

CP VIOLATION IN ATOMIC AND NUCLEAR PHYSICS

E.D. Commins

Physics Dept. U.C. Berkeley and LBNL
Berkeley, CA 94720

XXVII SLAC SUMMER INSTITUTE ON PARTICLE PHYSICS

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CP VIOLATION + CPT INVARIANCE IMPLY:

T - VIOLATION

SEARCHES FOR T-VIOLATION IN NUCLEAR AND ATOMIC PHYSICS

- “DETAILED BALANCE” IN NUCLEAR REACTIONS
(very brief).
- “T-ODD” SPIN-MOMENTUM CORRELATIONS IN
nuclear beta decay
mixed multipole nuclear gamma transitions
neutron transmission experiments
....
(brief).
- PERMANENT ELECTRIC DIPOLE MOMENTS (**EDMs**)
OF ELEMENTARY PARTICLES, NUCLEI, ATOMS, AND
MOLECULES (VIOLATION OF **P, T**)
(extended).

THE TIME-REVERSAL TRANSFORMATION

- ANTI-UNITARY

- TRANSITION:

$$A(p_i, s_i) \rightarrow B(p_f, s_f)$$

- S- MATRIX ELEMENT:

$$S_{BA} = \delta_{BA} - i K_{BA} \quad K \text{ is the "transition operator"}$$

$$K_{BA} = \langle B | K | A \rangle$$

- TIME REVERSAL:

- REVERSE ALL MOMENTA AND SPINS
- INTERCHANGE INITIAL AND FINAL STATES

$$K'_{AB} = \langle A(-p_i, -s_i) | K | B(-p_f, -s_f) \rangle$$

TIME REVERSAL INVARIANCE:

$$| K'_{AB} | = | K_{BA} |$$

“DIRECT” TEST OF T-INVARIANCE IN STRONG INTERACTIONS

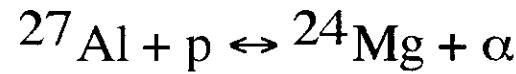
C, T invariances of strong interaction known from direct experiments only to limited precision:

$$P \approx 10^{-5}$$

$$C \approx 10^{-2} - 10^{-3}$$

$$T \approx 10^{-2} - 10^{-3}$$

- DETAILED BALANCE IN NUCLEAR REACTIONS:



[E. Blanke et al, Phys. Rev. Lett. **51** 355 (1983)]

HOW DO WE TEST
T - INVARIANCE
 IN WEAK PROCESSES ?

EXAMPLE: neutron decay $n \rightarrow p e^- \bar{\nu}_e$

$p e^- \bar{\nu}_e \rightarrow n$ **NOT POSSIBLE !!**

HOWEVER:

$$S = I - i K$$

$$\begin{aligned} S S^\dagger &= I \\ &= (I - iK)(I + iK^\dagger) \\ &= I - iK + iK^\dagger + K K^\dagger \end{aligned}$$

IF WE CAN NEGLECT $K K^\dagger \dots$

$$K = K^\dagger$$

THEN:

$$K_{BA} = \langle B(p_f, s_f) | K | A(p_i, s_i) \rangle = \langle A(p_i, s_i) | K | B(p_f, s_f) \rangle^*$$

MEANWHILE the **TIME- REVERSED** amplitude is :

$$K'_{AB} = \langle A(-p_i, -s_i) | K | B(-p_f, -s_f) \rangle$$

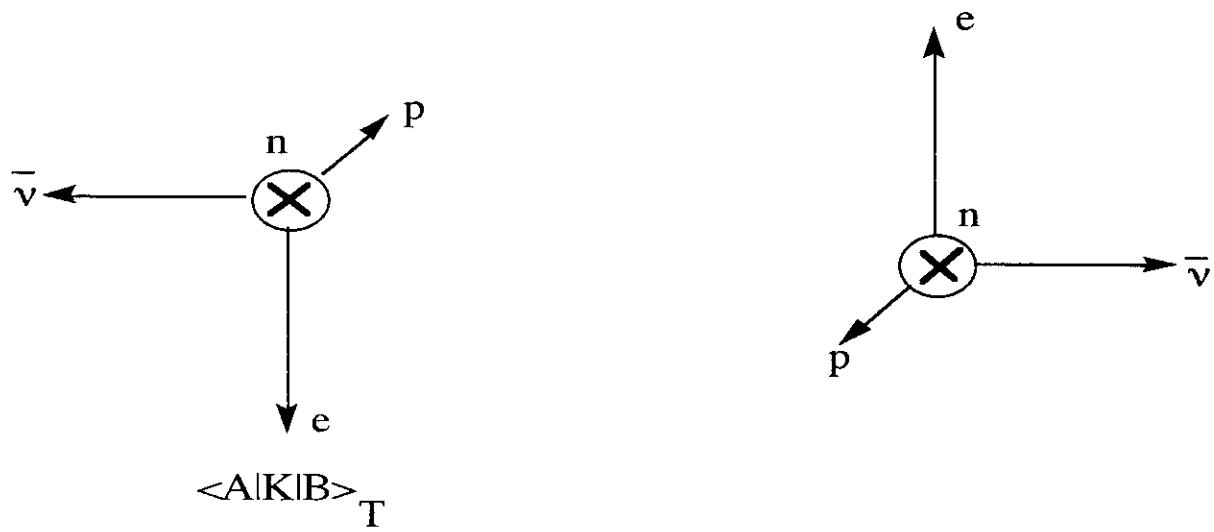
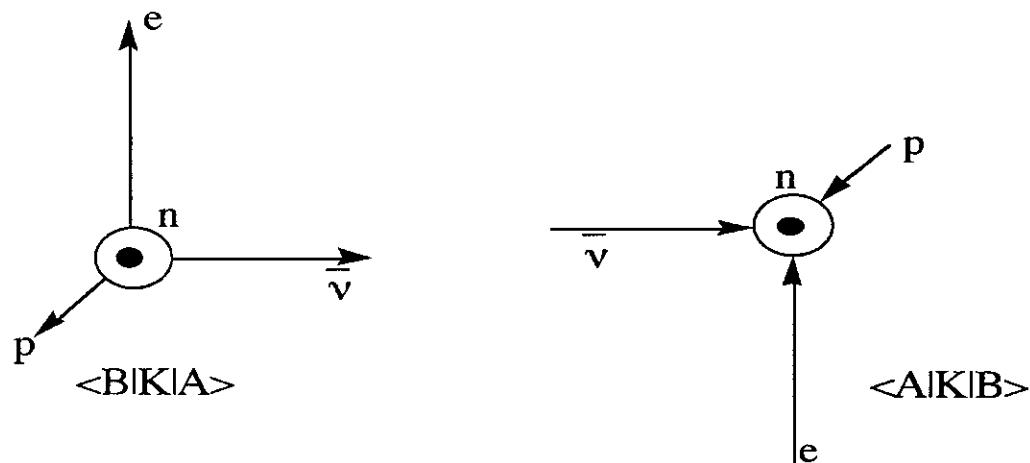
TIME REVERSAL INVARIANCE IF...

