Fundamental Interactions and Symmetries

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Workshop on Atomic Physics Research at the Future GSI Facility
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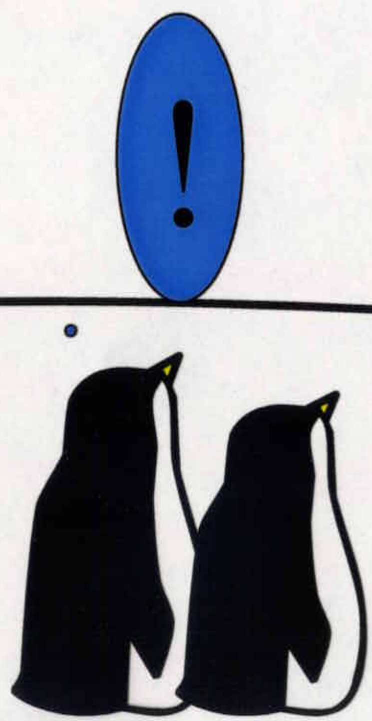
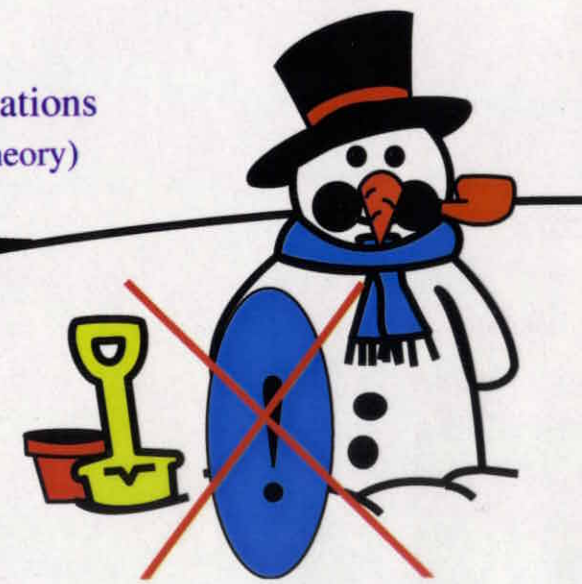
Global Symmetries ⇒ Conservation Laws
Local Symmetries ⇒ Forces

Space Time Symmetries
Discrete Symmetries
Charge Conjugation (C), Parity (P), Time Reversal (T), CP, CPT

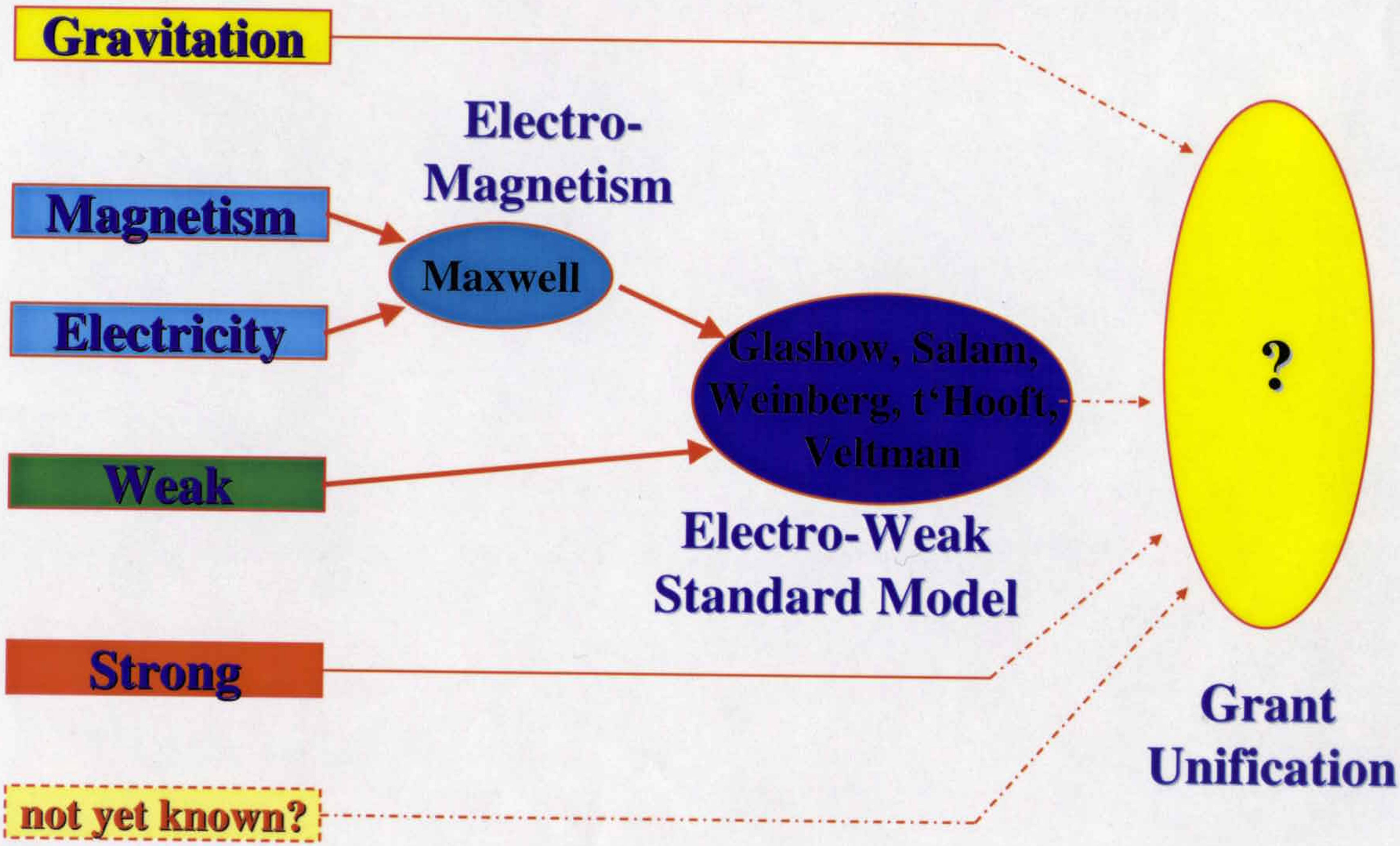


Theory ⇔ Experiments
Novel Models ⇔ Searches for Deviations (from Standard Theory)



