Fundamental Symmetries – II
Nuclear Beta Decay

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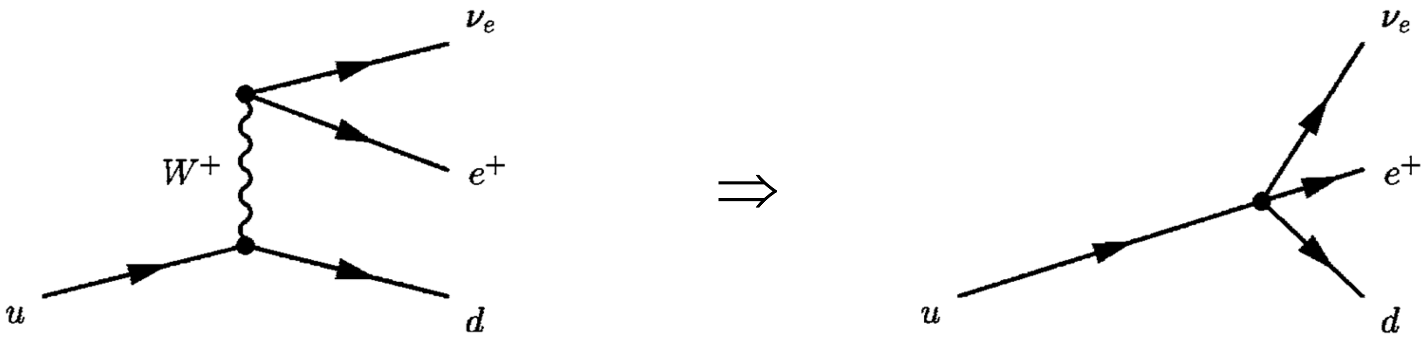
SM Interaction for low energy processes

- Since W is very massive, can treat nuclear, pion, and muon beta decay as a point interaction



- This reverts to early formulation of nuclear beta decay by Fermi but with only (V-A) in the interaction

Questions to consider

- What is the difference between a ‘nuclear’ beta decay expressed at the quark level versus the nucleon level?
- What might cause the overlap matrix element in a pure Fermi decay to differ from ‘1’?
- How do we measure neutrino kinematics in a nuclear beta-decay process? What are the experimental requirements to do this? What recent developments have made this more feasible to do?

Nuclear Beta Decay Form - I

- Recall that weak interaction SM Hamiltonian is a current-current interaction form:

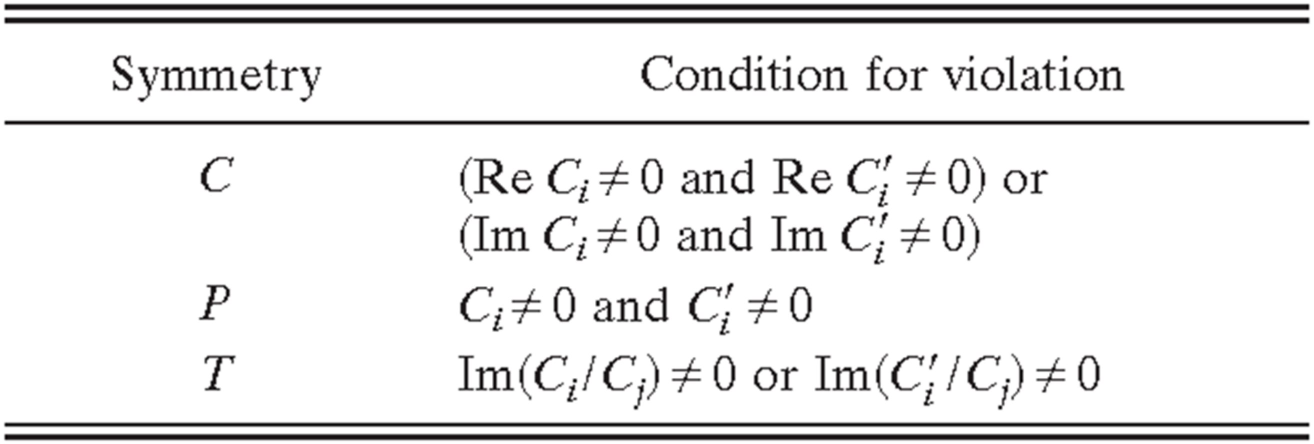
$$H_W = \frac{G_F}{\sqrt{2}} {J_\mu}^{\dagger} J_\mu + H.C.$$

$$J_\mu = {J_\mu}^{had} + {J_\mu}^{lep}$$

- For nuclear beta decay, general form for decay is
- $H_\beta = (\bar{p}n)[\bar{e}(C_s + {C_s}'\gamma_5)\upsilon] + \left(\bar{p}\gamma_\mu n\right)\left[\bar{e}\gamma_\mu(C_V + {C_V}'\gamma_5)\upsilon\right] +$ $\frac{1}{2}\left(\bar{p}\sigma_{\lambda\mu}n\right)\left[\bar{e}\sigma_{\lambda\mu}(C_T + {C_T}'\gamma_5)\upsilon\right] - \left(\bar{p}\gamma_\mu\gamma_5 n\right)\left[\bar{e}\gamma_\mu\gamma_5(C_A + {C_A}'\gamma_5)\upsilon\right] +$ $(\bar{p}\gamma_5 n)[\bar{e}\gamma_5(C_P + {C_P}'\gamma_5)\upsilon]$, with $\sigma_{\lambda\mu} = \frac{i}{2}\left(\gamma_\lambda\gamma_\mu - \gamma_\mu\gamma_\lambda\right)$
- Note interacting fields are associated with nucleons and leptons
- The C's are complex and give interaction amplitude

Nuclear Beta Decay Form – II

- The C and C’ are connected to symmetries by



Symmetry	Condition for violation
C	$(\mathrm{Re}\ C_i \neq 0$ and $\mathrm{Re}\ C_i' \neq 0)$ or $(\mathrm{Im}\ C_i \neq 0$ and $\mathrm{Im}\ C_i' \neq 0)$
P	$C_i \neq 0$ and $C_i' \neq 0$
T	$\mathrm{Im}(C_i/C_j) \neq 0$ or $\mathrm{Im}(C_i'/C_j) \neq 0$

- In the SM, C’s are real, $C_V/C_V'=1$, $C_A/C_A'=1$, and all others are 0
- In extensions of the SM, these values change
- In addition, there are recoil order terms for nuclear beta decay

Nuclear Beta Decay Form – III

- Including recoil order terms in the V and A hadronic part of interaction gives
- $V_\mu = \bar{p}\left[g_V(q^2)\gamma_\mu + f_M(q^2)\sigma_{\mu\nu}\frac{q_\upsilon}{2M} + if_S(q^2)\frac{q_\mu}{m_e}\right]n$
- $A_\mu = \bar{p}\left[g_A(q^2)\gamma_\mu\gamma_5 + f_T(q^2)\sigma_{\mu\nu}\gamma_5\frac{q_\upsilon}{2M} + if_P(q^2)\frac{q_\mu}{m_e}\gamma_5\right]n$
- The terms $g_V(q^2)$ and $g_A(q^2)$ are the leading decay terms associated with Fermi and GT transitions
- A consequence of the SM is the conservation of the vector current ⇒ $g_V(q^2)$ = 1, and it relates the weak magnetism term $f_M(q^2)$ to an analog M1 γ decay

Nuclear Beta Decay Form – IV

- The axial current has no electromagnetic analog and is not conserved but PCAC seems to work
- A transformation called G parity is defined by

$$G = Ce^{i\pi T_2}$$

- Strong interaction symmetric under G
- In weak interaction, define 1st and 2nd class currents by G parity operation
- SM allows only 1st class currents
- Generating a decay spectrum from interaction is tedious – early work by Jackson, Treiman and Wyld with follow up work by Holstein

Nuclear beta decay tests of SM

- Super-allowed transitions **
- Correlation experiments
  - – β-α angular correlations
  - – β-γ angular correlations
  - – β asymmetry from aligned nuclei
  - – β-ν correlations**
- Neutron lifetime and decay studies***
- Double β decay – covered by Boris K.

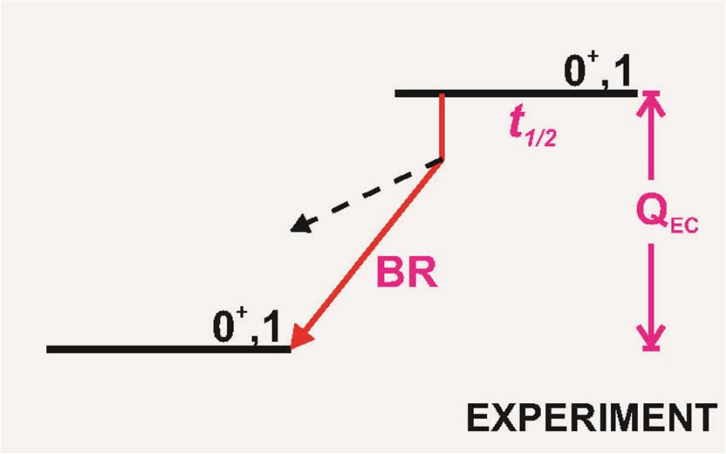
What have we learned from β-α and β-γ correlations?

- Most work done in ‘70’s and ‘80’s
- No evidence for recoil order second-class currents (<10% of allowed terms)
- CVC confirmed (uncertainties around 10%) in comparing weak magnetism to M1 dipole transitions

$0^+ \rightarrow 0^+$ β decay

- Measure life-time and branching ratio to get

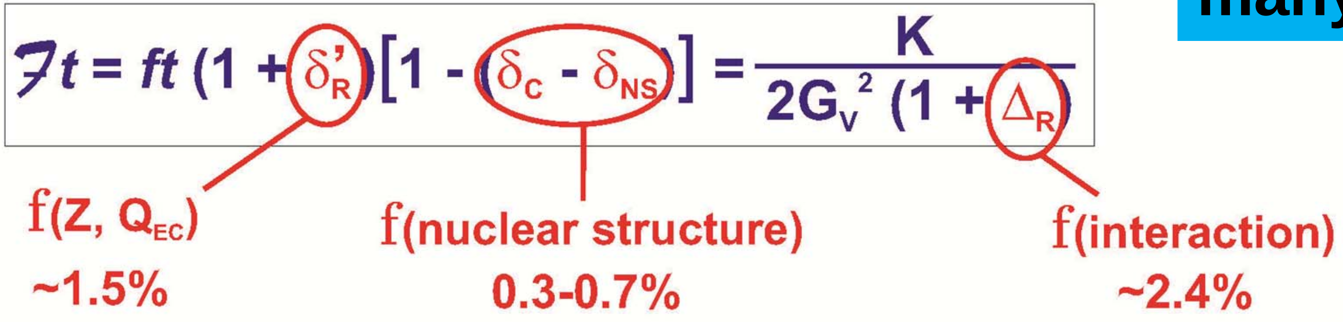
$$ft = \frac{K}{G_V^2 < \tau >^2}$$



  - *f* = statistical function [f(Z,QEC)]
  - *t* = partial half-life [f($t_{1/2}$,BR)]
  - G_V = vector coupling constant
  - <τ> = Fermi Matrix element

- Include corrections

G_V constant for many decays?