$$|\langle A(p_i, s_i) | K | B(p_f, s_f) \rangle| = |\langle A(-p_i, -s_i) | K | B(-p_f, -s_f) \rangle|$$

THUS T-INVARIANCE IF:

$$|\langle B(p_f, s_f) | K | A(p_i, s_i) \rangle| = |\langle B(-p_f, -s_f) | K | A(-p_i, -s_i) \rangle|$$

neutron decay



$$\sigma_n \cdot \mathbf{p}_e \times \mathbf{p}_{\bar{\nu}}$$

NEGLECTING NUCLEAR RECOIL AND FINAL STATE INTERACTIONS:

$$dW = \frac{G_F^2 \cos^2 \theta_C}{(2\pi)^5} \delta(E_e + E_\nu - \Delta) F(Z, E) d^3 p_e d^3 p_\nu \cdot \\ \xi \left[1 + a \frac{\mathbf{p}_e \cdot \mathbf{p}_\nu}{E_e E_\nu} + \frac{\langle J_i \rangle}{J_i} \cdot \left(A \frac{\mathbf{p}_e}{E_e} + B_e \frac{\mathbf{p}_\nu}{E_\nu} + D \frac{\mathbf{p}_e \times \mathbf{p}_\nu}{E_e E_\nu} \right) \right]$$

$$\xi = |C_V|^2 |\langle 1 \rangle|^2 + |C_A|^2 |\langle \sigma \rangle|^2$$

$$\xi A = \pm \kappa |C_A|^2 |\langle \sigma \rangle|^2 - (C_V C_A^* + C_A C_V^*) \langle 1 \rangle \langle \sigma \rangle \left(\frac{J_i}{J_i+1} \right)^{1/2}$$

$$\xi B = \mp \kappa |C_A|^2 |\langle \sigma \rangle|^2 - (C_V C_A^* + C_A C_V^*) \langle 1 \rangle \langle \sigma \rangle \left(\frac{J_i}{J_i+1} \right)^{1/2}$$

$$\xi D = i(C_V C_A^* - C_A C_V^*) \langle 1 \rangle \langle \sigma \rangle \left(\frac{J_i}{J_i+1} \right)^{1/2}$$

$$\kappa = \begin{cases} 1 & \text{for } J_f = J_i - 1 \\ (J_i + 1)^{-1} & \text{for } J_f = J_i \\ -J_i (J_i + 1)^{-1} & \text{for } J_f = J_i + 1 \end{cases} \quad \pm \text{ for } e^\pm$$

J.D.Jackson, S.B.Treiman, and H.W.Wyld
 Nuc. Phys. **4**, 206 (1957)

D: FINAL STATE INTERACTION EFFECT

[C.G. Callan & S. B. Treiman Phys. Rev. **162**, 1494 (1967)]

Interference between Coulomb interaction, weak magnetism

$$D_n^{WM} = \frac{E_e^2}{p_e m_n} \left(-0.032 + 0.040 \frac{m_e^2}{E_e^2} \right)$$
$$= -5.7 \cdot 10^{-5} \quad \text{at max. } p_e$$

$$D_{\text{neon}}^{WM} \approx 3 \cdot 10^{-4}$$

THEORETICAL LIMITS ON D

THEORETICAL MODEL	D
STANDARD MODEL	$< 10^{-12}$
THETA- QCD	$< 10^{-14}$
SUPERSYMMETRY	$< 10^{-6}$
LEFT-RIGHT SYMMETRY	$< 10^{-4}$
EXOTIC FERMION	$< 10^{-4}$
<i>LEPTOQUARK MODELS</i>	LIMITED BY EXPT

MEASUREMENTS OF D IN NEUTRON BETA DECAY

$$D = (-1.1 \pm 1.7) \cdot 10^{-3} \quad \text{I.L.L.}$$

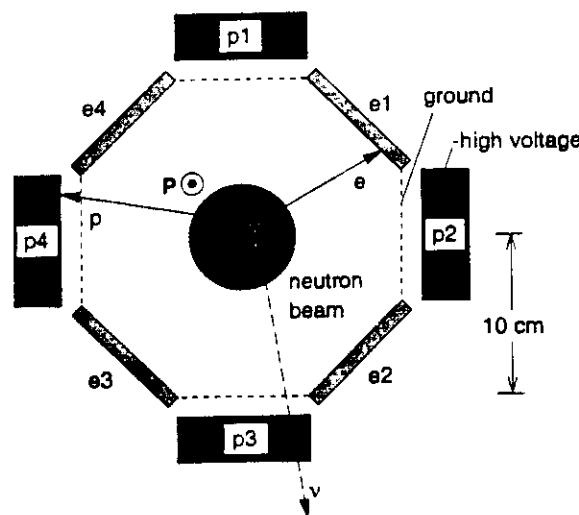
R.I. Steinberg et al *Phys. Rev. Lett.* **33**, 41 (1974)

$$D = (2.2 \pm 3.0) \cdot 10^{-3} \quad \text{Kurchatov}$$

A.V. Vorobiov et al *Nucl Instr. Methods* **A284**, 127 (1989)

$$D = (-0.1 \pm 1.3 \pm 0.7) \cdot 10^{-3} \quad \text{N.I.S.T., Gaithersburg}$$

(unpublished)



