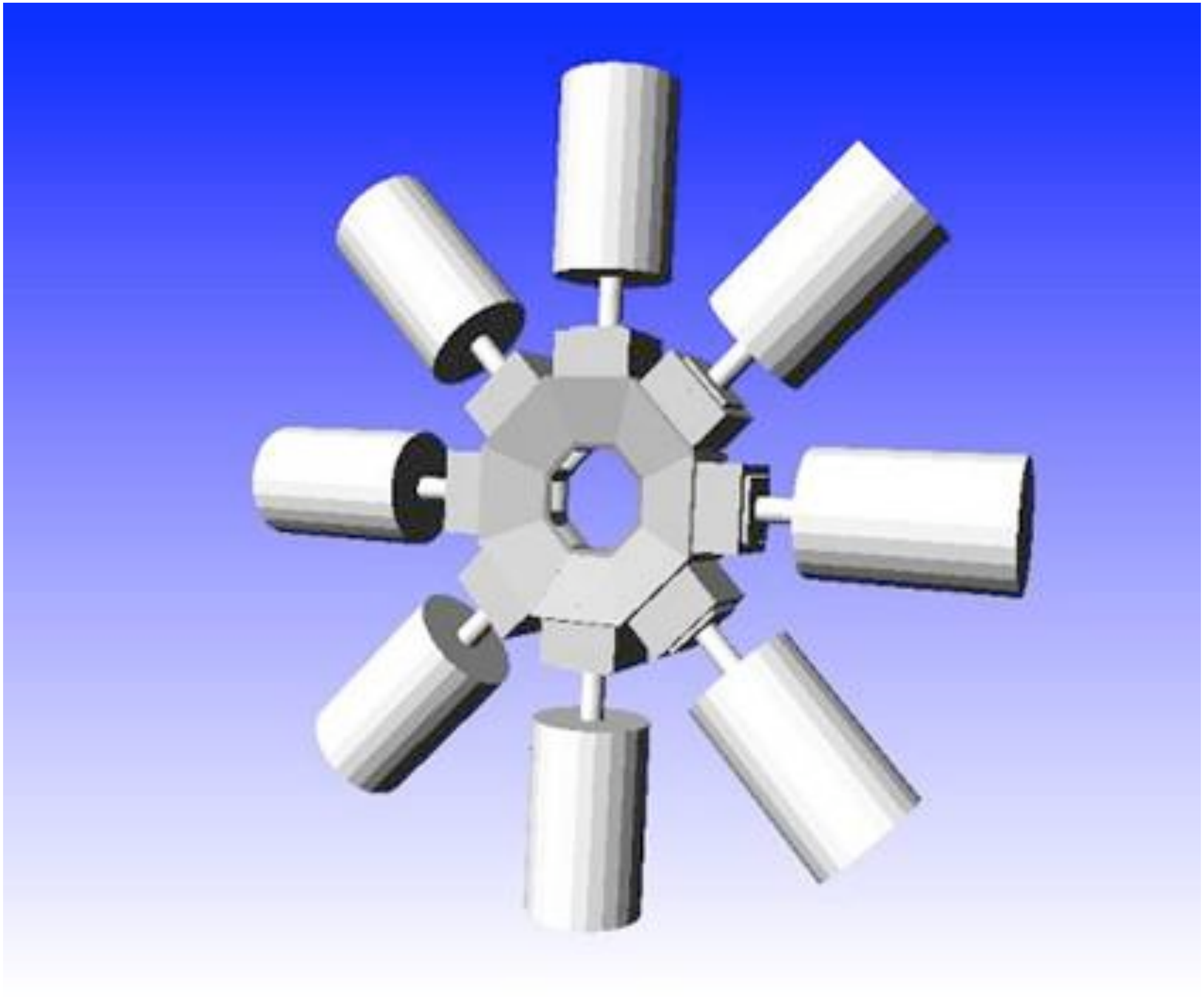
We only need beam 10% of the time

1-10x CP sensitivity of ^{199}Hg

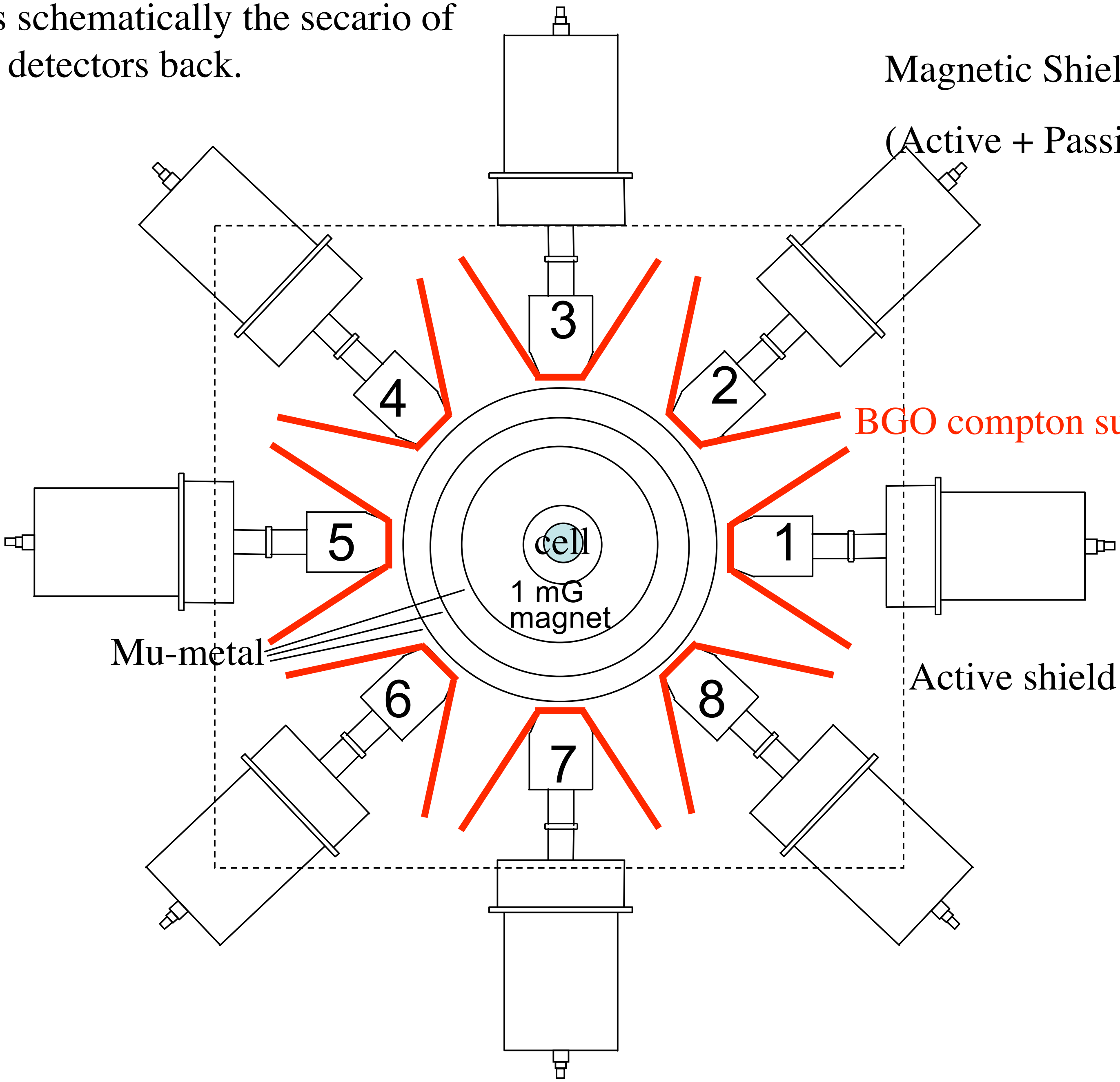
Statistics Limited by Tigress Count Rate



Tigress/Griffin



This shows schematically the secario of pulling the detectors back.