$$\mathcal{F}t = ft\,(1 + \delta_R')[1 - (\delta_C - \delta_{NS})] = \frac{K}{2G_V^2\,(1 + \Delta_R)}$$

f(Z, Q_{EC})
~1.5%

f(nuclear structure)
0.3-0.7%

f(interaction)
~2.4%

V_{ud} and the CKM Matrix

- Cabbibo, Kobayashi, Maskawa Matrix connects weak to mass eigenstates
- Standard Model ⇒ matrix is unitary

$$[V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 1]$$

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix}$$

weak eigenstates

mass eigenstates

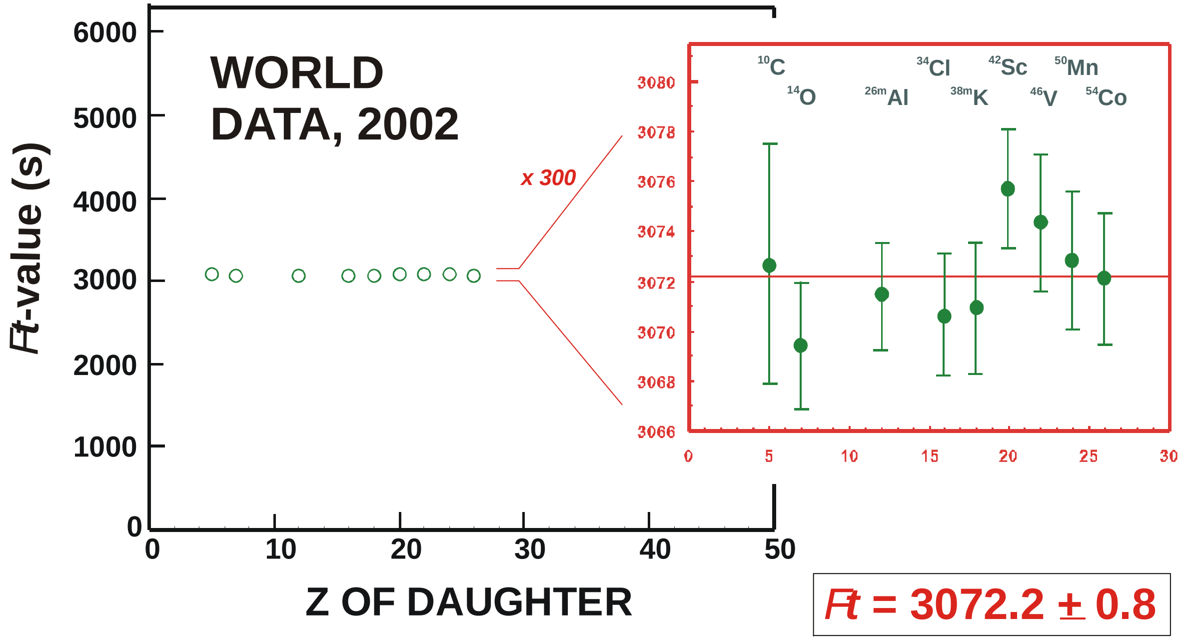
$V_{ud}^2 = G_V^2/G_\mu^2$

V_{us} from K decay

V_{ub} from B decay

$0^+ \rightarrow 0^+$ β decay and the SM

- As of 2002, there were 9 precision measurements



Test of **CVC**

$\mathcal{F}t$ = 3072.2 ± 0.8

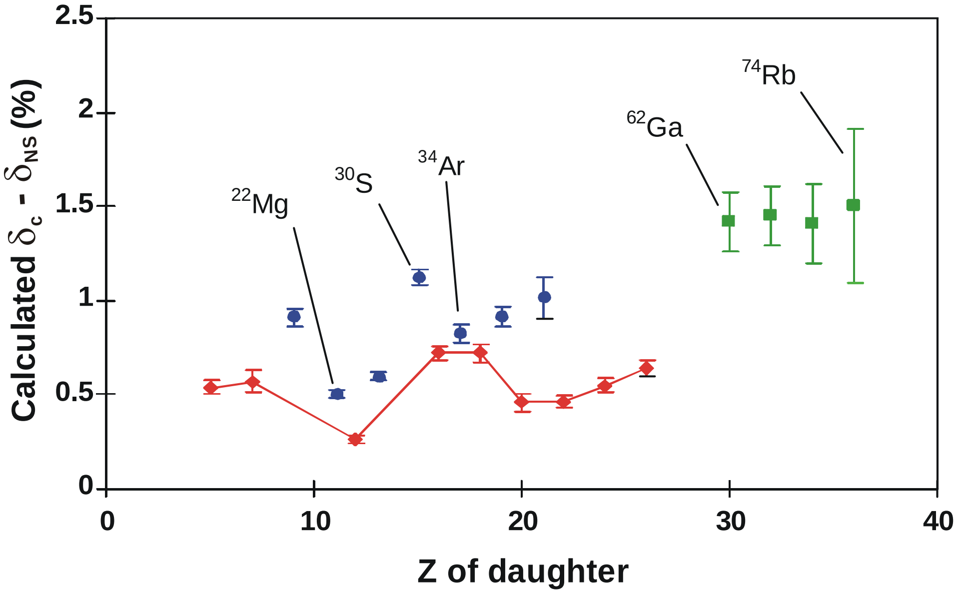
$\chi^2/\nu = 0.6$

- Extracting V_{ud}(0.9740), with V_{us}(0.2196), and V_{ub}(0.0036) $\Rightarrow$

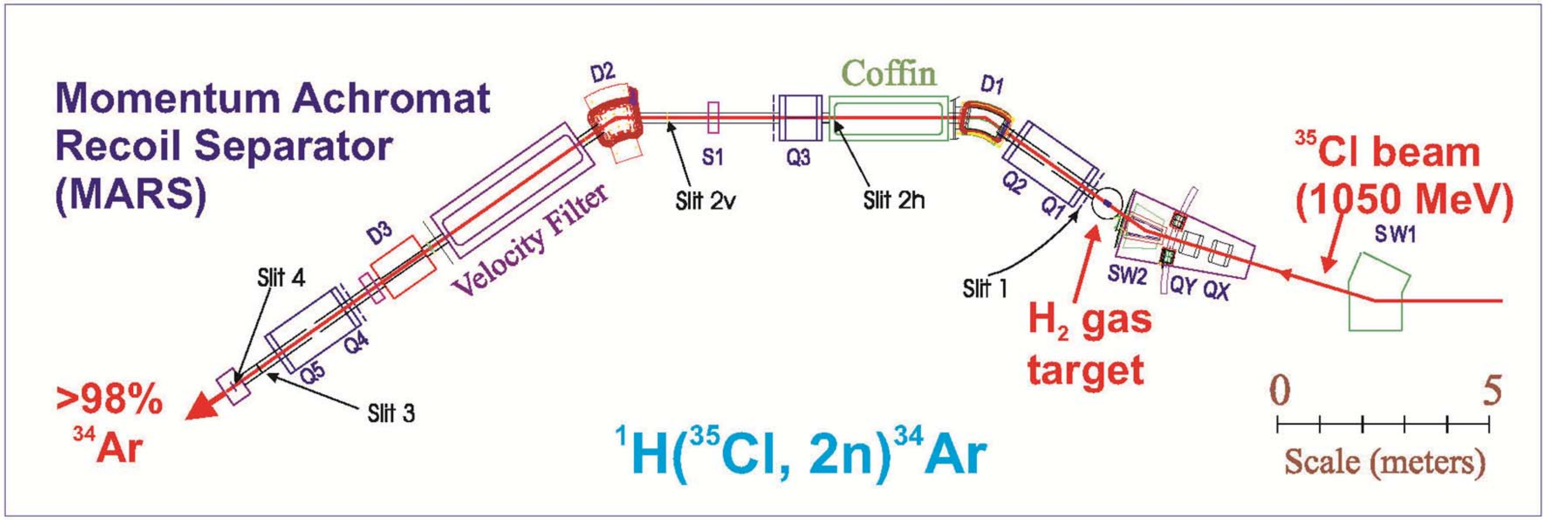
$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.9968 \pm 0.0014$$

$0^+ \rightarrow 0^+$ β **decay** and the **SM**

- Test δ_C - δ_{NS} to verify and improve calculations
  - measure $0^+ \rightarrow 0^+$ decay for A=62 (**TAMU**)
  - measure $0^+ \rightarrow 0^+$ decays (T_z=-1) for 18≤A≤42 (**TAMU**)
  - measure masses (Penning traps) and new partial half-lives for nine known cases (**TAMU** + other locations)