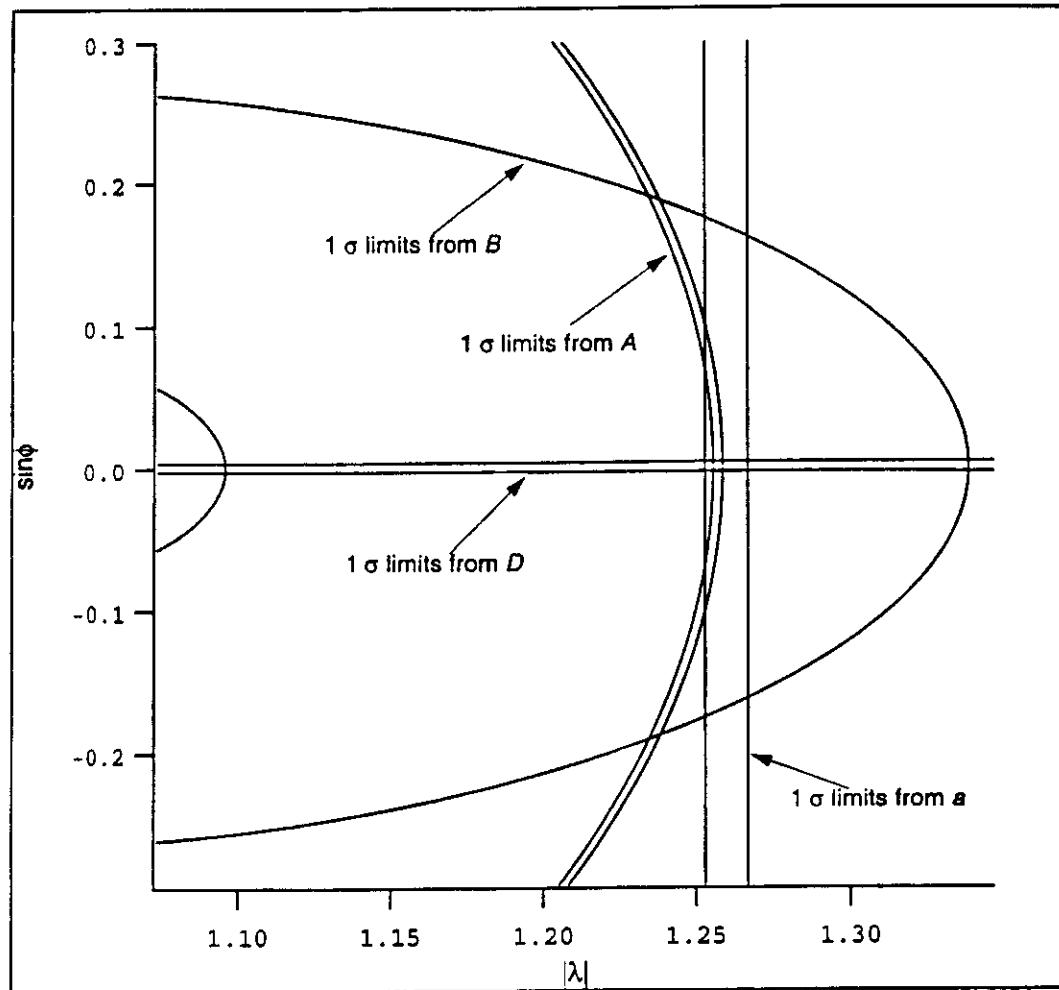


Figure 2.2: The correlation coefficients a , A , B , and D all depend on ratio $\lambda = g_A/g_V = |\lambda|e^{i\phi}$. Shown are the one standard deviation experimental limits.

MEASUREMENT OF D IN ^{19}Ne BETA DECAY

$$D = (4 \pm 8) \cdot 10^{-4} \quad \text{PRINCETON}$$

A.L. Hallin et al Phys. Rev. Lett **52**, 337 (1984)

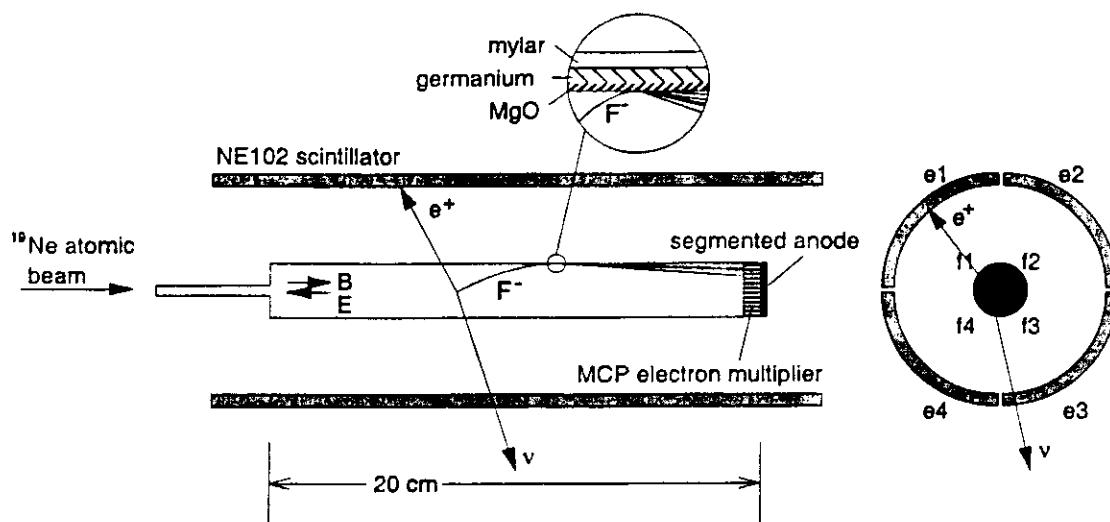


Figure 2.6: The apparatus of Hallin et al. for measuring D in Ne.

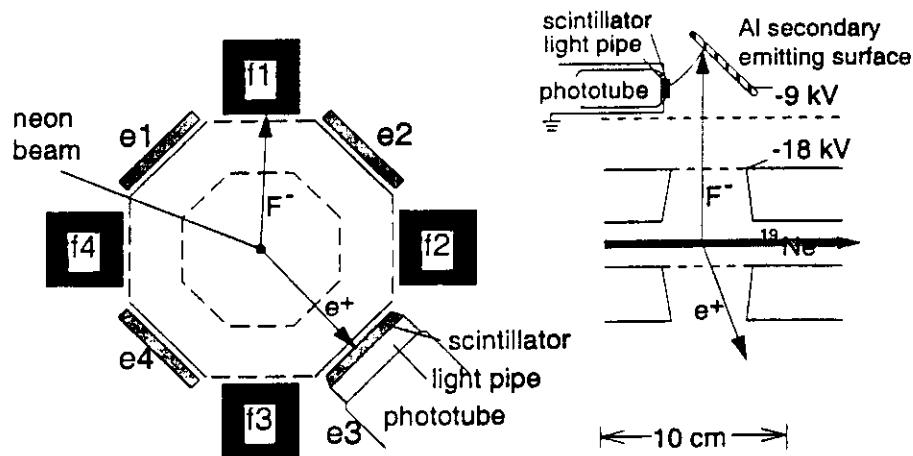


Figure 2.7: The apparatus of Calaprice et al.