Magnetic Shielding

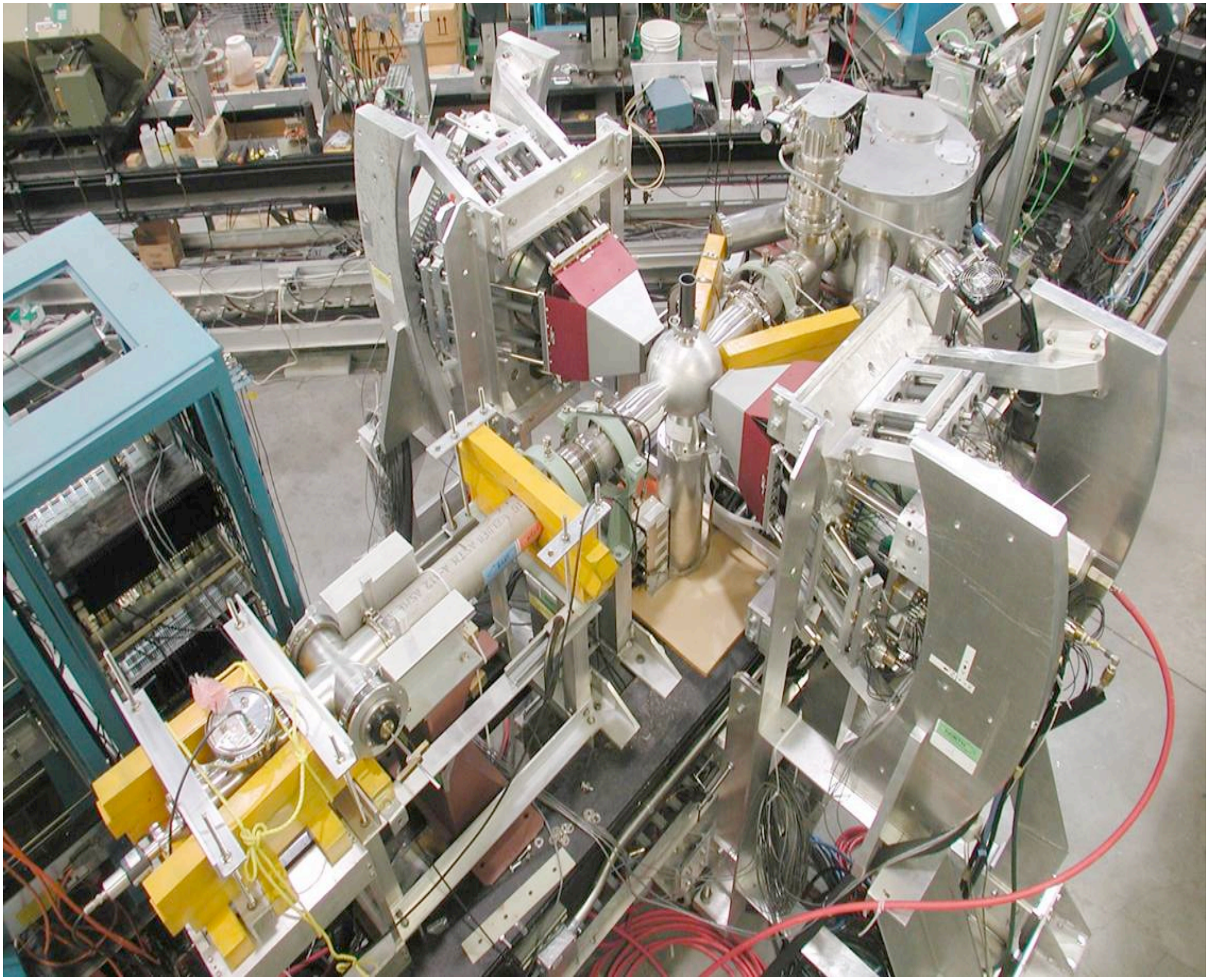
(Active + Passive)