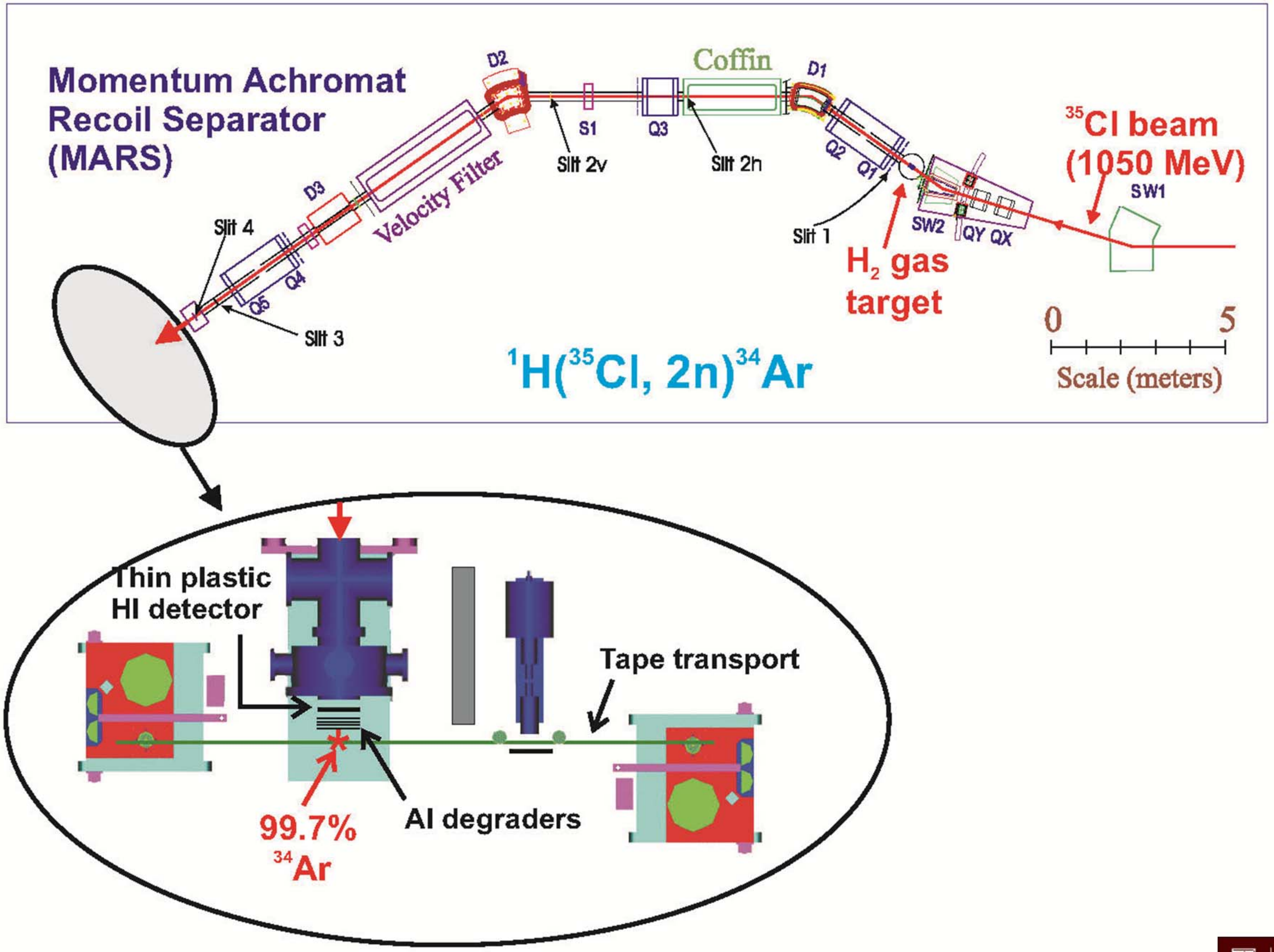


PRECISION DECAY MEASUREMENTS AT TAMU



$^{1}H(^{35}Cl, 2n)^{34}Ar$

PRECISION DECAY MEASUREMENTS AT TAMU



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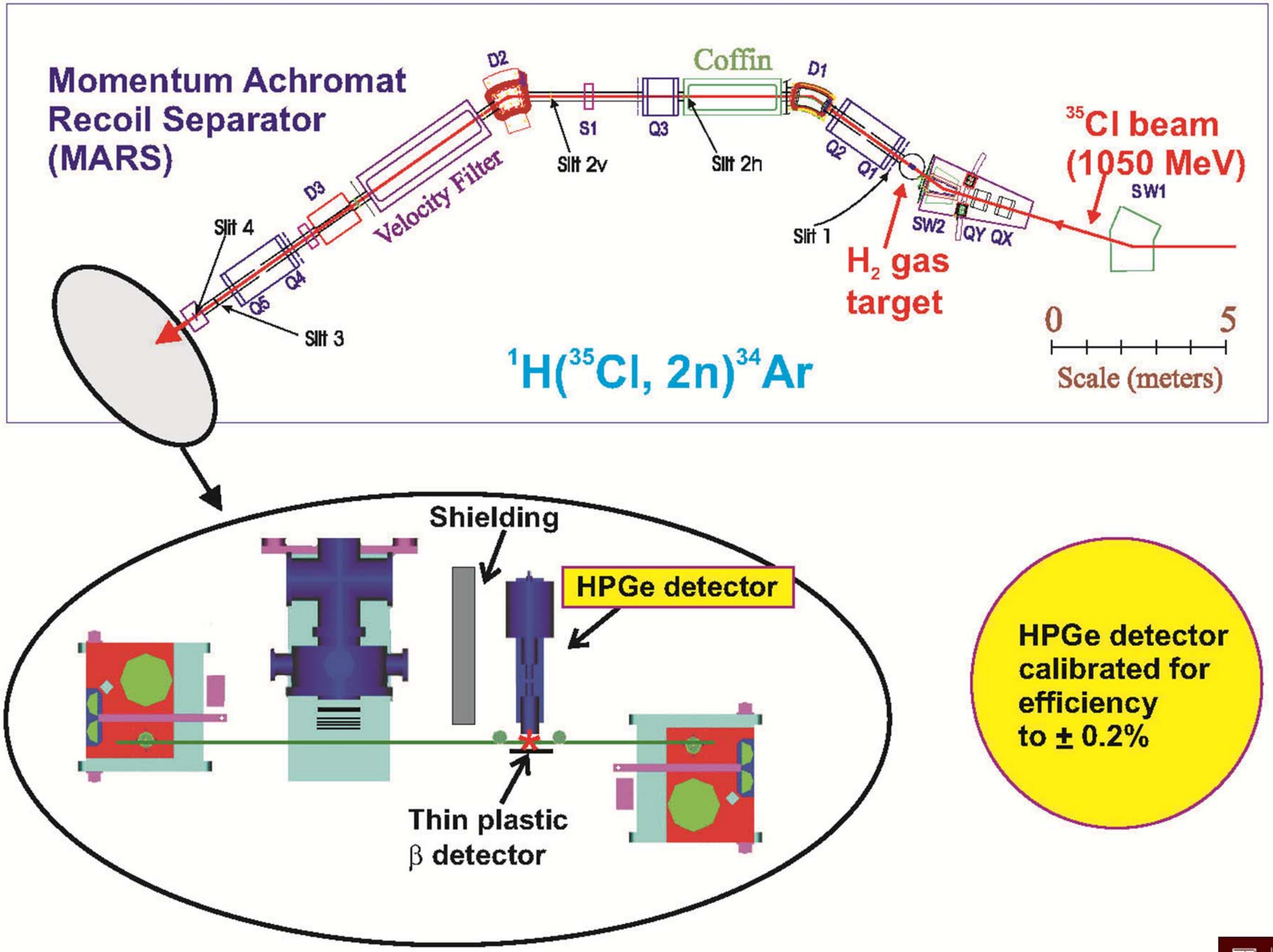


$^{1}H(^{35}Cl, 2n)^{34}Ar$

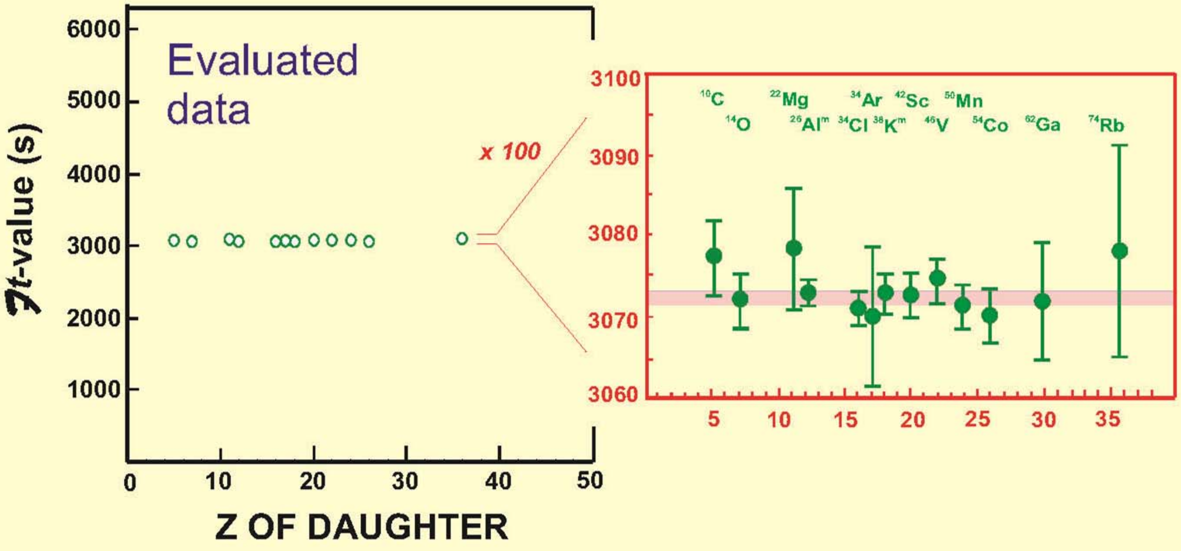
HPGe detector calibrated for efficiency to ± 0.2%

$0^+ \rightarrow 0^+$ β decay Today

1) G_V constant

$$\mathcal{F}t = \frac{K}{2G_V^2\,(1 + \Delta_R)}$$

✓ verified to ± 0.013%



$\overline{\mathcal{F}t}$ = 3072.2(8)

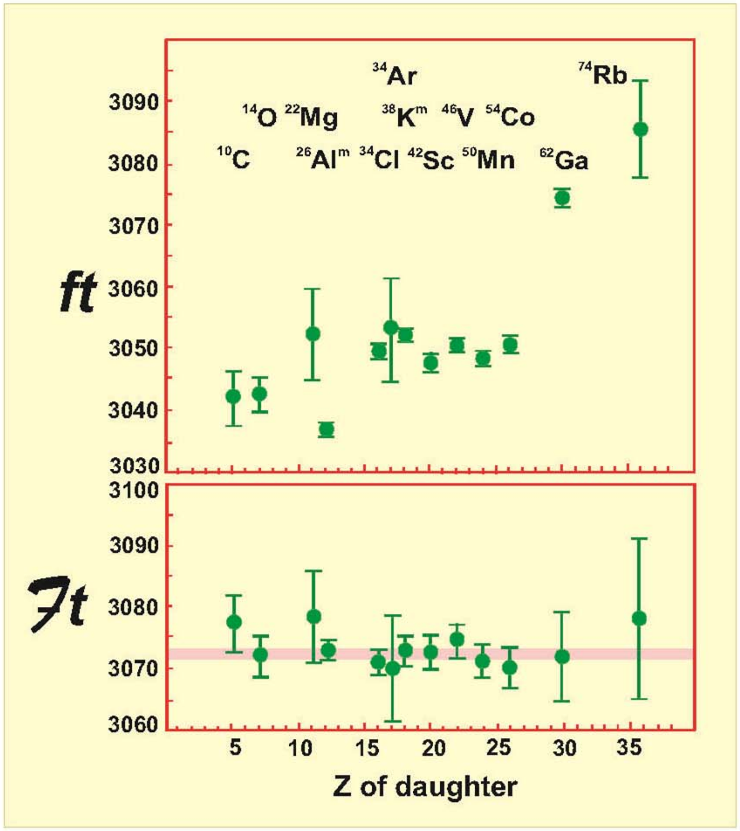
$G_V(1+\Delta_R)^{1/2}/(\hbar c)^3$
$= 1.14961(15)$
$\times 10^{-5}$ GeV^{-2}

$\chi^2/\nu = 0.3$

$0^+ \rightarrow 0^+$ β decay Today

1) G_V constant $\mathcal{F}t = \frac{K}{2G_V^2(1+\Delta_R)}$ ✔ verified to ± 0.013%

2) Correction terms validated ✔

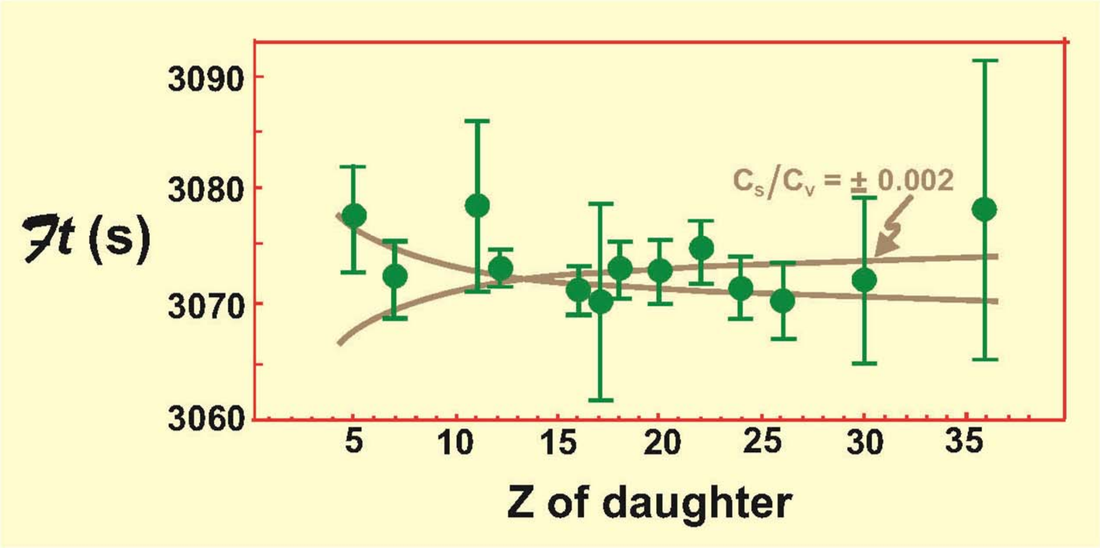


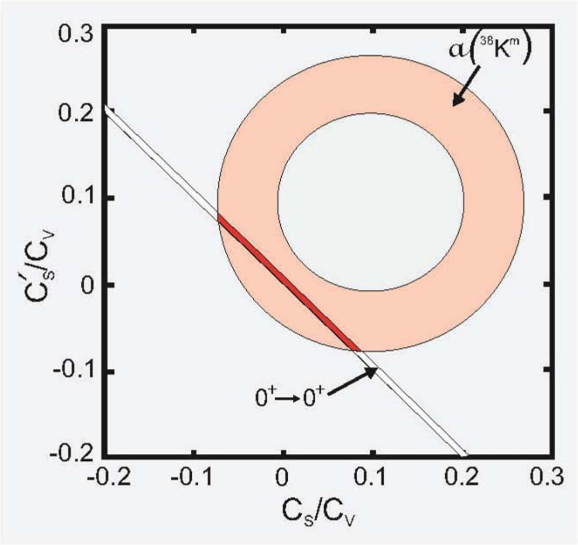
$0^+ \rightarrow 0^+$ β decay Today

1) G_V constant $\boxed{\mathcal{F}t = \dfrac{K}{2G_V^{\,2}\,(1 + \Delta_R)}}$ ✓ verified to ± 0.013%