OTHER T- ODD OBSERVABLES IN BETA DECAY

$$R \sigma_n \cdot (\sigma_e \times p_e)$$

$$L \sigma_e \cdot (p_e \times p_\nu)$$

- L NEVER MEASURED IN ANY DECAY
- R MEASURED IN ${}^8\text{Li}$ DECAY:

$$R({}^8\text{Li}) = (0.9 \pm 2.2) \cdot 10^{-3}$$

(Measurement in neutron decay is planned).

- $R = 0$ for pure V,A regardless of V,A phase.
Requires interference between S and A, and/or
T and V couplings. From ${}^8\text{Li}$ result:

$$-0.015 < \text{Im} \left(\frac{C_T + C'_T}{C_A} \right) < 0.009$$

- Indirect limits from EDM expts on T-odd scalar,tensor
couplings are MORE SENSITIVE:

I.B. Khriplovich JETP Lett **52**, 461 (1990)

ELECTRIC DIPOLE MOMENTS (EDMs)

OF

ELEMENTARY PARTICLES

NUCLEI

ATOMS

MOLECULES

AN EDM CAN EXIST ONLY IF
P, T VIOLATION

$$H_{MAG} = -\mu \cdot \mathbf{B} = \text{const } \sigma \cdot \mathbf{B}$$

$$H'_{EDM} = -d \cdot \mathbf{E} = \text{const } \sigma \cdot \mathbf{E}$$

WEAK INTERACTION P C
CP VIOLATION \leftrightarrow T

EDM from P,T-odd radiative corrections to
C,P,T-conserving electromagnetic interaction.

“NORMAL” DIRAC ELECTRON:

$$L_{\text{DIRAC}} = \bar{\Psi} [i \gamma^\mu (\partial_\mu + ieA_\mu) - m] \Psi$$

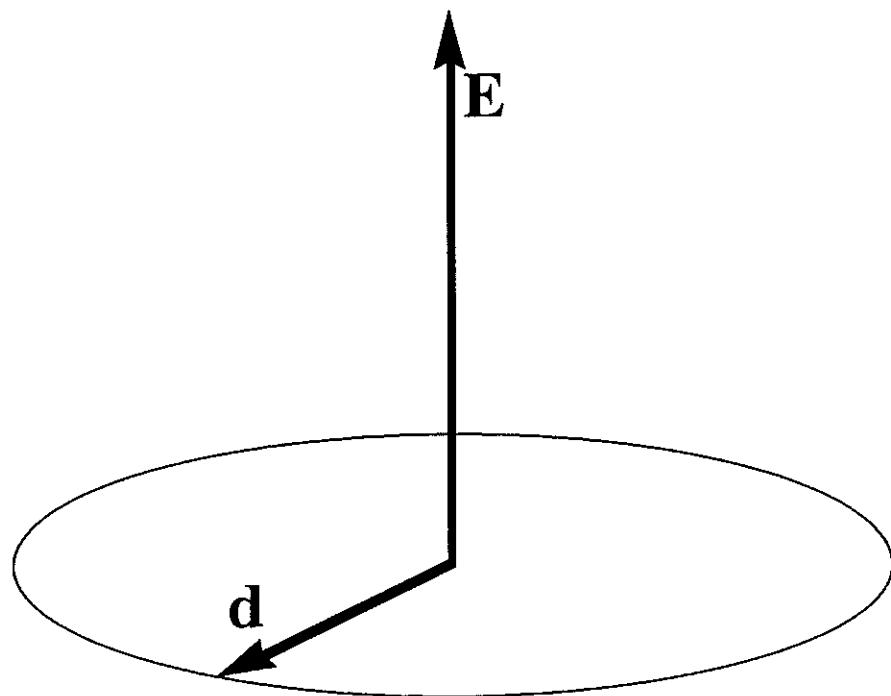
ANOMALOUS MAGNETIC MOMENT:

$$L_{\text{anom}} = -\kappa \bar{\Psi} \sigma_{\mu\nu} \Psi \cdot F^{\mu\nu}$$

EDM:

$$L_{\text{EDM}} = -i \frac{d}{2} \bar{\Psi} \gamma^5 \sigma_{\mu\nu} \Psi \cdot F^{\mu\nu}$$

$$H_{\text{EDM}} = -d \gamma^0 \vec{\sigma} \cdot \vec{E} + i d \vec{\gamma} \cdot \vec{B}$$