TRIμP

Fundamental Interactions



Some Questions Left Open by Standard Model

- **Fundamental Fermions** (leptons, quarks) three families ? Masses

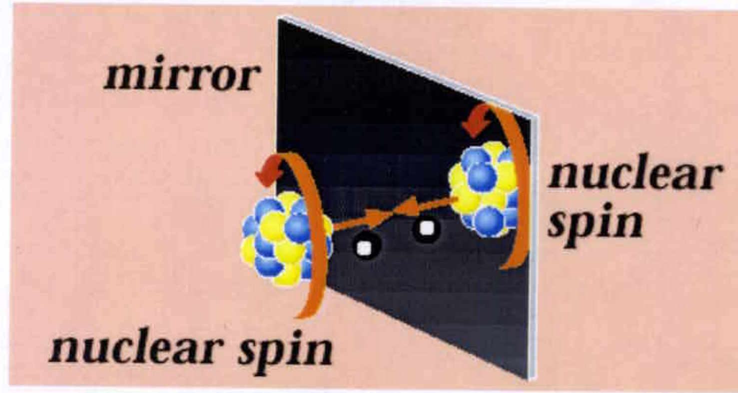
u	d	s	c	b	t
e	ν_e	μ	ν_μ	τ	ν_τ

- **Origin of Parity Violation** in Weak Interactions

(nature prefers lefthandedness)

$\Rightarrow$ details of β-decays

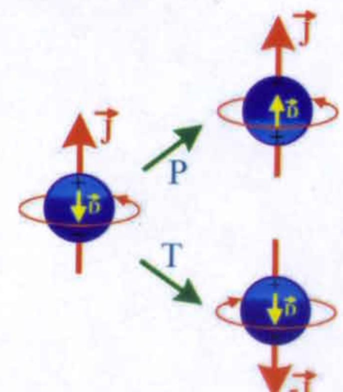
($\Rightarrow$ atomic parity violation)



- **Dominance of Matter over Antimatter** in Universe ?

CP - Violation, Time Reversal Symmetry

$\Rightarrow$ permanent electric dipole moments ?



What to do in view of the present situation with muon g-2

- **There are several 3 σ anomalies:**
  - a_μ
  - $\sin^2\Theta_w(M_Z)$ — $A_{FB}^{l^+l^-}$ and A_{FB} versus $A_{FB}^{b\bar{b}}$ gives **3.6σ**
  - m_W — direct e^+e^- & $p\bar{p}$ versus NuTeV $\sin^2\Theta_W = 1 - \frac{m_W^2}{m_Z^2}$ gives **3.6σ**

1.6σ respectively 3σ deviation depending on theory!

- **Electroweak fits do not converge very well any more, only (sub) % probability !**

Note: Running of QED coupling constant has hadronic corrections related to hadronic corrections in g-2 α(s)

- **Consequences for Higgs Mass?**

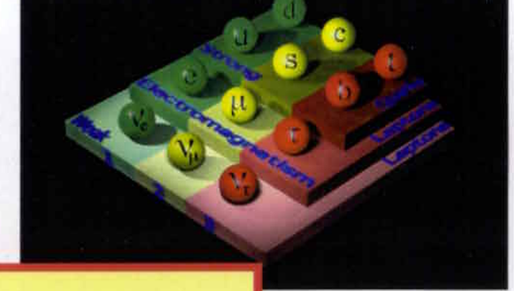
with e^+-e^- data

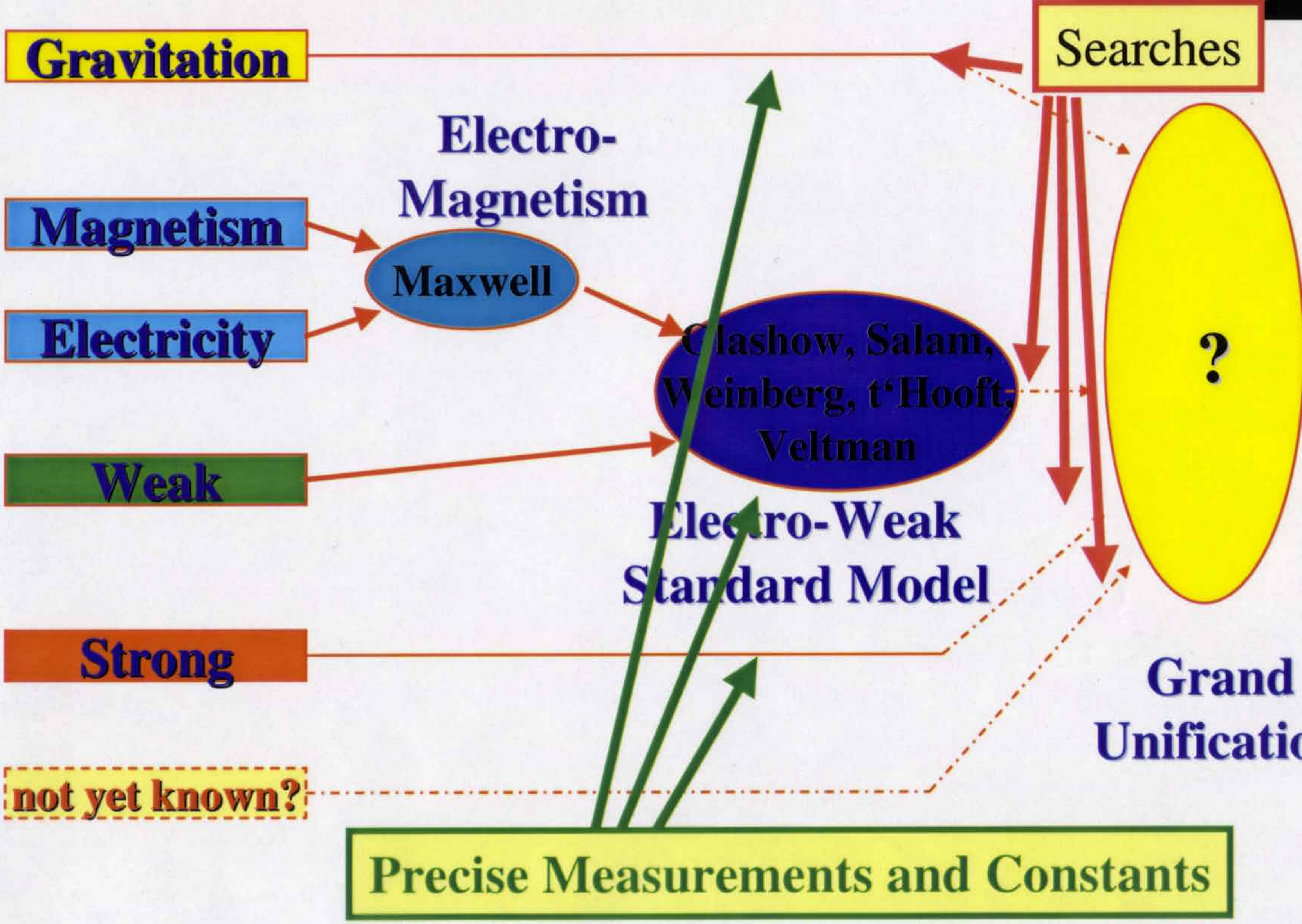
m_W= 80.451(33) GeV/ c^2 ⇒ $m_H \approx$ 38 GeV/c^2
SLAC A_{LR} ⇒ $m_H \approx$ 50 GeV/c^2 } (Marciano Oct. 2002)

lower by 16 % with τ data
lower by 32 % if all g-2 deviation assumed to be due to hadronic vac. pol.

direct search limits ⇒ m_H >110 GeV/c^2 (95%C.L.)