2) Correction terms validated ✓

3) Scalar current zero ✓ limit, $C_S/C_V = 0.0011\ (14)$

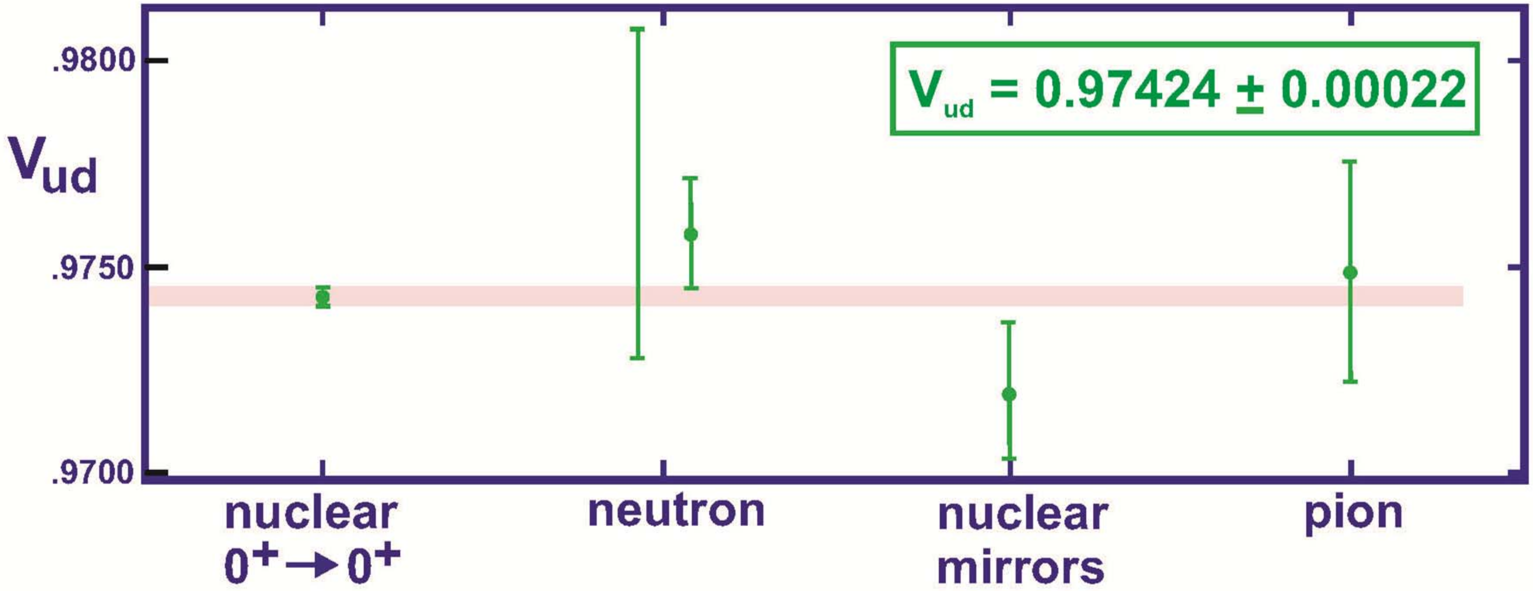




V_{ud} and CKM Today

- **G_V** determined by several methods:
- **$0^+ \rightarrow 0^+$** β decay $\Leftarrow$ **most accurate**, **by far**
- **neutron** β decay
- **pion** β decay
- **Mirror nuclear** β decay

V_{ud} and CKM Today



$$V_{ud}^2 + V_{us}^2 + V_{ub}^2 = 0.99995(61)$$

V_{ud}^2: 0.9491(4)

V_{us}^2: 0.0508(4)

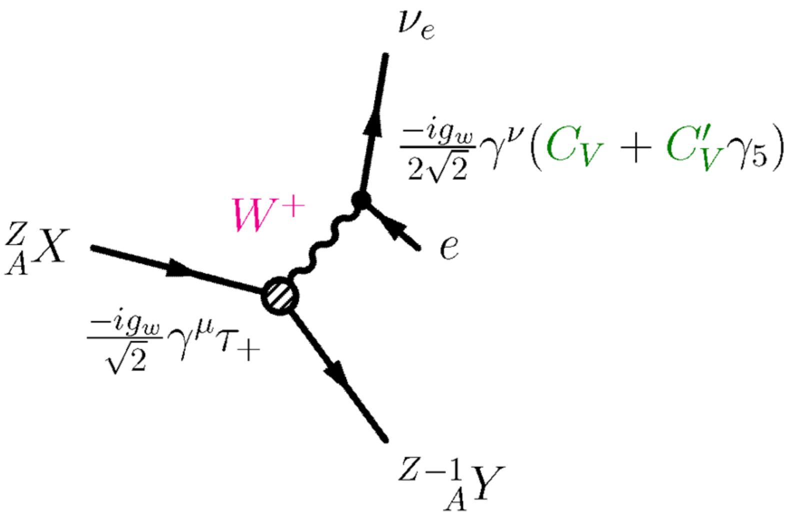
V_{ub}^2: <0.0001

β-ν Correlations

- Pure Fermi decay ($0^+ \rightarrow 0^+$)

$$\frac{d^5W}{dE_e\,d\Omega_e\,d\Omega_\nu} \sim p_e E_e (A_\circ - E_e)^2 \left(1 - \frac{A_\circ - 3(E_e - \vec{p}_e \cdot \hat{p}_\nu)}{M}\right)$$

$$\times\ \xi\left(1 + a_{\beta\nu}\frac{\vec{p}_e \cdot \vec{p}_\nu}{E_e E_\nu} + b_F\frac{\Gamma m_e}{E_e}\right)$$

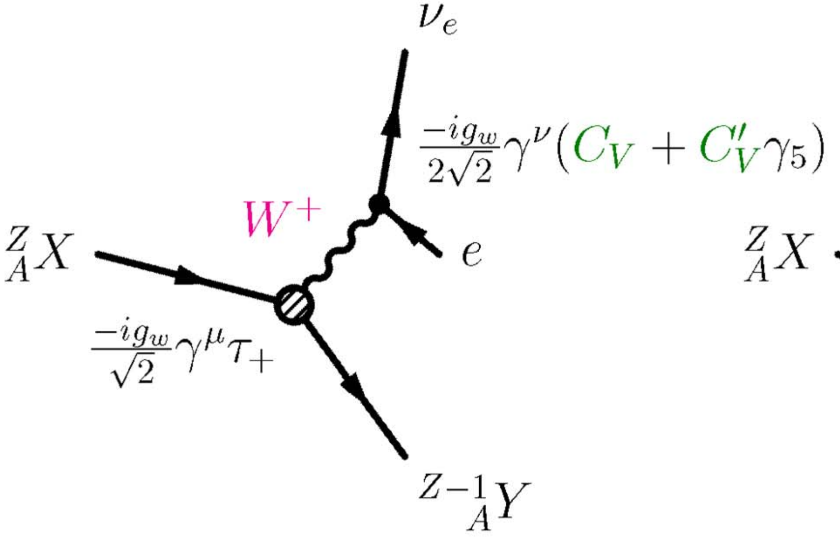


vector propagator

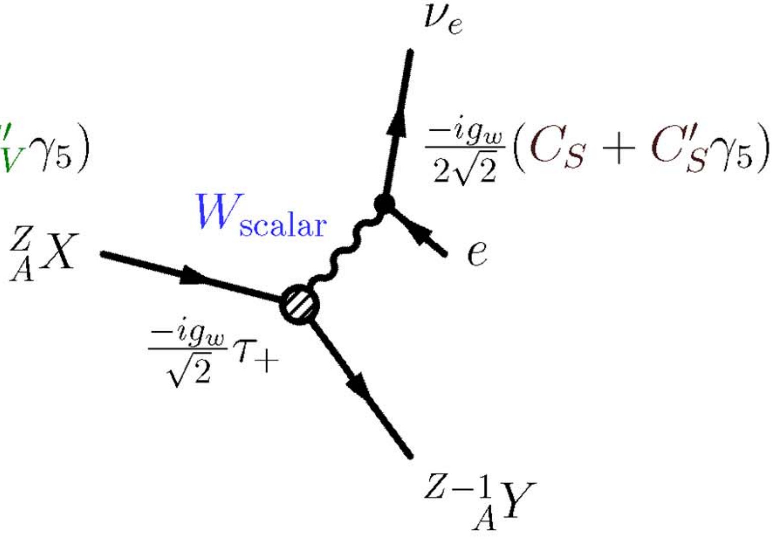
$$a_{\beta\nu} \equiv 1$$

$$b_F \equiv 0$$

A closer look . . .



(a) vector propagator:



(b) scalar propagator:

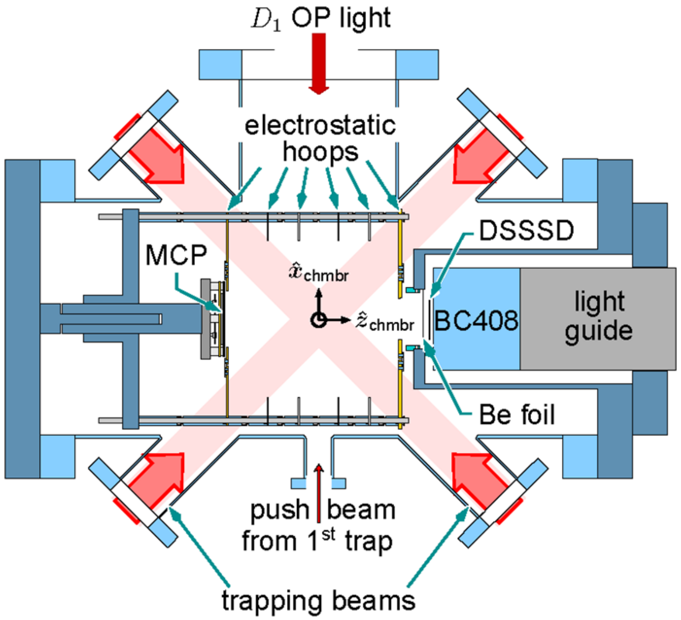
$$a_{\beta\nu} = \frac{|C_V|^2+|C'_V|^2 - |C_S|^2-|C'_S|^2 + \frac{2\alpha Z m_e}{p_e}\Im m(C_S C_V^* + C'_S C'^*_V)}{|C_V|^2 + |C'_V|^2 \ + \ |C_S|^2 + |C'_S|^2} \overset{?}{=} 1$$

$$b_F = \frac{-2\Re e(C_S^* C_V + C'^*_S C'_V)}{|C_V|^2 + |C'_V|^2 \ + \ |C_S|^2 + |C'_S|^2} \overset{?}{=} 0$$

A case study: ^{38m}K

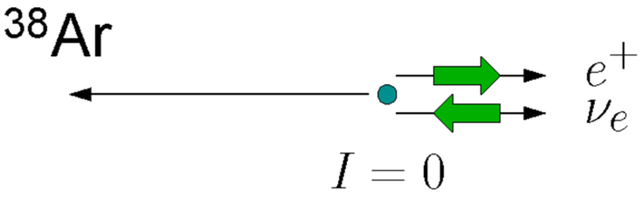
- 0^+ to 0^+ transition – capture K in ion trap

^{38m}K decay in the back-to-back geometry:

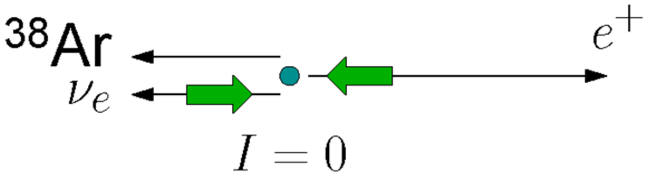


- Decay can occur with ν in two orientations

Vector Interaction

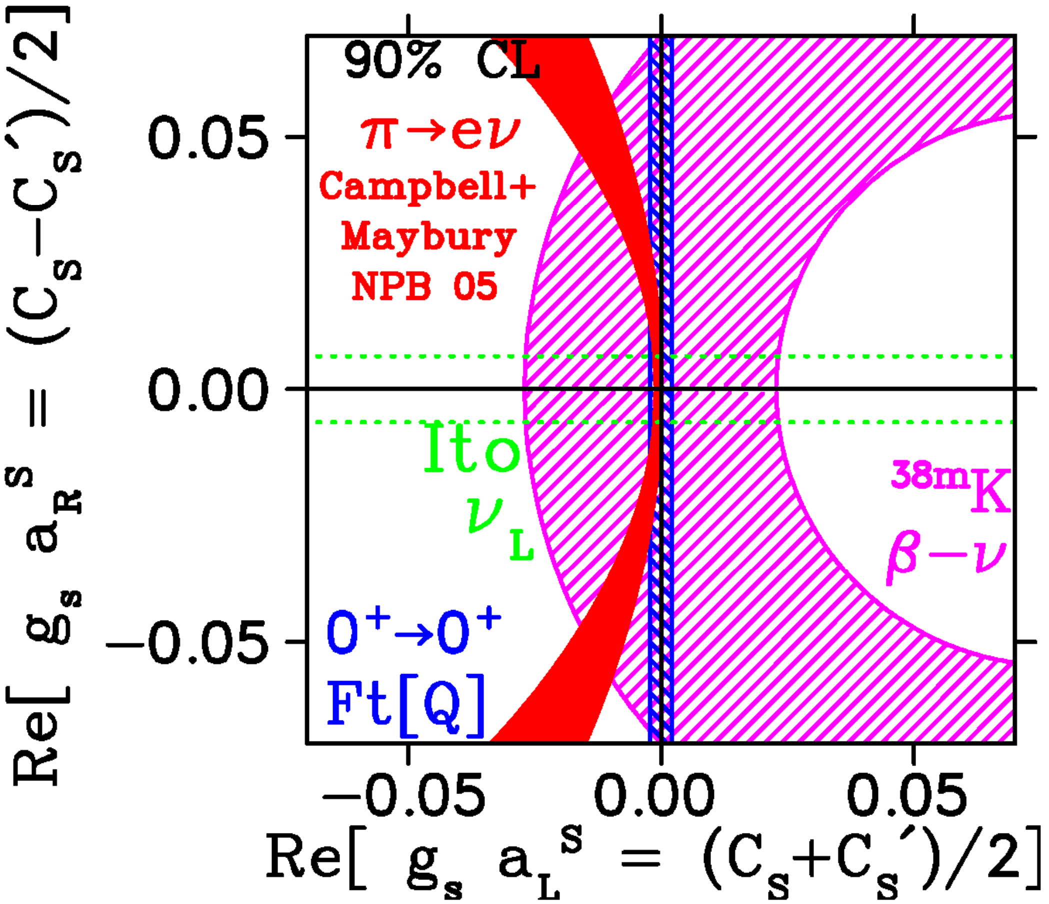


Scalar Interaction



Results

Current limits on a scalar interaction (allowing $\Im m$ couplings):



Mixed **F/GT** decays

Angular distribution of the decay:

$$dW \sim 1 + a\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_eE_\nu} + b\Gamma\frac{m}{E_e} + \frac{\vec{I}}{I}\cdot\left[\boldsymbol{A_\beta}\frac{\vec{p}_e}{E_e} + \boldsymbol{B_\nu}\frac{\vec{p}_\nu}{E_\nu} + \boldsymbol{D}\frac{\vec{p}_e\times\vec{p}_\nu}{E_eE_\nu}\right]$$

$$(+\ \textbf{alignment term})$$

$$(+\ \beta - \textbf{polarization terms})$$

$$A_\beta = \frac{-2\rho}{1+\rho^2}\left(\sqrt{\frac{3}{5}} - \frac{\rho}{5}\right)$$

$$B_\nu = \frac{-2\rho}{1+\rho^2}\left(\sqrt{\frac{3}{5}} + \frac{\rho}{5}\right)$$

where $\rho = \frac{G_A M_{GT}}{G_V M_F}$

D is T violating term and should be 0 in SM

RHCs would affect correlation parameters

In the presence of **new physics**, the **angular distribution of β decay** will be affected.

$$A_\beta = \frac{-2\rho}{1+\rho^2}\left(\sqrt{\frac{3}{5}} - \frac{\rho}{5}\right) \quad \rightarrow \quad \frac{-2\rho}{1+\rho^2}\left[(1-xy)\sqrt{\frac{3(1+x^2)}{5(1+y^2)}} - \frac{\rho(1-y^2)}{5(1+y^2)}\right]$$

$$B_\nu = \frac{-2\rho}{1+\rho^2}\left(\sqrt{\frac{3}{5}} + \frac{\rho}{5}\right) \quad \rightarrow \quad \frac{-2\rho}{1+\rho^2}\left[(1-xy)\sqrt{\frac{3(1+x^2)}{5(1+y^2)}} + \frac{\rho(1-y^2)}{5(1+y^2)}\right]$$

and $R_{\text{slow}} = 0 \quad \rightarrow \quad y^2$

where $x \approx (M_L/M_R)^2 - \zeta$ and $y \approx (M_L/M_R)^2 + \zeta$

are RHC parameters that are zero in the SM.

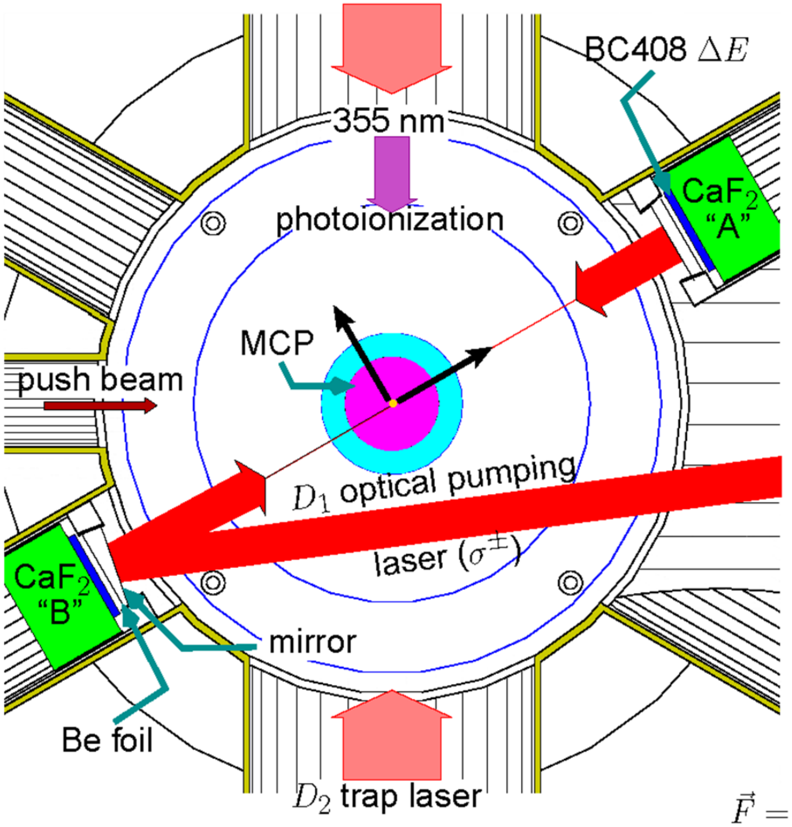
$\Rightarrow$ Precision measurements test the SM

Goal must be $\lesssim 0.1\%$

(see Profumo, Ramsey-Musolf and Tulin, PRD **75** (2007))

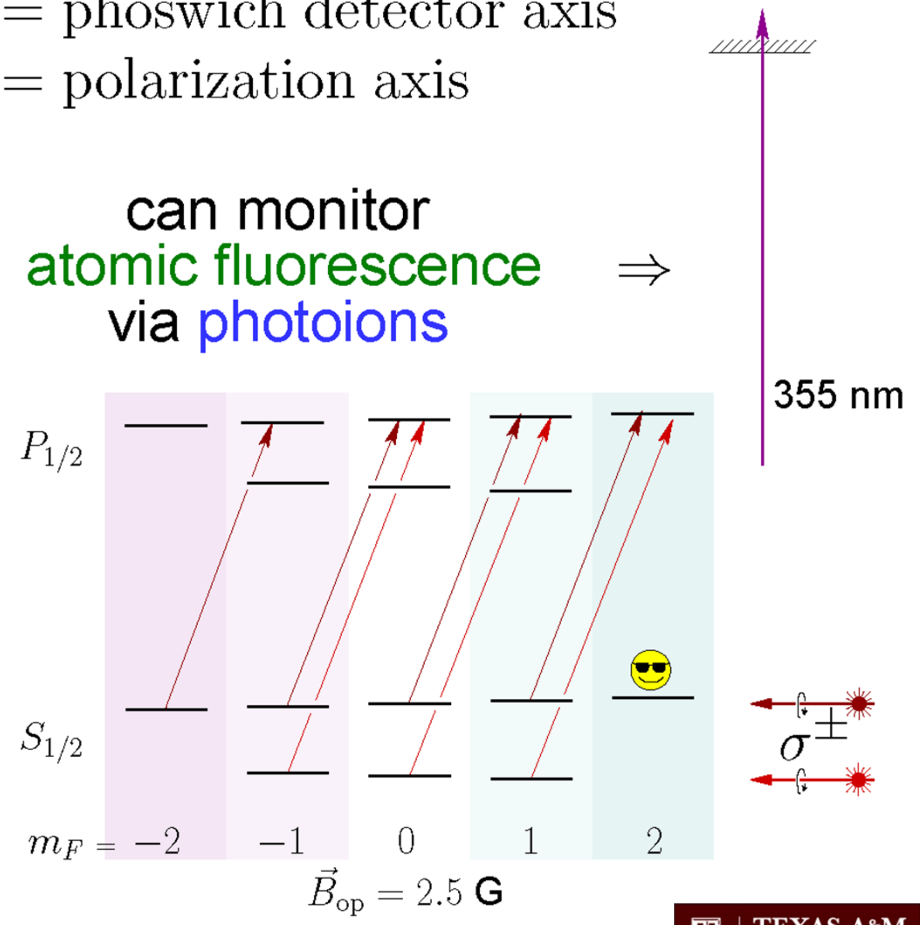
A case study: ^{37}K

- $3/2^+$ to $3/2^+$ transition – again capture K in trap



$\hat{z}$ = MCP – β-telescope axis
$\hat{x}$ = phoswich detector axis
= polarization axis

can monitor
atomic fluorescence
via photoions $\Rightarrow$



$\vec{F} = \vec{I} + \vec{J}$
$I = \frac{3}{2}$
$J = \frac{1}{2}$

Optical Pumping to
fix hyperfine state

CP Violation and Baryogenesis

- The combination of BBN and what appears to be a matter dominated world, even though we expect equal amounts of matter and antimatter initially, produces major question
- Need a mechanism to break the matter-antimatter symmetry during early phase
- Could occur in quantum gravity but unlikely
- Best option $\Rightarrow$ CP violation beyond the SM
- Has resulted in searches for CP violation in a variety of systems
- Observations in K decay consistent with CKM phase

CP Violation – **EDM**’s

- Non-zero **EDM** could point the way toward the missing physics
- Searches for **EDM** in electron, atoms and particles
- Different sensitivity to new physics for different systems
- SM **EDM** through CKM phase is very small
- Low energy searches underway or planned in
  - radioactive atoms
  - neutron (SM $\Rightarrow$ ~10^{-32} e-cm)
  - deuteron

Physics Beyond the Standard Model

- New physics (e.g. SUSY) often includes additional CP violating phases in couplings
  - φ_{CP} should be ~ 1

- Contributions to EDMs depends on masses of new particles

$$d_n \propto \left(\frac{M_p}{M_{SUSY}}\right)^2 \sin\varphi_{CP}$$

  - In MSSM (Minimal Supersymmetric Standard Model)
    - $d_n \sim 10^{-25}$ e-cm x $\sin\varphi_{CP}(200\ \mathrm{GeV}/M_{SUSY})^2$

Present limit: $d_n < 3 \times 10^{-26}$ e-cm

Slide from B.F.