BGO compton supressors

Mu-metal

Active shield - 3 dimensions

Tigress



Beta Asymmetry

$$R = R_0(1 + \frac{p_e}{E_e} A_\beta \hat{J} \cdot \hat{r})$$

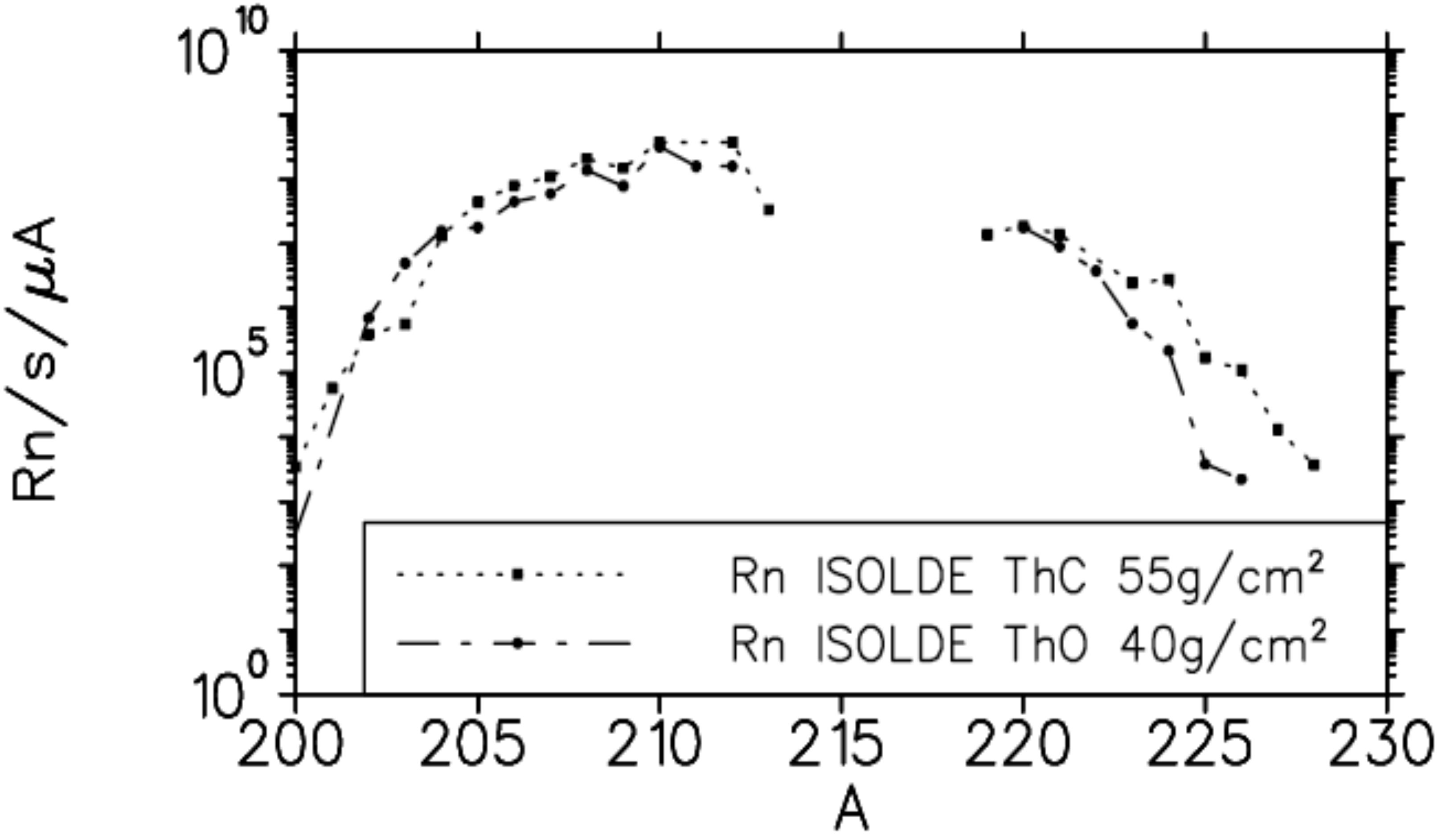
$$\xi A_\beta = \pm\kappa |g_A|^2 | < \sigma > |^2 - (g_V g_A^* + g_A g_V^*) < 1 >< \sigma > \sqrt{\frac{J_i}{1 + J_1}}$$

J_i^π	J_f^π	A_β	note
7/2	9/2	+7/9	100% β^- decay; pure GT
	7/2	-2/9	not pure GT
	5/2	-1	pure GT

- No count rate limit (current detection mode)
- Discriminate species only by frequencies
- Scattered betas (lower effective A, Background)

	Gamma Anisotropy	beta asymmetry	
		ISAC	ISAC× 20
Count Rate (s^{-1})	1.2×10^5	5×10^6	4×10^7
A	0.2	0.2	0.2
Background	0.01	0.3	0.3
Total N (100 Days)	1×10^{12}	4×10^{13}	8×10^{14}
σ_{d_A} (e-cm)	1×10^{-26}	4×10^{-27}	5×10^{-28}

Rn Yields (extracted)



Systematics

Leakage currents -- must be minimized: **Multiple species**

Electric quadrupole moment (gradients/walls)

Change cells, cell shape/orientation: **Multiple species**

Electric field effects on shields, electronics, etc.