Standard Model
present input by Atomic Physics





Exclusive measurements

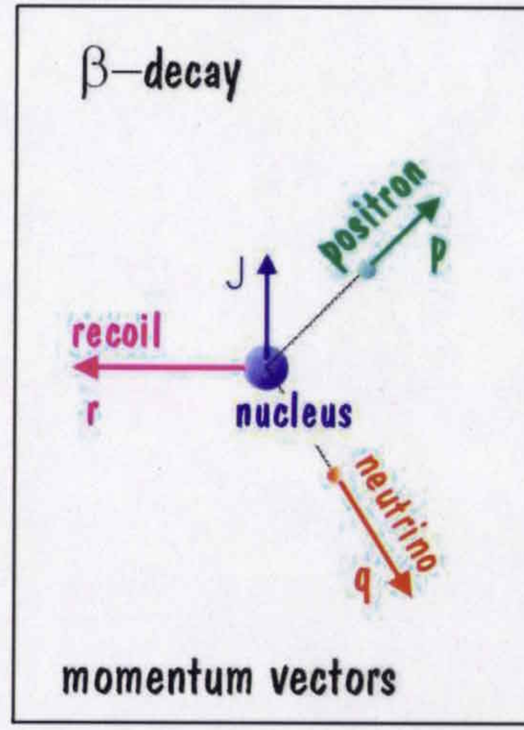
$$\frac{d^2W}{d\Omega_e d\Omega_\nu} \sim 1 + a\frac{\boldsymbol{p}\cdot\hat{\boldsymbol{q}}}{E} + b\Gamma\frac{m_e}{E}$$

$$+ \langle \boldsymbol{J} \rangle \cdot \left[A\frac{\boldsymbol{p}}{E} + B\,\hat{\boldsymbol{q}} + D\frac{\boldsymbol{p}\times\hat{\boldsymbol{q}}}{E} \right]$$

$$+ \langle \boldsymbol{\sigma} \rangle \cdot \left[G\frac{\boldsymbol{p}}{E} + Q\langle \boldsymbol{J} \rangle + R\langle \boldsymbol{J} \rangle \times \frac{\boldsymbol{p}}{E} \right]$$

integrate over all spin variables
only *a* and *b* remain

$$dW = 1 + a\beta_e \cos\theta_{e\nu}$$



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Some Weak Interaction Experiments

Experiments on β-Decays in Traps

β–ν correlations	**^{6}He, ^{14}O, ^{19}Ne, ^{35}Ar, ^{38m}K**	GANIL,ANL,LBNL, ISOLDE,TRIUMF, K
β– asymmetry	**^{19}Ne, ^{20}Na, ^{21}Na, ^{37}K, ^{82}Rb**	LBNL,TRIUMF, LANL, KVI
inclusive measurements	**^{6}He, ^{32}Ar**	ISOLDE/Seattle, Leuv GANIL

Experiments on Parity Violation in Traps

Atomic parity violation	**^{210}Fr, ^{211}Fr**	Stony Brook, JILA, INFN

a lot of activity ⇒ concentrate on your strength

Some Weak Interaction Experiments

Experiments on β-Decays in Traps

β–ν correlations	**^{6}He, ^{14}O, ^{19}Ne, ^{35}Ar, ^{38m}K**	GANIL … , IS… , KVI
β– asymmetry	**^{19}Ne, ^{20}Na, ^{21}Na, ^{37}…**	…NL, TRIUMF, LANL, KVI
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Exper… Parity Violation in Traps

… parity violation	**^{210}Fr, ^{211}Fr**	Stony Brook, JILA, INFN

a lot of activity ⇒ concentrate on your strength

Parity violation in Atoms @ GSI

- Atomic Parity Violation was essential in the verification of the STANDARD MODEL

- Lots of activities these days:
  - Fr isotopes
  - Cs isotopes
  - Ra^+ isotopes

  } effects of n-distributions

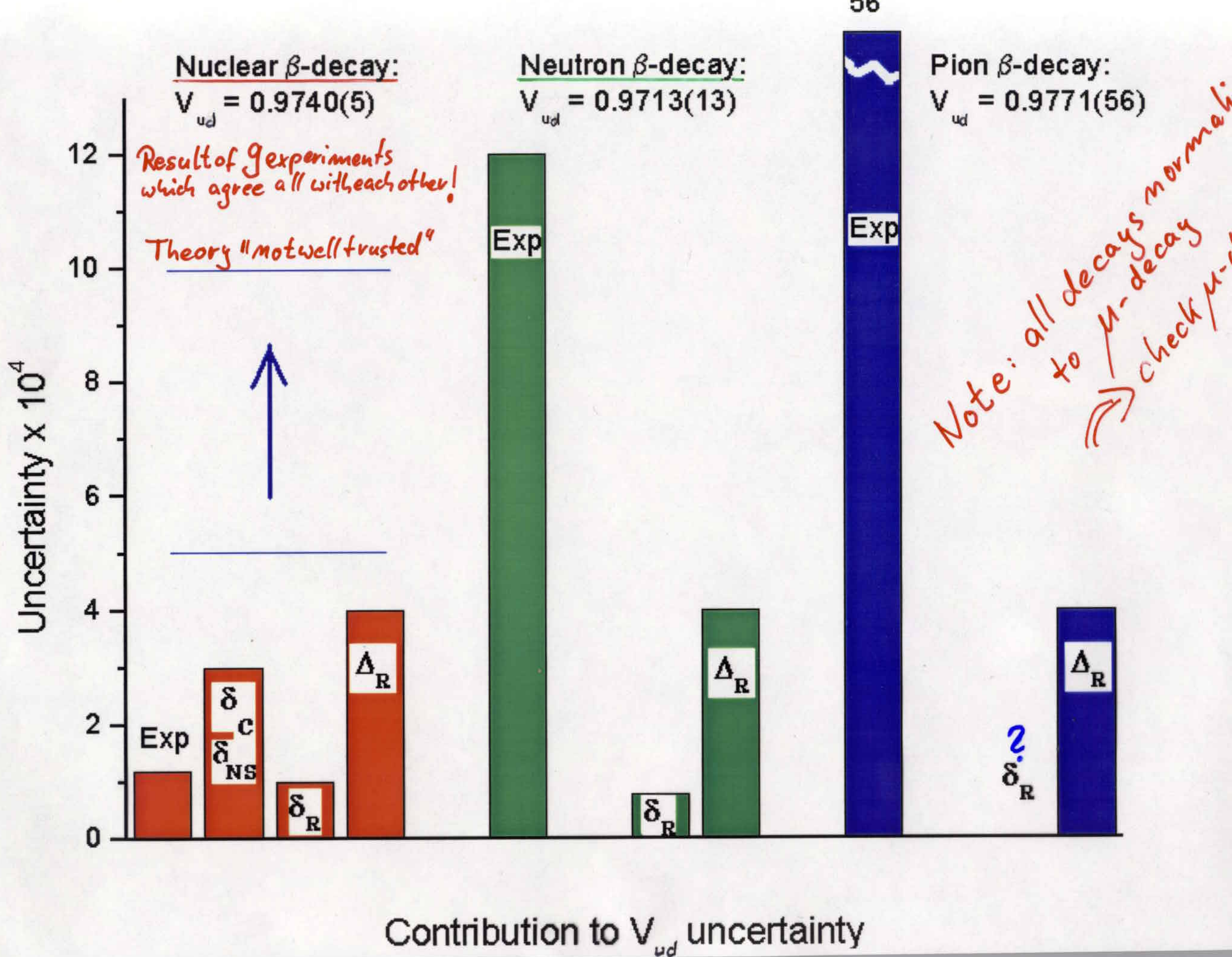
  (Nothing special for GSI)