$$W = - \mathbf{d} \cdot \mathbf{E}$$

$$\vec{\tau} = \mathbf{d} \times \mathbf{E}$$

THEORETICAL PREDICTIONS FOR EDMs

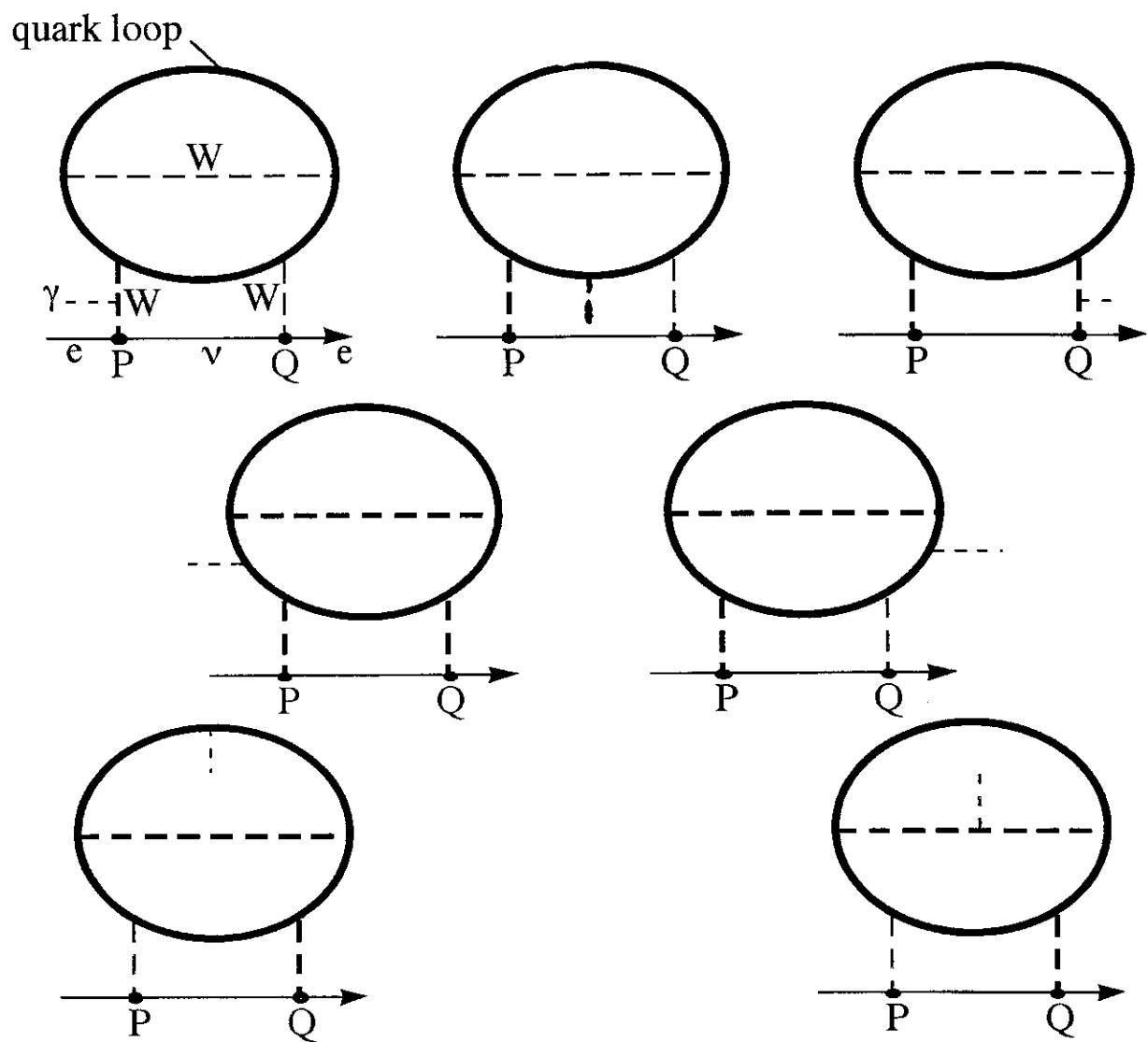
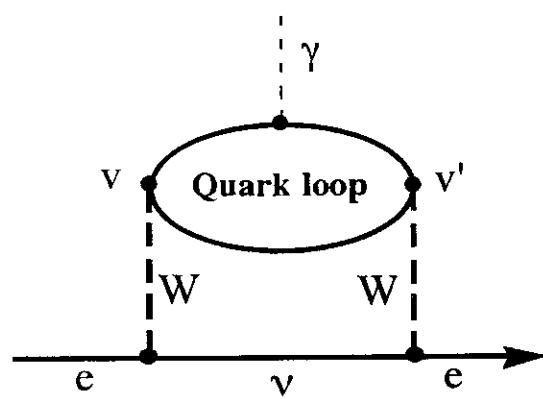
CP VIOL MODEL NEUTRON (e cm) ELECTRON (e cm)

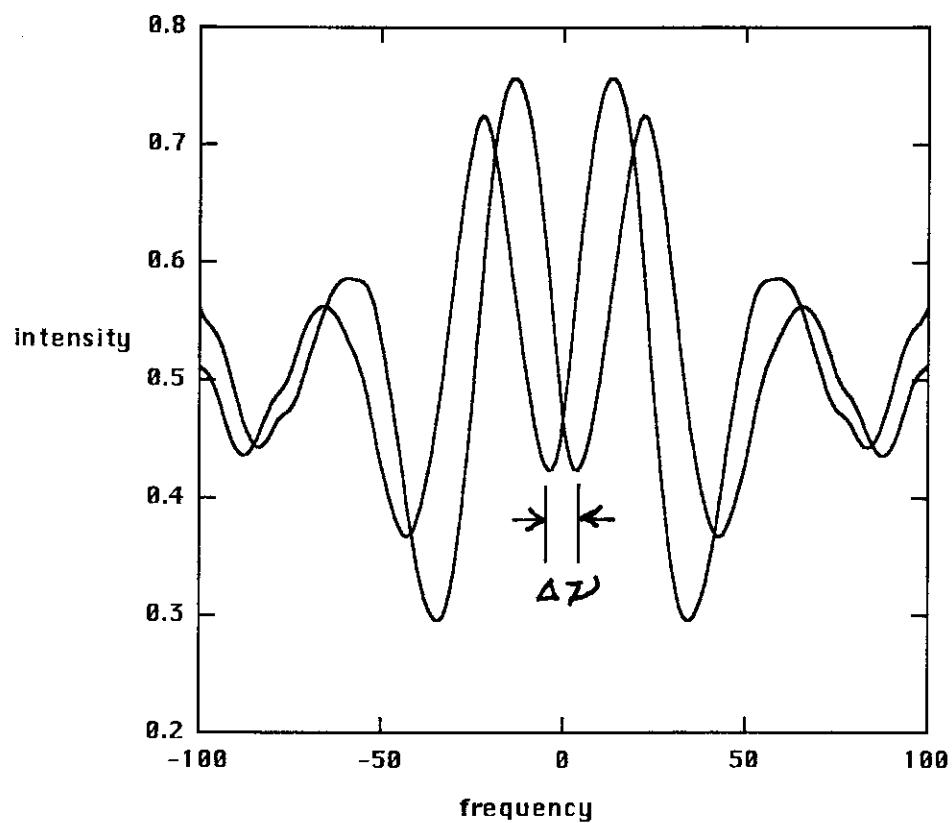
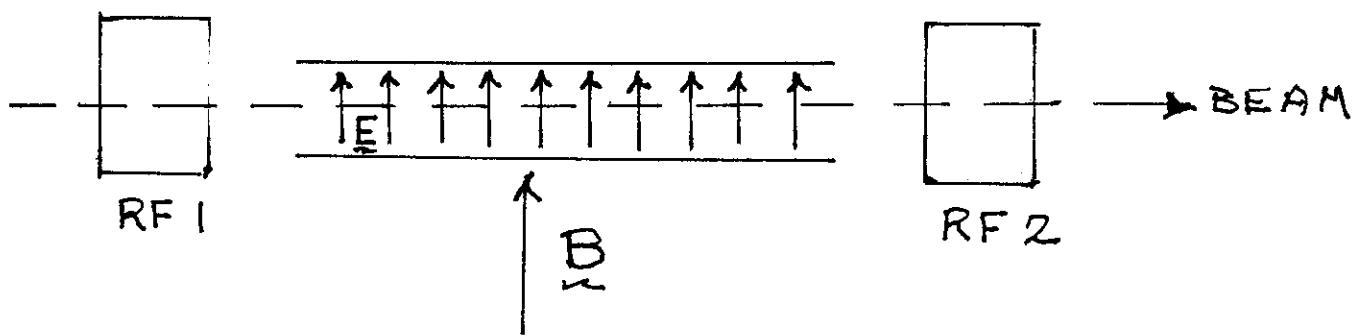
• STANDARD	$10^{-32} - 10^{-34}$	$\approx 10^{-40}$
• Minimal SUSY	$10^{-25} - 10^{-26}$	$10^{-26} - 10^{-28}$
• SUSY GUT [SO(10)]	$10^{-25} - 10^{-27}$	$10^{-26} - 10^{-28}$
• L-R SYMMETRIC	$10^{-25} - 10^{-27}$	$10^{-26} - 10^{-28}$
• MULTI-HIGGS	$10^{-25} - 10^{-27}$	$10^{-26} - 10^{-28}$
• LEPTON-FLAVOR CHANGING	-----	$10^{-27} - 10^{-29}$