Check and measure with E=0

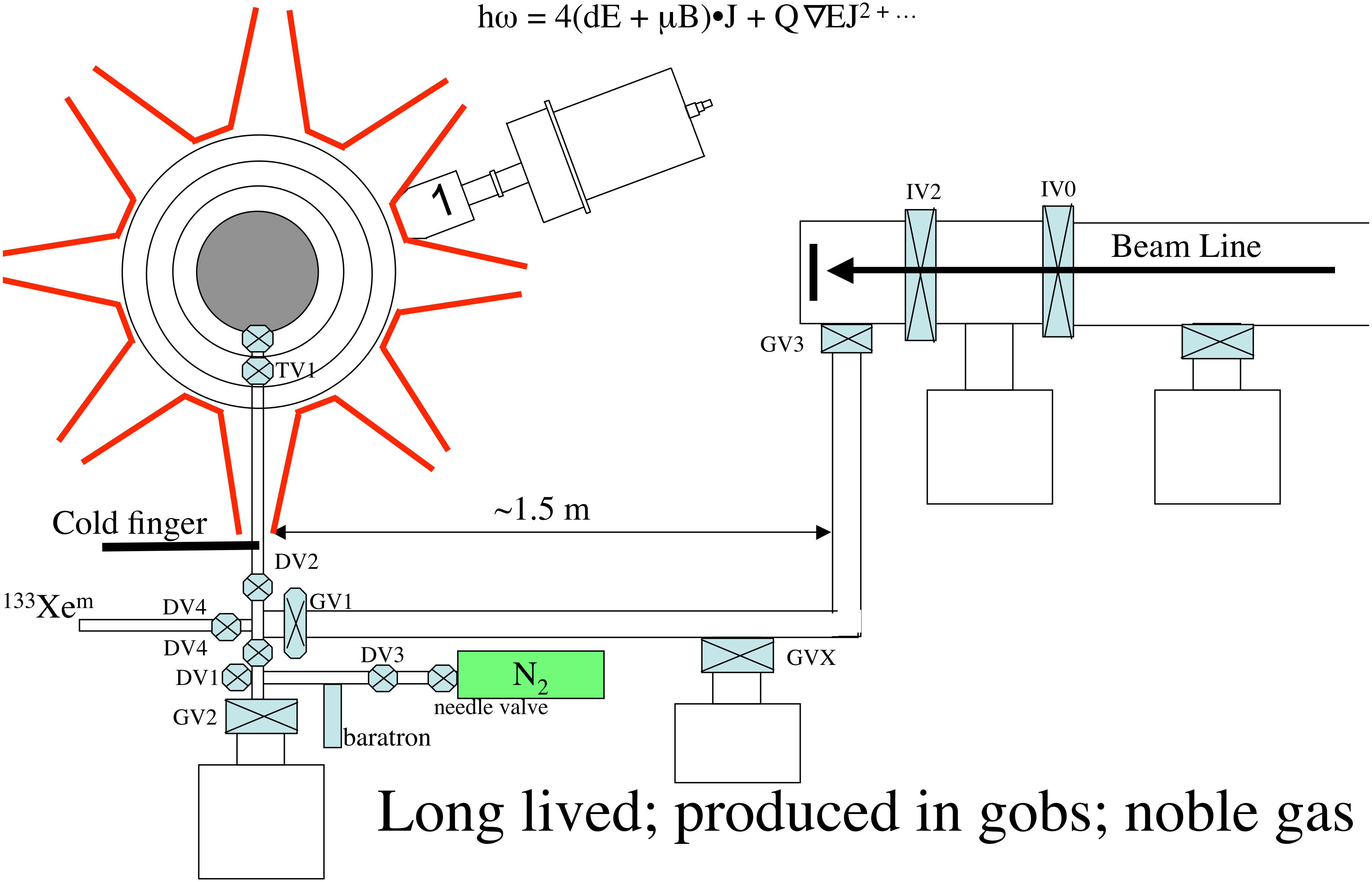
∇E^2 and |E| effects (Stark shifts)

Multiple Species: J=1/2, 3/2, etc.

Motional effects $\langle v \times \mathbf{E} \rangle$ (negligible in gas cells)

Comagnetometers

$$h\omega = 4(dE + \mu B)\bullet J + Q\nabla E J^{2} + \cdots$$



Long lived; produced in gobs; noble gas

Progress

- Noble gas collection with ^{120}Xe
- ^{209}Rn polarization and relaxation at Stony Brook
- ISAC Floor space
- EDM cell development
- Tigress delivery
- Increaseing work-load and collaboration

Summary

- EDMs have been a hot topic for >50 years
  - P violating and T(CP) violating
  - Window to Physics Beyond SM and Physics of Baryogenesis
- We wait with bated* breath for … the next result

  *"Every eye fixed itself upon him; with parted lips and bated breath the audience hung upon his words, taking no note of time, rapt in the ghastly fascinations of the tale". S. Clemens in *Tom Sawyer*

- Thanks: E. Hinds , N. Fortson, A. Leanhardt, D. deMille, Z.T. Lu, D. Budker and many more