Why Multiple EDM exps?

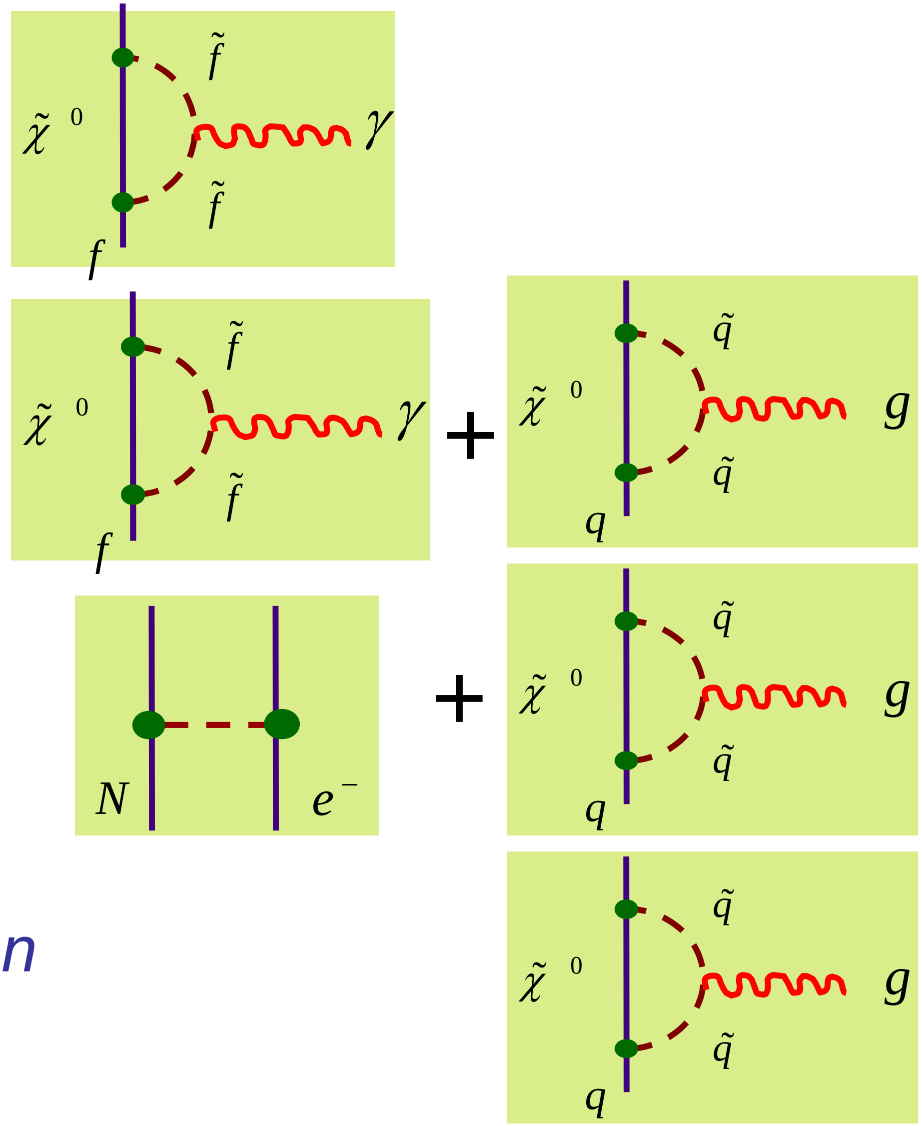
To identify origin of new $\not{CP}$

Electron

Neutron

Neutral Atoms

Deuteron



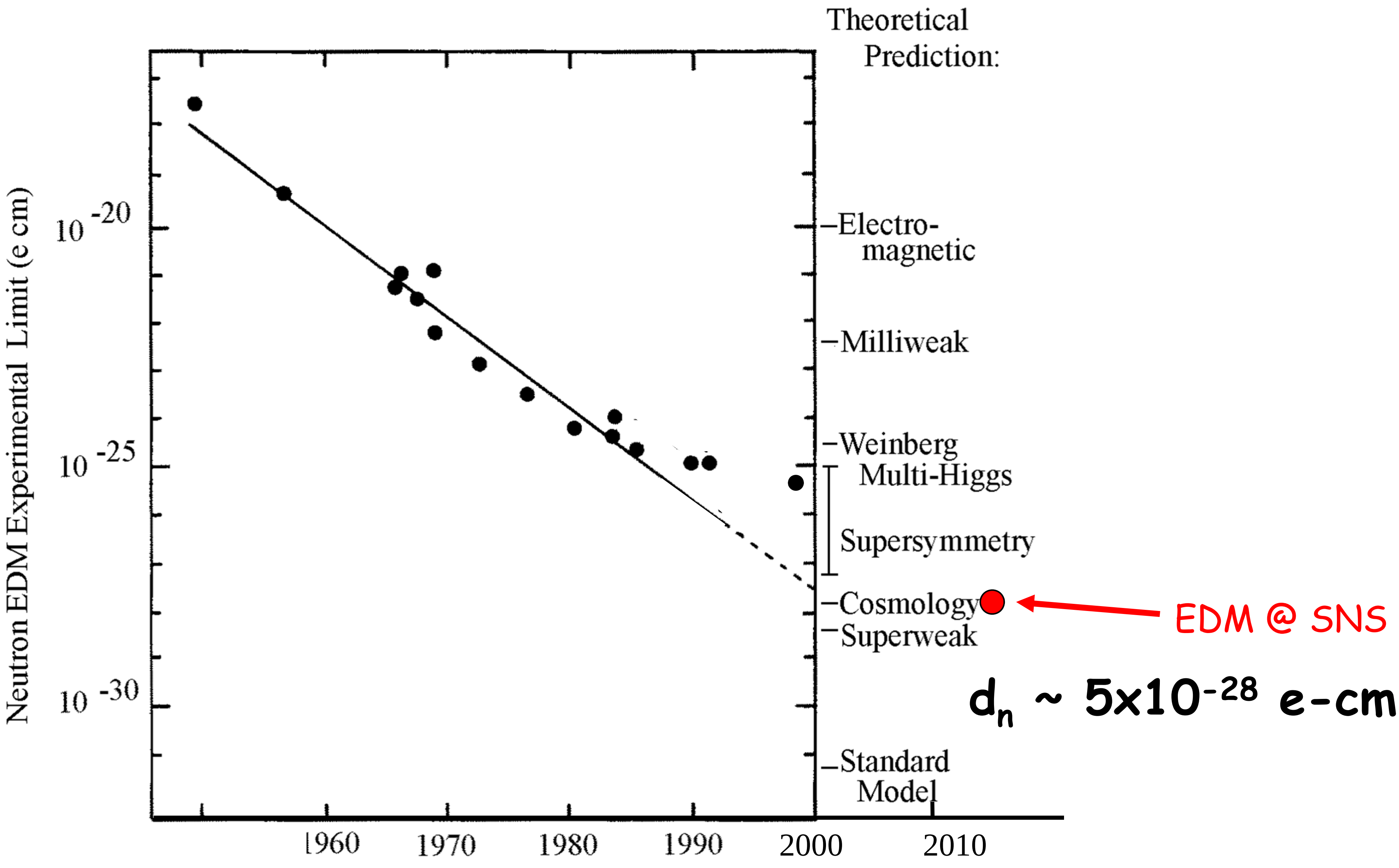
$+ \theta_{QCD}$

$+ \theta_{QCD}$

$+ \theta_{QCD}$

Slide from B.F.

New n-EDM Sensitivity



$d_n \sim 5\text{x}10^{-28}$ e-cm

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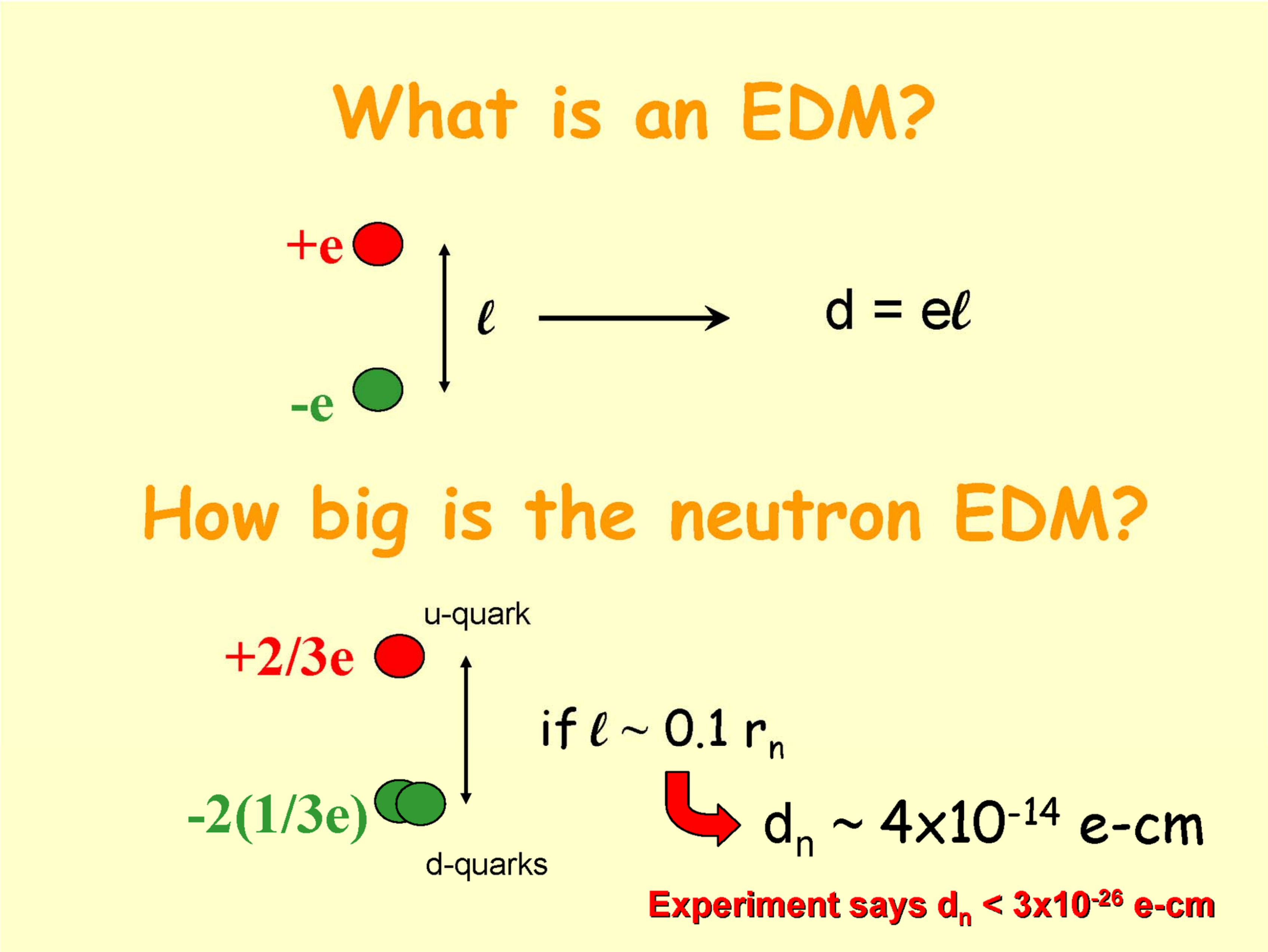


What is an EDM?