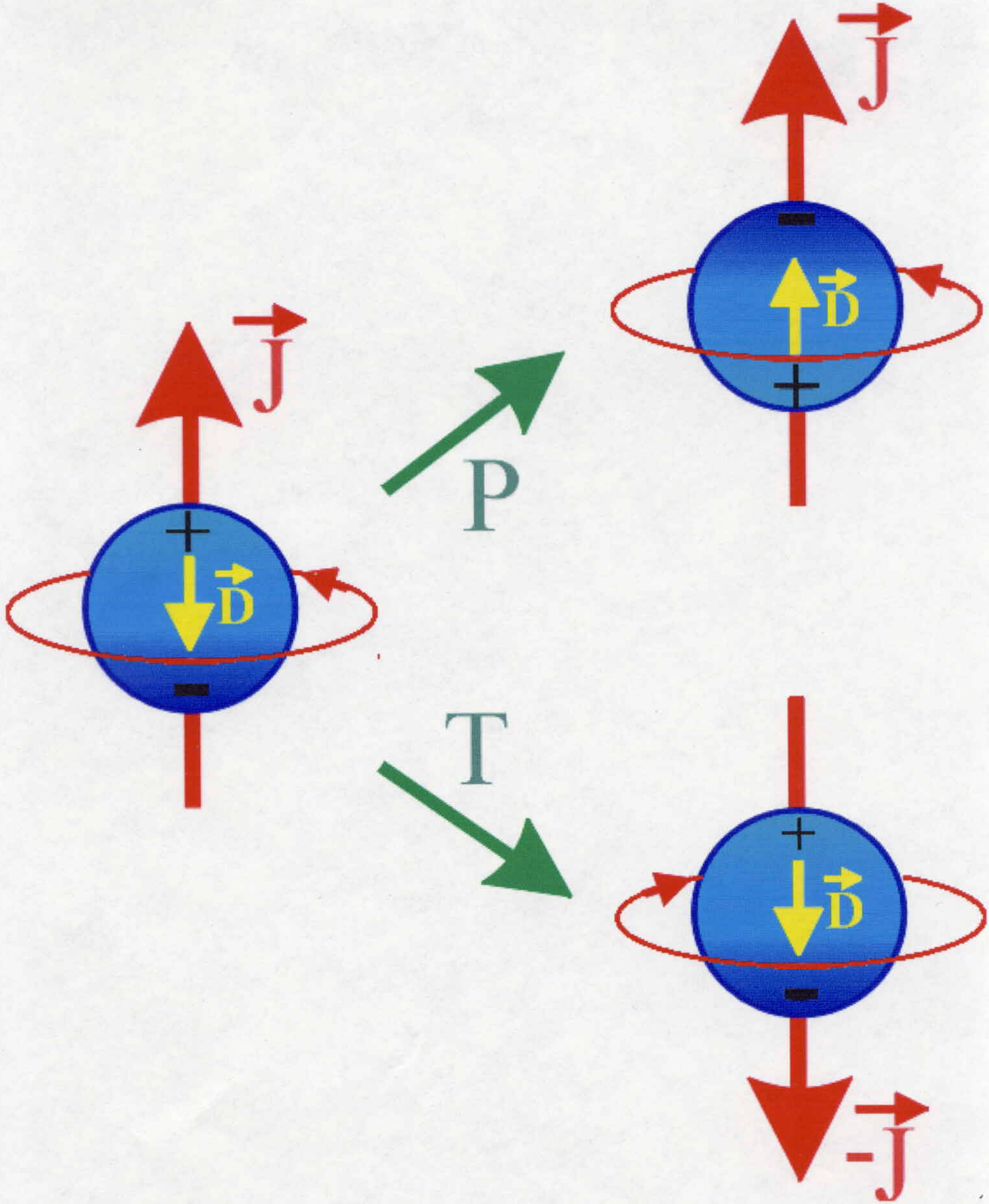
- At GSI one could
  - employ highly charged ions (simpler theory)
  - take advantage of high velocities, i.e. Doppler shift to excite
    - H-like
    - He-like
    - Li-like

    systems

- Low motivation from fundamental interaction point of view (at most leptoquark models)

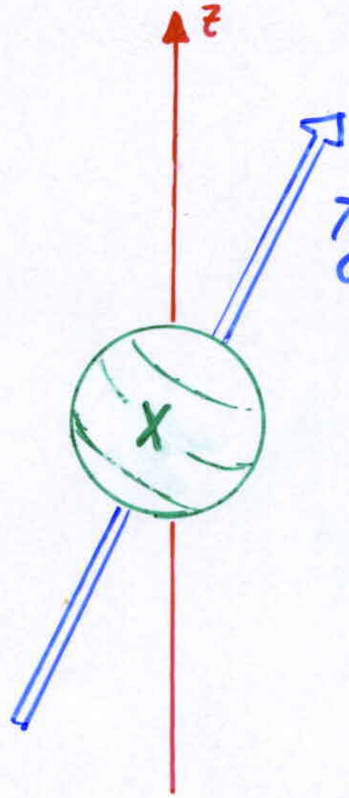
- Could be motivated from nuclear physics
  - anapole moments
  - n-distributions


Nuclear β-decay:
V_ud = 0.9740(5)
Neutron β-decay:
V_ud = 0.9713(13)
Pion β-decay:
V_ud = 0.9771(56)
56
Uncertainty x 10^4
0
2
4
6
8
10
12
Exp
δ_C
δ_NS
δ_R
Δ_R
Exp
δ_R
Δ_R
Exp
?
δ_R
Δ_R
Result of 9 experiments which agree all with each other!
Theory "not well trusted"
Note: all decays normali
to μ-decay
check μ-
Contribution to V_ud uncertainty



$\vec{J}$
$\vec{D}$
P
T
$\vec{J}$
$\vec{D}$
$\vec{D}$
$-\vec{J}$

Permanent Electric Dipole Moment (edm)



$\vec{J}$ is the only vecto[r] characterizing a non degenerate quantum system any additional vector would brin[g] in additional quantum numbe[r] i.e. degeneracy.