PRESENT LIMITS:

$$|d_n| < 6 \cdot 10^{-26} \text{ e cm} \quad (\text{I.L.L. 1999})$$

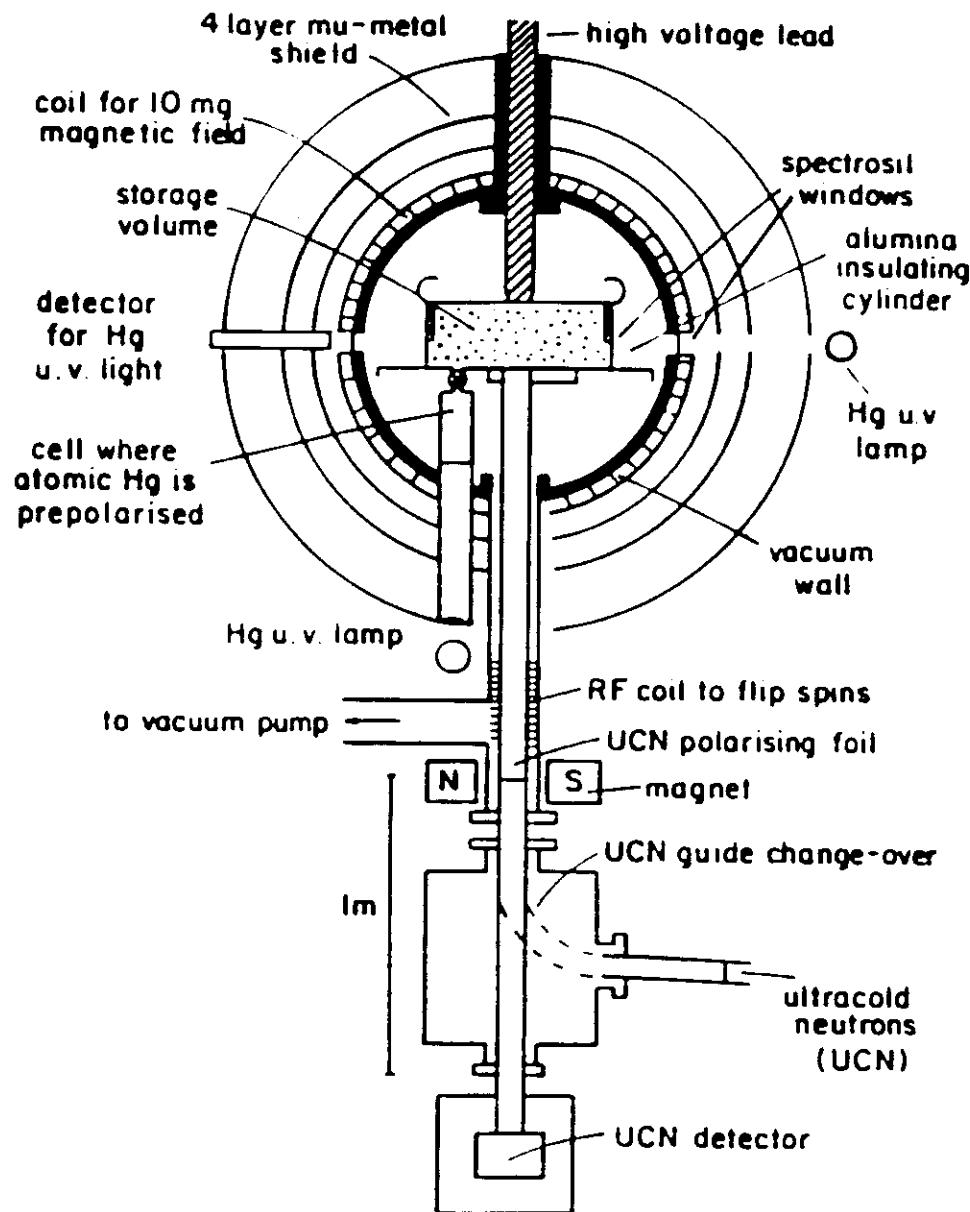
$$|d_e| < 4 \cdot 10^{-27} \text{ e cm} \quad (\text{Berkeley, 1994})$$