+e

ℓ

$d = e\ell$

-e

How big is the neutron EDM?

u-quark

+2/3e

if $\ell \sim 0.1\ r_n$

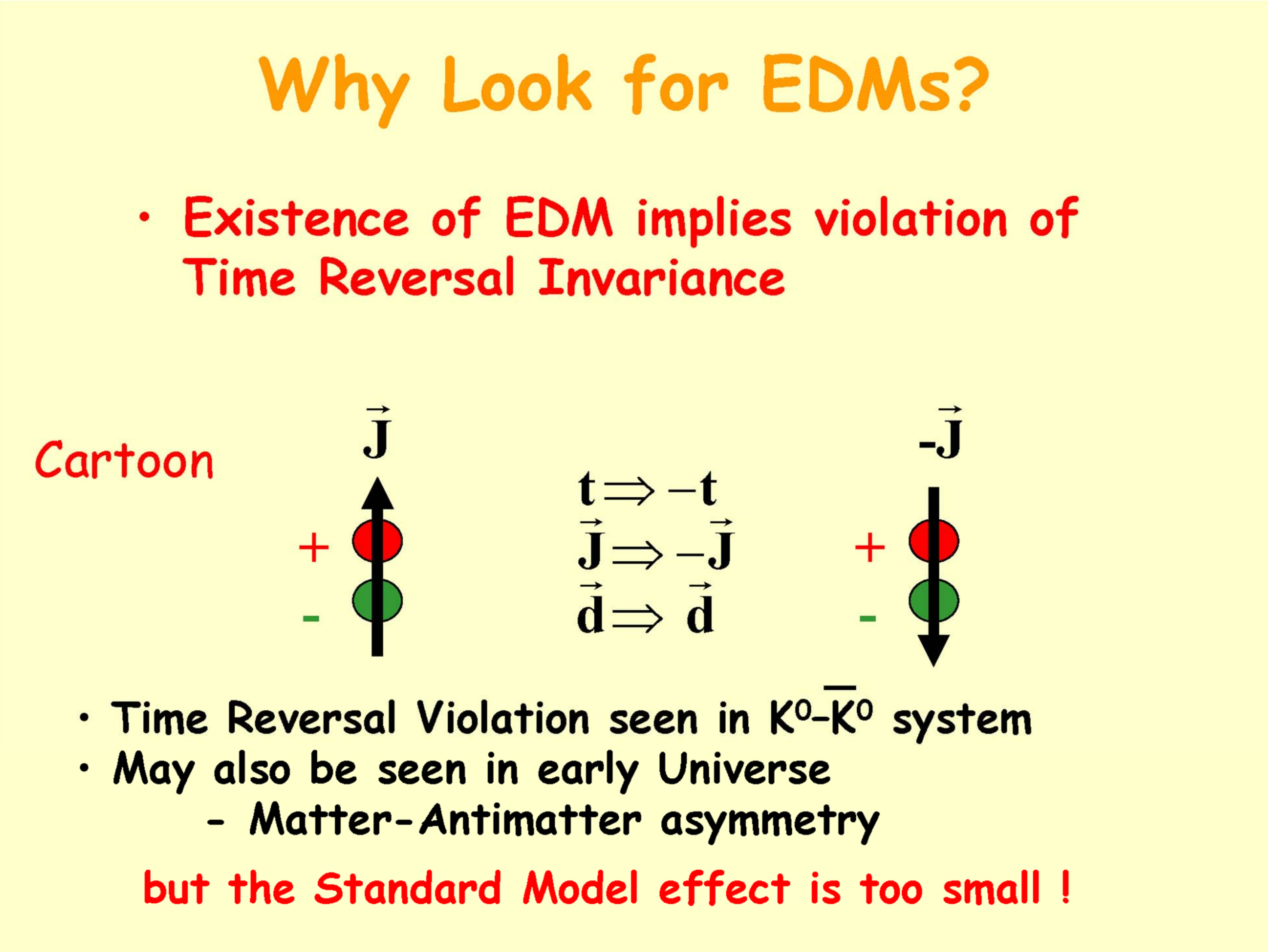
$d_n \sim 4 \times 10^{-14}$ e-cm

-2(1/3e)

d-quarks

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

Slide from B.F.



Why Look for EDMs?

- Existence of EDM implies violation of Time Reversal Invariance

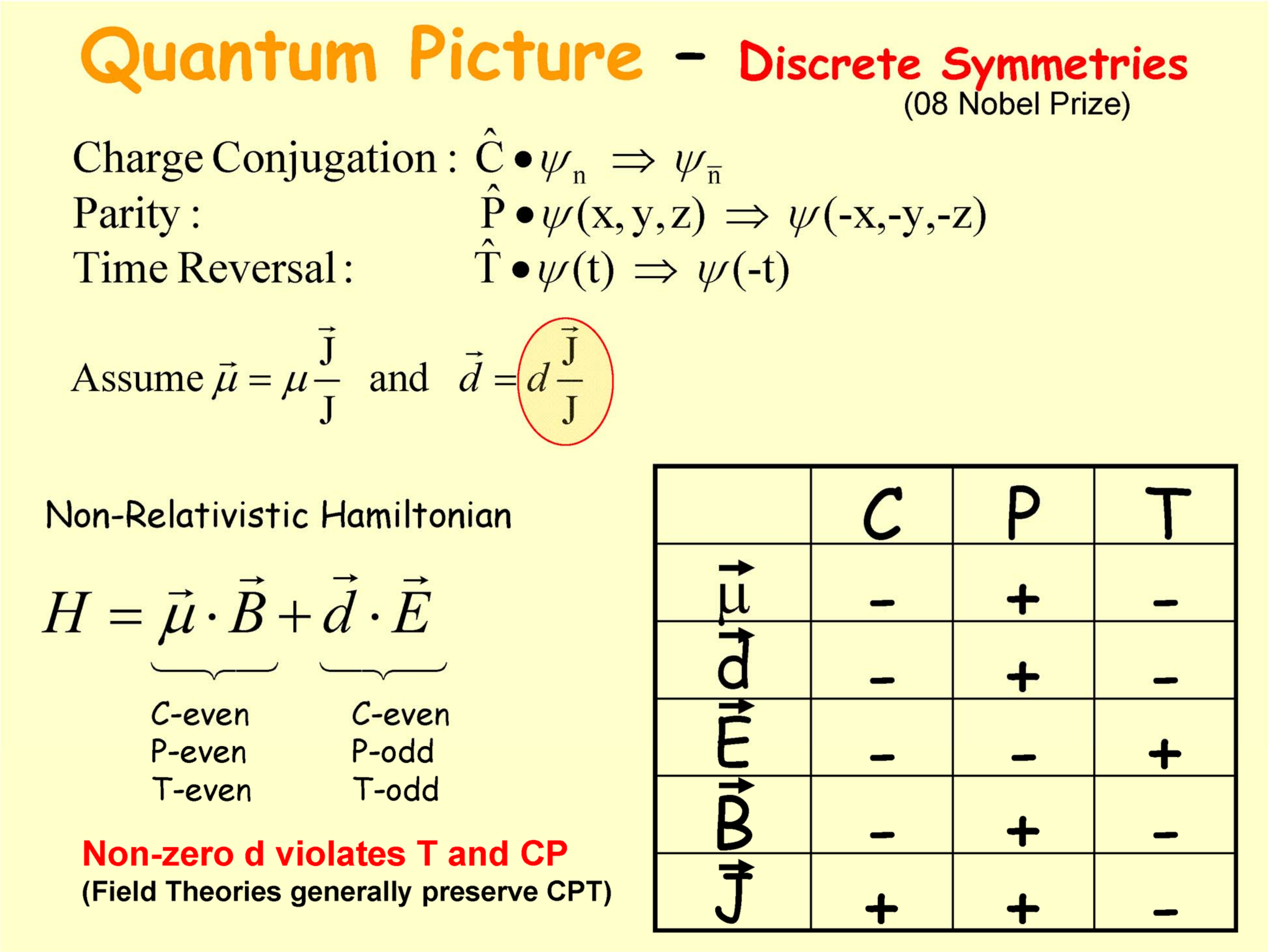
Cartoon

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

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

but the Standard Model effect is too small !

Slide from B.F.



Quantum Picture – Discrete Symmetries

(08 Nobel Prize)

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

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

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

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

Non-Relativistic Hamiltonian

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

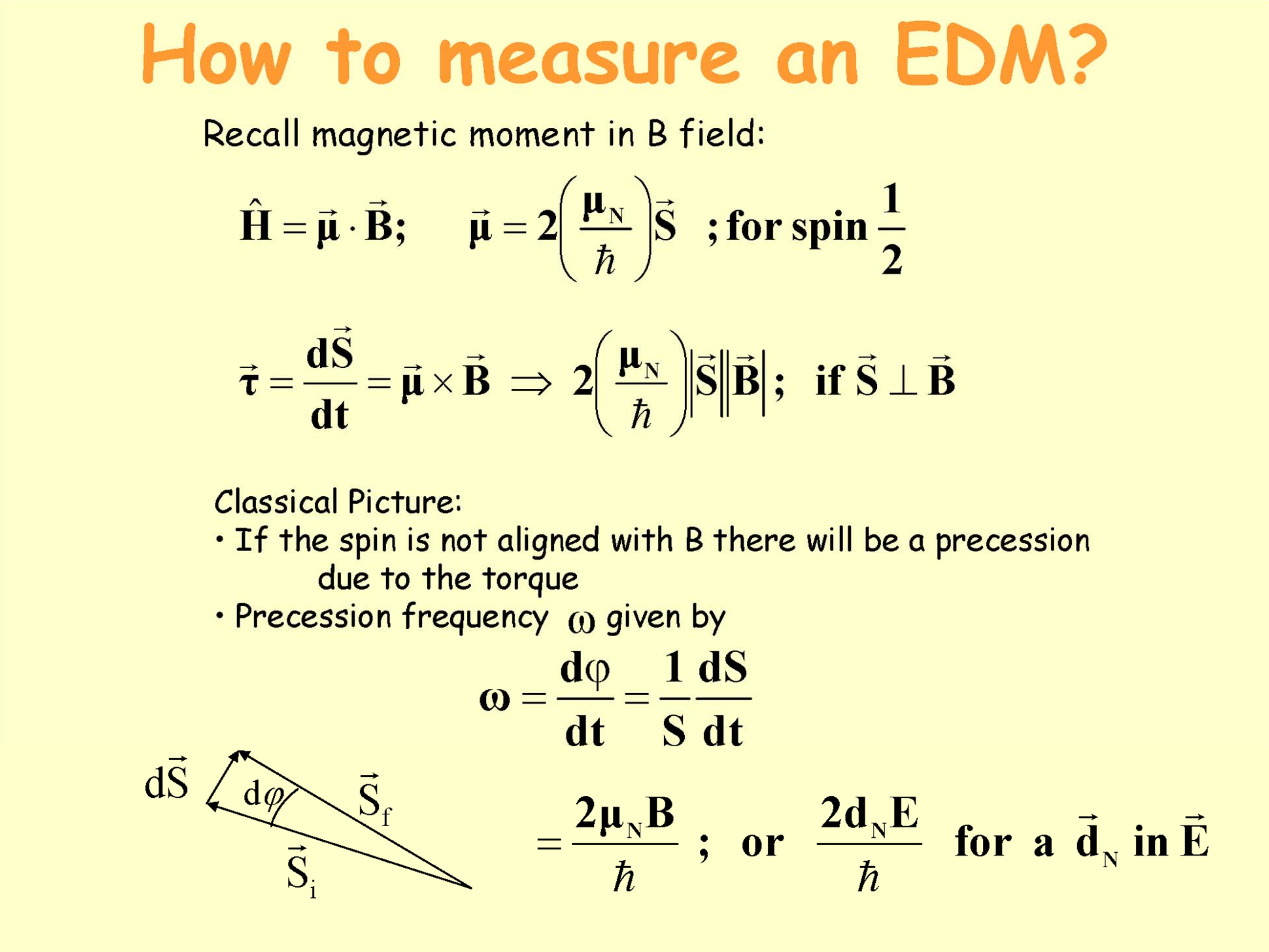
C-even	C-even
P-even	P-odd
T-even	T-odd

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

Non-zero d violates T and CP

(Field Theories generally preserve CPT)

Slide from B.F.