- magnetic moment

$$\vec{\mu} = g \cdot \mu_x \cdot \vec{J} \; ; \quad \mu_x = \frac{q\hbar}{2m_x}$$

- perm. electric dipole moment

$$\vec{d} = \eta \cdot c^{-1} \mu_x \cdot \vec{J}$$

by definition $\vec{d} = q\vec{r}_0$

- η contains all physics
- Non Standard Model Theory:

$$c^{-1} \mu_x \cdot J_z = \begin{cases} 9.7 \cdot 10^{-12} \; e \cdot cm & \text{electron} \\ 4.7 \cdot 10^{-14} \; e \cdot cm & \text{muon} \end{cases}$$

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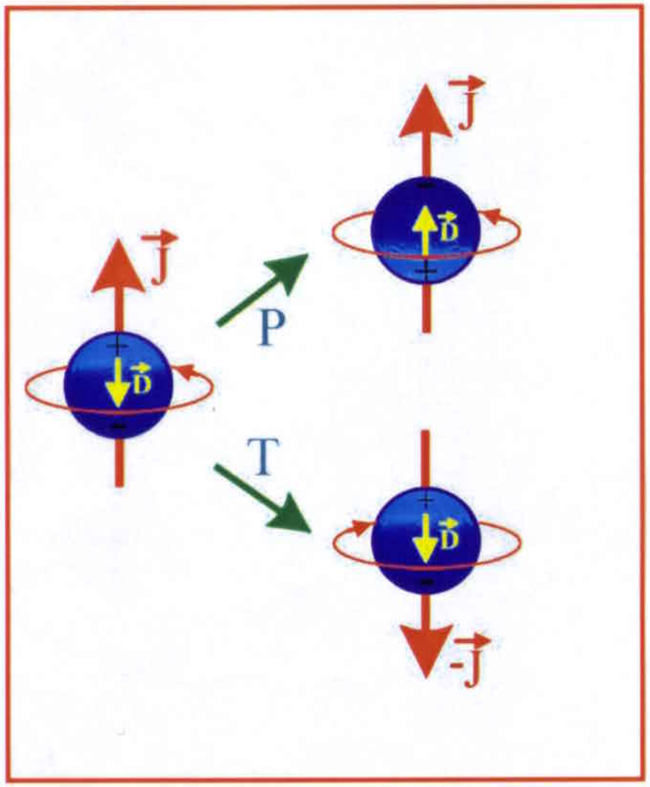
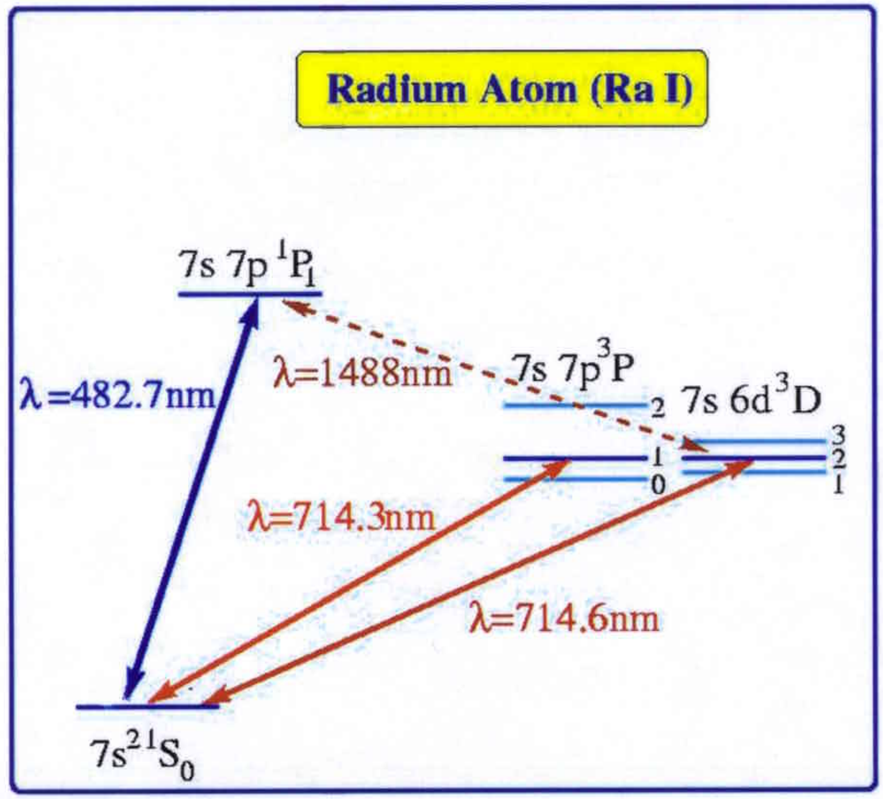
Radium Permanent Electric Dipole Moment