NEUTRON

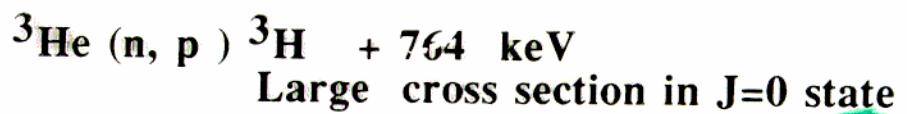
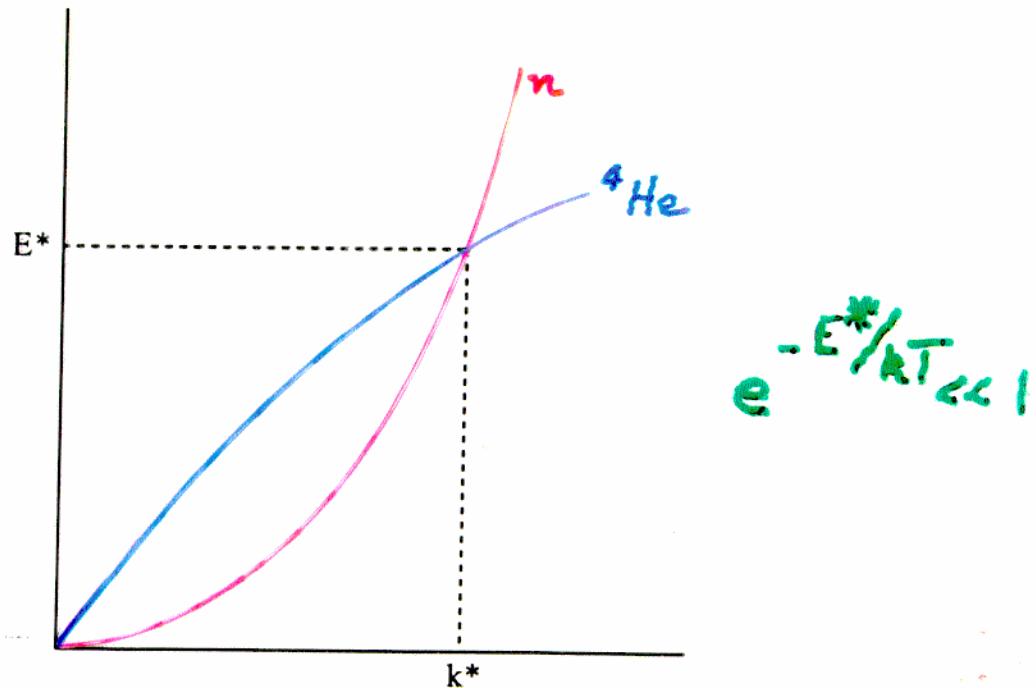
- ILL (GRENOBLE) PRESENT EXPERIMENT



NEUTRON

- ULTRA-COLD NEUTRONS TRAPPED IN SUPERFLUID ^4He
- + dilute solution SPIN-POLARIZED ^3He

Lamoreaux, Golub, Pendlebury, ...



Scintillations in Liq. ^4He **PROVIDE A WAY**
TO MONITOR PRECESSION OF π^\uparrow
IN APPLIED E-FIELD.

MUON

- PRECESSION OF POLARIZED FREE MUONS IN
g-2 EXPERIMENT modified by presence of EDM
- Bargmann-Michel-Telegdi Equation:
Motional **E** field in muon rest frame couples to EDM
- **J. BAILEY ET AL [CERN MUON STORAGE RING]**
NUCL. PHYS. B 150, 1 (1979)
 $|d_\mu| < 7 \cdot 10^{-19} \text{ e cm}$
- **Y. SEMERTZIDIS and co-workers (Brookhaven)**
Possible improvement by 4 orders of magnitude

THE BMT EQUATION

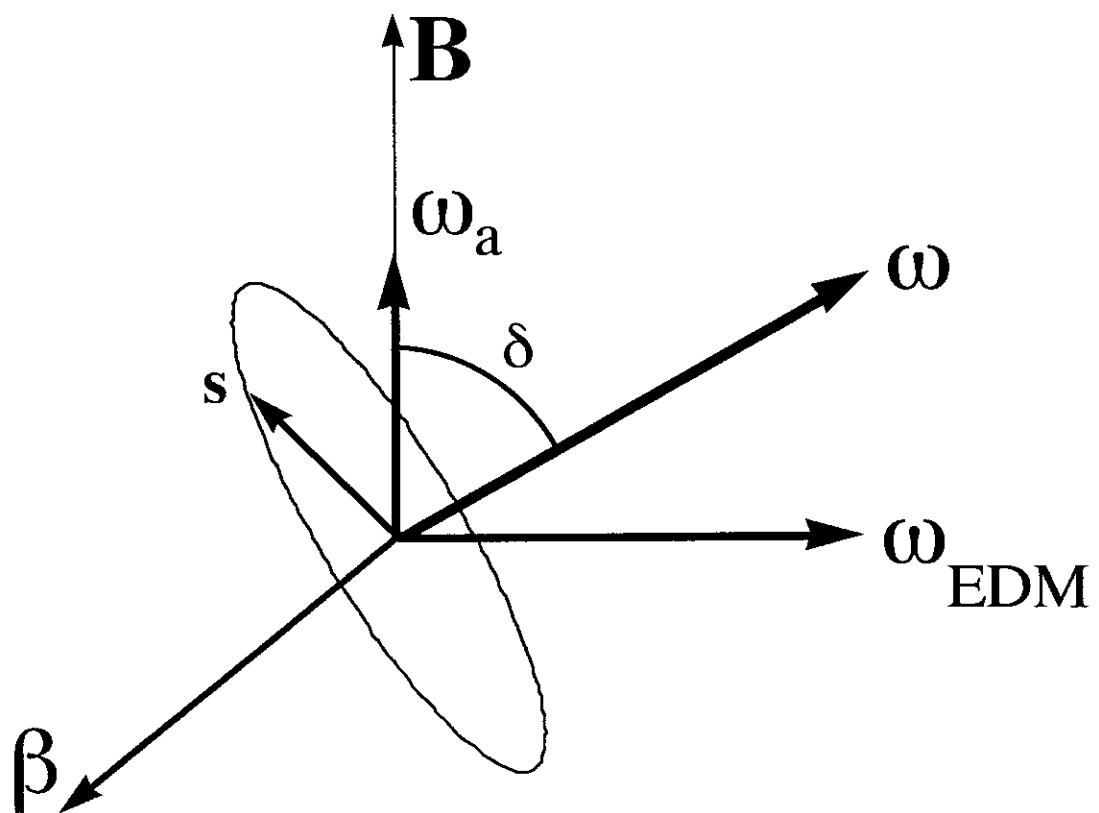
$$\frac{ds}{d\tau} = \frac{e}{m} \left[\frac{g}{2} \mathbf{F} \cdot \mathbf{s} + \left(\frac{g}{2} - 1 \right) (\mathbf{s} \cdot \mathbf{F} \cdot \mathbf{u}) \mathbf{u} \right]$$