How to measure an EDM?

Recall magnetic moment in B field:

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

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

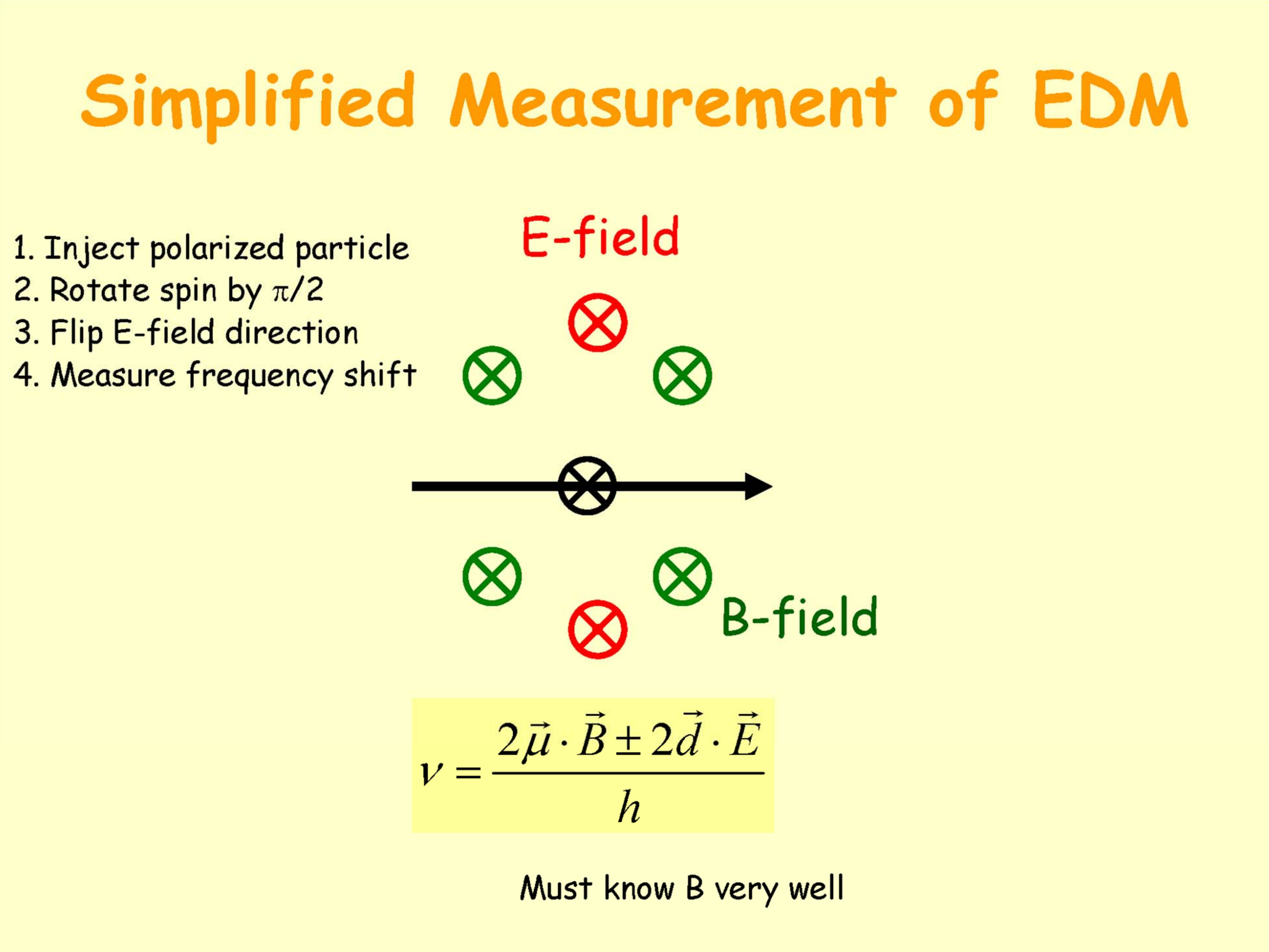
Classical Picture:

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

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

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

Slide from B.F.



Simplified Measurement of EDM

1. Inject polarized particle
2. Rotate spin by π/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

Slide from B.F.

Polarized ^{3}He Co-magnetometer

- *Use very* small amount of polarized ^{3}He in ^{4}He (^{3}He/^{4}He ~ 10^{-10})

- ^{3}He has tiny EDM < 3 x 10^{-5} d_n
  (Dzuba, Flambaum, & Ginges PRA **76**, 034501 2007)

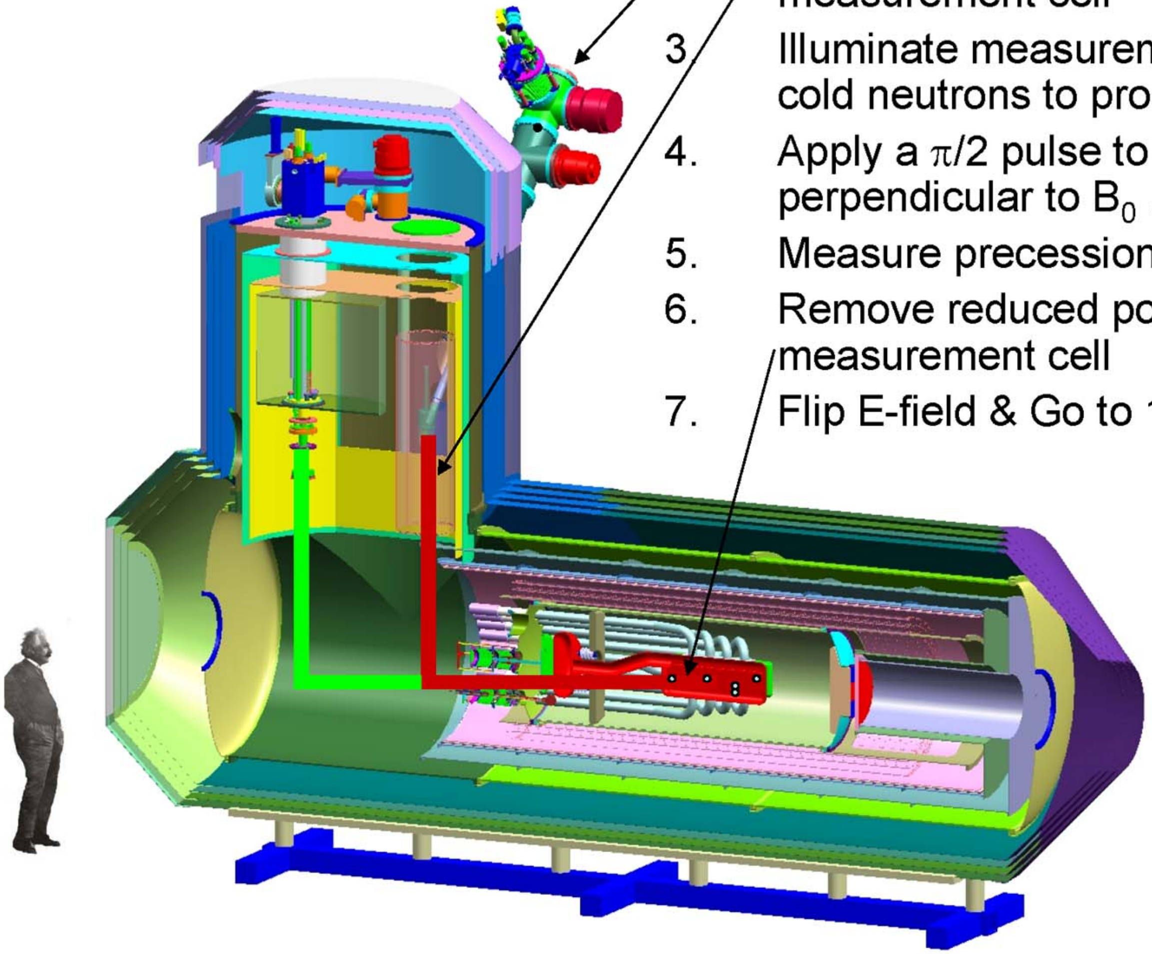
- Detect capture via scintillation in ^{4}He: $\vec{n} + {}^3\vec{\mathrm{He}} \Rightarrow \mathrm{t} + \mathrm{p} \quad (\text{with } \sigma_{\uparrow\downarrow} >> \sigma_{\uparrow\uparrow})$
  - UV photons converted to visible (in tetraphenyl butadiene - TPB)
  - Measure difference of ω_n and ω_3

- Can use SQUIDs to measure ^{3}He precession – calibrates B-field since $\omega_3 \propto |\vec{B}|$
  - ^{3}He co-magnetometer measures B-field over "same" volume as neutrons

- Independent technique using "dressed" spins suppresses sensitivity to fluctuations in B-field
  - Additional RF field can match ^{3}He and neutron precession frequency

Slide from B.F.

Measurement cycle



1. Load collection volume with polarized ^{3}He atoms
2. Transfer polarized ^{3}He atoms into the measurement cell
3. Illuminate measurement cell with polarized cold neutrons to produce polarized UCN
4. Apply a $\pi/2$ pulse to rotate spins perpendicular to B_0
5. Measure precession frequency
6. Remove reduced polarization ^{3}He atoms from measurement cell
7. Flip E-field & Go to 1.

Slide from B.F.

Worldwide nEDM experiments

Exp	UCN source	cell	Measurement techniques	σ_d (10^{-28} e-cm)
ILL **CryoEDM**	**Superfluid ^{4}He**	**^{4}He**	Ramsey technique for ω External SQUID magnetometers	**Phase1 ~ 50** **Phase2 < 5**
PNPI – ILL	**ILL turbine** **PNPI/Solid D_2**	**Vac.**	Ramsey technique for ω $\vec{E}=0$ cell for magnetometer	**Phase1<100** **< 10**
ILL Crystal	**Cold n Beam**	solid	Crystal Diffraction	**< 100**
PSI EDM	**Solid D_2**	**Vac.**	Ramsey technique for ω External Cs & $^3\vec{\mathrm{He}}$ magnetom.	**~ 50** **~ 5**
SNS EDM	**Superfluid ^{4}He**	**^{4}He**	$^3\vec{\mathrm{He}}$ capture for ω $^3\vec{\mathrm{He}}$ comagnetometer SQUIDS & Dressed spins	**~ 5**
TRIUMF	**Superfluid ^{4}He**	**Vac.**	Under Development	**?**
JPARC	**Superfluid ^{4}He**	**Vac.**	Under Development	**?**

Slide from B.F.

All about muons

Topics:

- Lifetime – MuLAN
- Normal decay – TWIST
- Exotic decays – MEGA, MEG, SINDRUM
- Anomalous Moment – (g-2)

Starting point for tomorrow’s lecture!