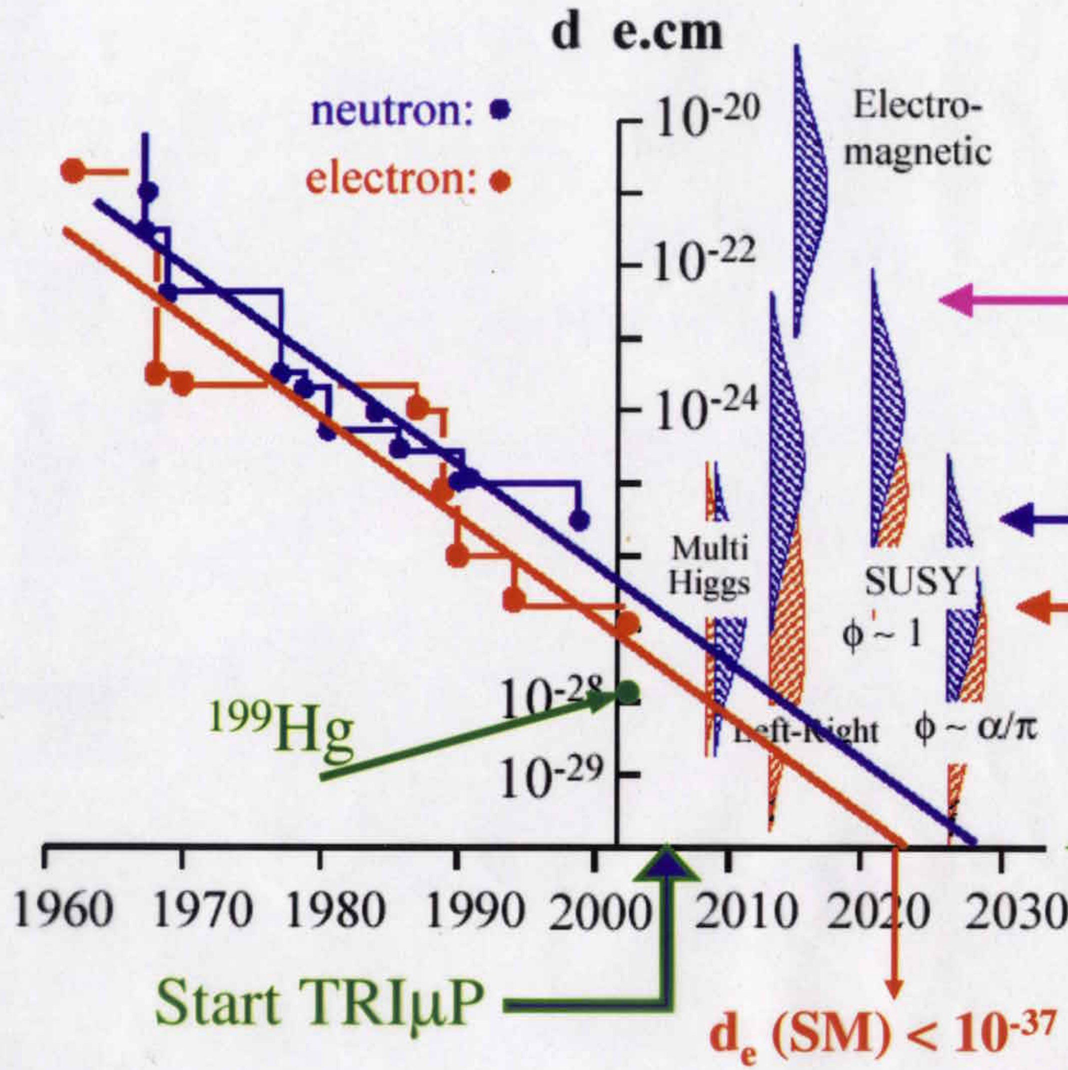


EDMs violate
- **P**arity
- **T**ime Reversal
- **CP** Symmetry

Advantage over "best" atom so far (^{199}Hg)
- close states of opposite parity
$\Rightarrow$ several **10 000 enhancement** possibl
- some nuclei strongly deformed
$\Rightarrow$ may give **nuclear enhancement**

EDM Now and in the Future

d(muon) < 7×10^{-19}



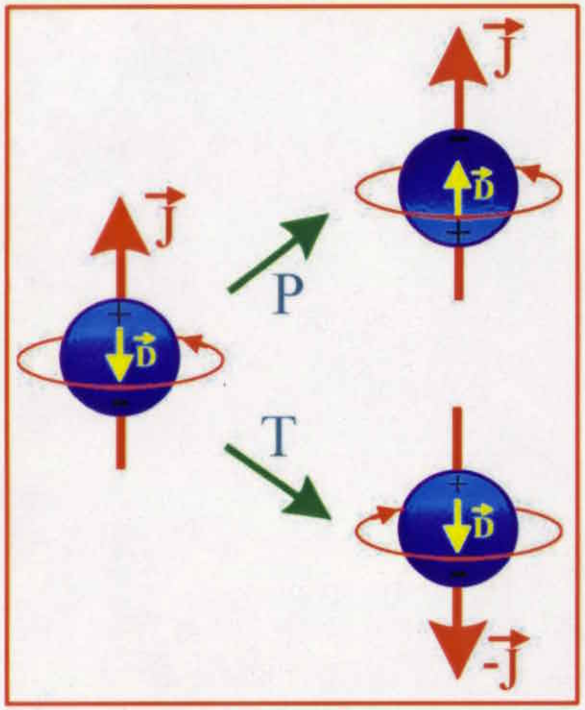
d(proton) < 6×10^{-23}

d(neutron) < 6×10^{-26}

d(electron) < 1.6×10^{-27}

Radium potential

Permanent Electric Dipole Moments



EDMs violate
- Parity
- Time Reversal
- CP Symmetry

S. Weinberg (1993):

" may be that the next exciting thing to come along will be the discovery of a neutron or atomic or electron electric dipole moment. These electric dipole moments ... seem to me to offer one of the most exciting possibilities for progress in particle physics."

R.L. Jaffe (2001)

"Electric dipole moments (EDM's) fascinate both theorists and experimenters. They probe CP violation, one of the most poorly understood aspects of the Standard Model. If all CP-violation is encoded in the CKM matrix, EDM's are too small to measure. For this reason EDM's are an excellent place to look for CP-violation beyond the Standard Model. The problem of baryogenesis in the early Universe continues to suggest that other sources of CP-violation are waiting to be discovered."

⇒ Just do it

Enhancement Effects for Permanent Electric Dipole Moments

- Any quantum object cannot have a permanent electric dipole moment unless there is P, T and CP violation.
- "Polar" objects like molecules (ammonia) or nuclei do not have a permanent electric dipole moment, despite listings in tables! These objects don't have such thing like a shape in a well defined energy state !!!!!
- A permanent electric dipole moment must be proportional to the spin
- Similar to atomic parity violation there is a **Z^3** enhancement
- There is an an enhancement due to induced dipole moments

$$D_A = \sum_{n'} \frac{< nl | -d_e(\beta - 1)\vec{\sigma}\cdot\vec{E} \,|\, n'(l+1) >< n'(l+1) \,|\, -e\vec{r} \,|\, nl >}{E_{nl} - E_{n'(l+1)}} + c.c.$$

- Some enhancement factors: Tl -585, Fr 1150, Ra 40000, YbF 10^6

Generic edm Experiment

Preparation of "pure" $\vec{J}$ state → Interaction with $\vec{E}$-field → Analysis of state

Polarization — Spin Rotation — Determination of Ensemble Spin Average

Interaction with $\vec{E}$-field

$$\vec{d} = \eta \cdot c^{-1} \cdot \mu_x \cdot \vec{J}$$

Precession frequency:

$$\vec{\omega}_e = \frac{\vec{d} \cdot \vec{E}}{\hbar} \cdot \frac{\vec{E} \times \vec{J}}{|\vec{E} \times \vec{J}|}$$

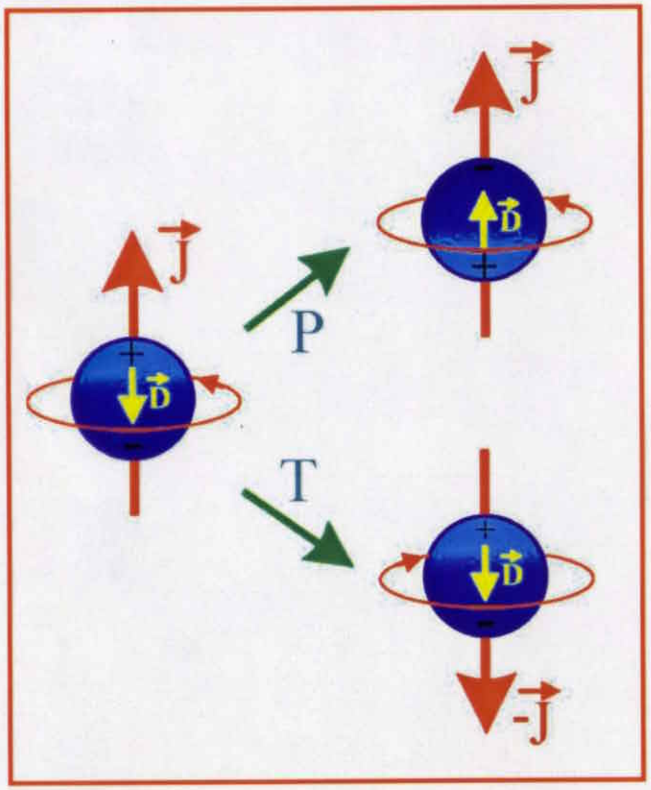
$\vec{E} \perp \vec{J}$; i.e. $\vec{E} \parallel J_z$

$$\boxed{\omega_e = \eta \cdot c^{-1} \cdot \mu_x \cdot E \cdot \frac{J_z}{\hbar}}$$