Now include an electric dipole moment:

additional term

$$-d [\mathbf{F}^* \cdot \mathbf{s} + (\mathbf{s} \cdot \mathbf{F}^* \cdot \mathbf{u}) \mathbf{u}]$$

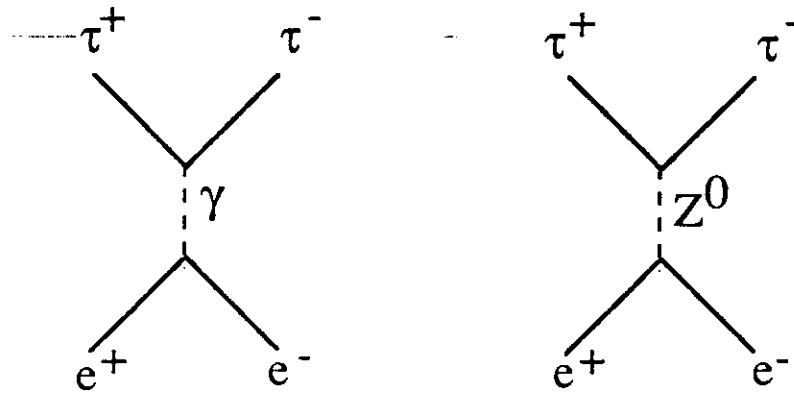
$$\mathbf{F} \rightarrow \mathbf{F}^* \quad \text{when } \mathbf{E} \rightarrow \mathbf{B}, \mathbf{B} \rightarrow -\mathbf{E}$$



$$\delta \approx \frac{d_\mu \beta}{a \frac{e\hbar}{2m_\mu c}}$$

$$a = \frac{1}{2}(g-2)$$

TAU LEPTON



$$L_{CP} = \frac{-i}{2} \bar{\Psi} \gamma^5 \sigma_{\mu\nu} \Psi [d_\tau F_{\mu\nu} + \tilde{d}_\tau (\partial_\mu Z_\nu - \partial_\nu Z_\mu)]$$

$$e^+ + e^- \Rightarrow \tau^+ + \tau^-$$

$$A^+ v_\tau \quad B^- \nabla_\tau$$

R. Akers et al [OPAL COLLABORATION] Z. Phys.
C66,31(1995)

D. Buskelic et al [ALEPH COLLABORATION]
PHYS. LETT. B 346,371 (1995)

$$|\tilde{d}_\tau| \leq 5.8 \cdot 10^{-18} \text{ e cm}$$

HOW TO OBSERVE EDM OF A **CHARGED NUCLEUS OR ELECTRON ?**

- FREE CHARGED PARTICLE ?

g - 2 STORAGE RING:

e^- (LOW SENSITIVITY) 1959

RADIOACTIVE NUCLEUS IN STORAGE RING
(suggestion by I. B. Khriplovich 1998)

- NUCLEUS, ELECTRON IN NEUTRAL ATOM ?

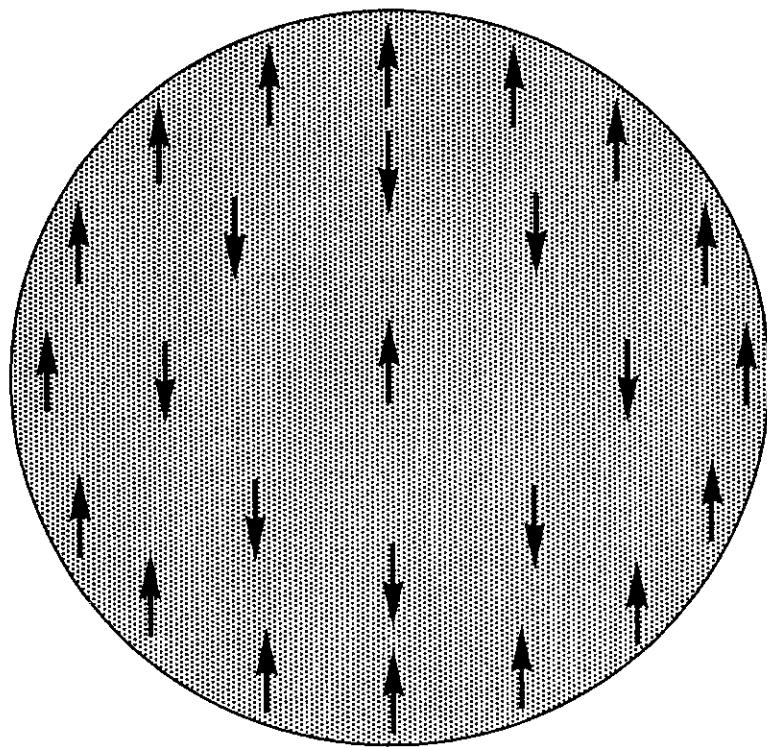
NEUTRAL ATOM NOT ACCELERATED IN UNIFORM E FIELD.

\therefore IF ALL FORCES ELECTROSTATIC, $\langle \mathbf{E} \rangle = 0$ AT EVERY CHARGE!

Ramsey & Purcell (1950).

L.I. Schiff (1963) [Schiff's theorem]

HOWEVER....



SCHIFF 1963:

IF NUCLEAR CHARGE DISTRIBUTION \neq
ELECTRIC DIPOLE DISTRIBUTION:

“SCHIFF MOMENT” Q [e-cm³]

PARAMAGNETIC ATOM (UNPAIRED VALENCE ELECTRON)

- P. G. H. SANDARS (OXFORD, U.K.) 1965

RELATIVISTIC EFFECTS:

$$R = \left| \frac{d_a}{d_e} \right| \approx 10 Z^3 \alpha^2$$