Example: $d = 10^{-24}$ ecm ; $E = 100 \frac{kV}{cm}$; $J = \frac{1}{2}$

$$\omega_e = 15.2 \text{ mHz}$$

Permanent Electric Dipole Moments



EDMs violate
- **P**arity
- **T**ime Reversal
- **CP** Symmetry

There can be only one vector in the system

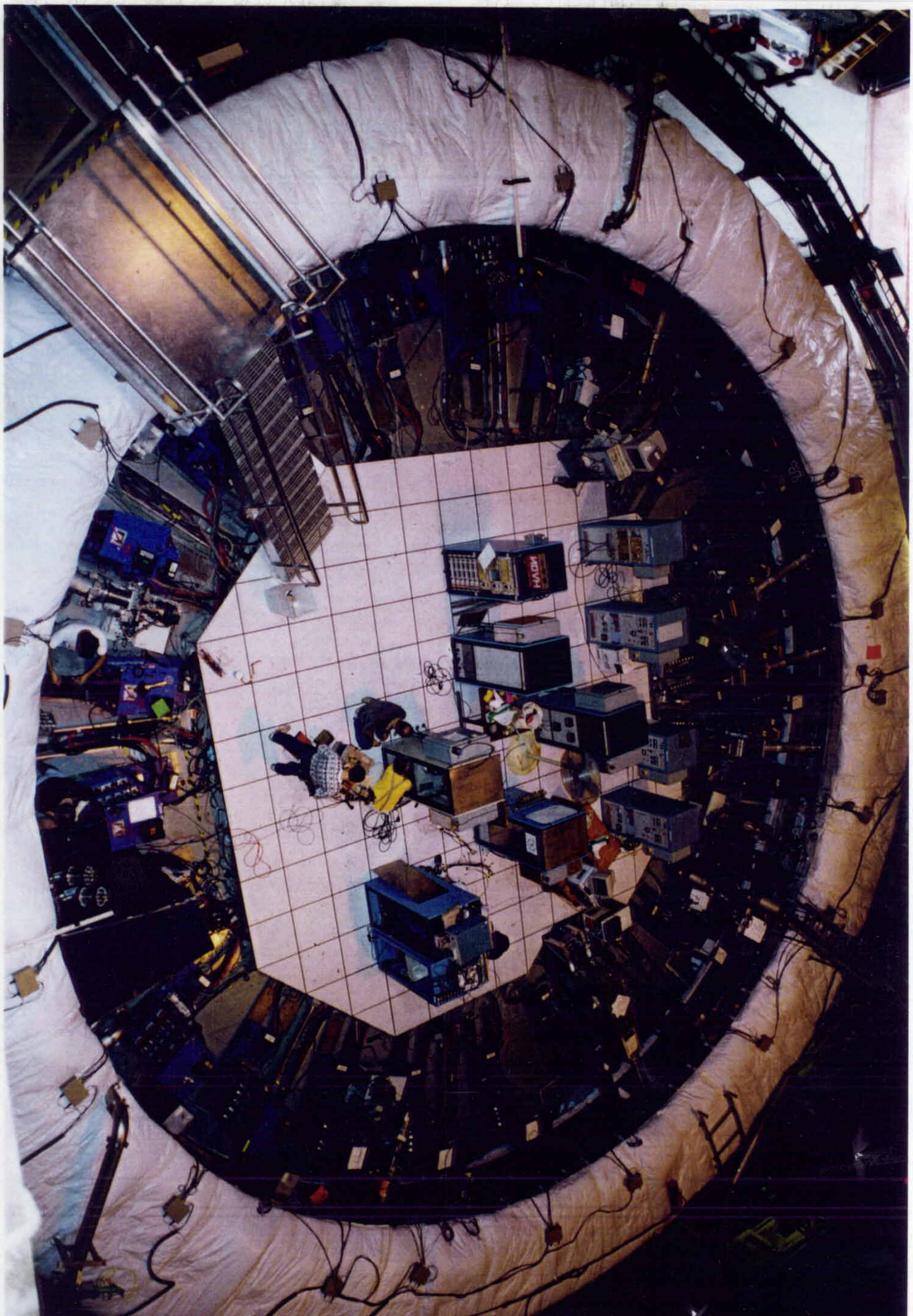
$$\Rightarrow \quad \vec{D} = \eta \bullet \mu_x \bullet c^{-1} \bullet \vec{J}$$

Spin precession in an Electric Field E

$$\Rightarrow \quad \vec{\omega} = \frac{\vec{D} \bullet \vec{E}}{\hbar} \frac{\vec{E} \times \vec{J}}{|\vec{E} \times \vec{J}|}$$

Sensitivity of spin precession experiments propostional to:

$$\frac{1}{\text{Polarization}^2 \bullet \text{efficiency} \bullet \sqrt{\text{number}} \bullet \text{tim}}$$



Spin Precession in Electromagnetic Field

$\vec{B}$ magnetic field $\vec{E}$ electric field $\vec{\beta} = \frac{\vec{v}}{c}$

a magnetic anomaly η electric dipole anomaly

q charge

M Mass

magnetic moment precession:

$$\vec{\omega}_m = \frac{q}{M}\left\{\left(a+\frac{1}{\gamma}\right)\vec{B} - a\frac{\gamma}{\gamma+1}\vec{\beta}(\vec{\beta}\cdot\vec{B}) + \left(a+\frac{1}{\gamma+1}\right)c\,\vec{\beta}\times\vec{E}\right\}$$

electric dipole moment precession:

$$\vec{\omega}_e = \frac{q}{M}\eta\left\{\vec{E} - \frac{\gamma c^{-1}}{\gamma+1}\vec{\beta}(\vec{\beta}\cdot\vec{E}) + c\,\vec{\beta}\times\vec{B}\right\}$$

cyclotron motion:

$$\vec{\omega}_c = \frac{q}{M}\left\{\frac{1}{\gamma}\vec{B} - \frac{\gamma c^{-1}}{\gamma-1}\vec{\beta}\times\vec{E}\right\}$$

with $\vec{\beta}\cdot\vec{B} = \vec{\beta}\cdot\vec{E} = 0$:

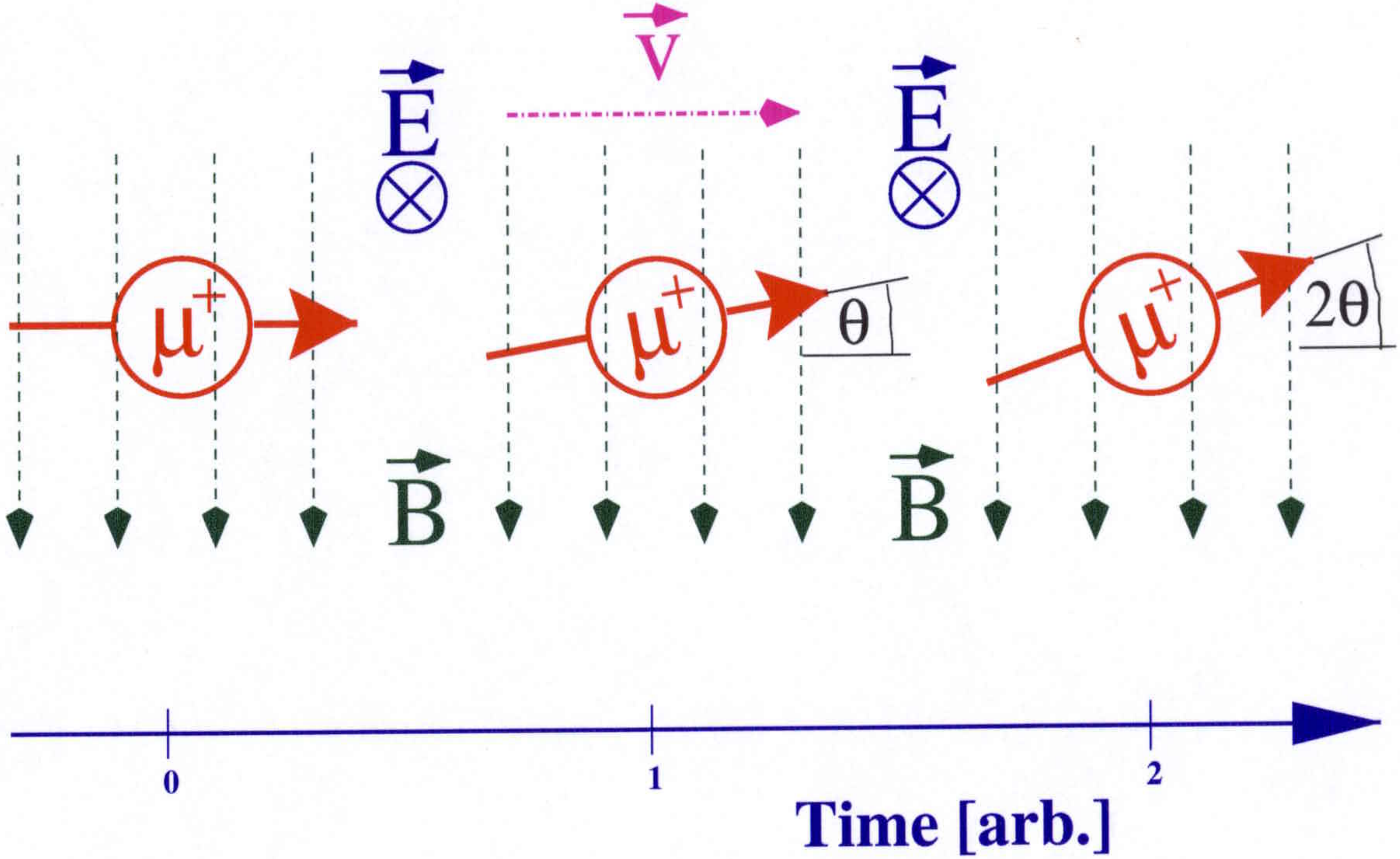
$$\vec{\omega} = \vec{\omega}_m + \vec{\omega}_e + \vec{\omega}_c = \frac{q}{M}\left\{\underbrace{a\vec{B} - c\left(a - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E}}_{\text{residual g-2 precession}} + \underbrace{\eta\left(\vec{E} + c\,\vec{\beta}\times \dots\right.}_{\text{edm precession}}$$

residual g-2 precession edm precession

$a = \frac{g-2}{\dots}$ for leptons ; $a = \frac{g_{eff}-2}{\dots} = \frac{\mu}{\mu_K}\cdot\frac{A}{Z\cdot J}\dots$

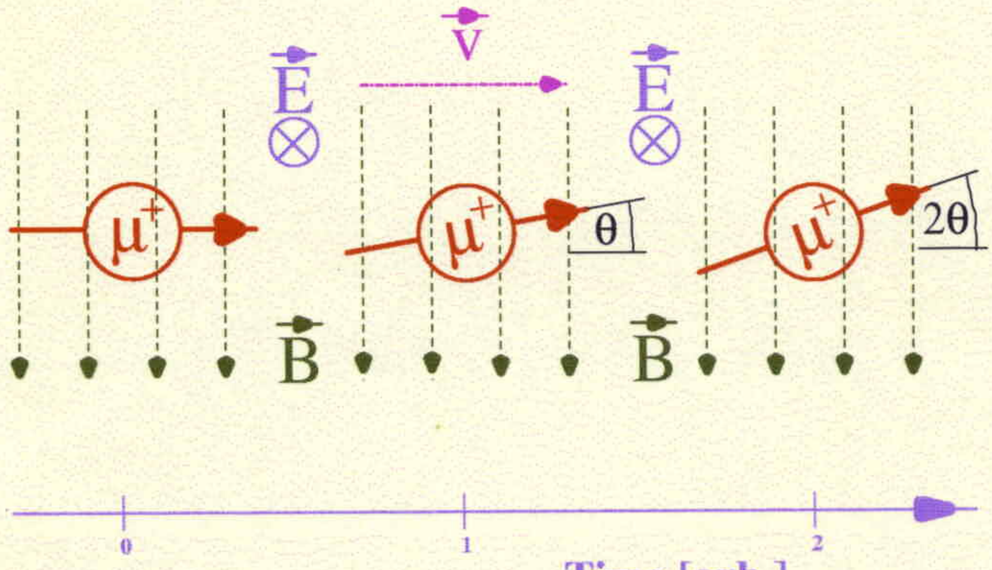
Some edm Experiments

	$\lvert d \rvert$ $[10^{-27}\ e\,cm]$	Method	E-Field $[\frac{kV}{cm}]$	Interaction [s]
e	1.8(1.2)(1.0)	^{205}Tl-beam	107	~ 0.01
μ	$< 1.05 \cdot 10^{9}$ (95% C.L.)	μ g-2 Experim.	$430 \cdot 10^{3}$	$\sim 64 \cdot 10^{-}$
τ	$< 3.1 \cdot 10^{11}$ (95% C.L.)	τ decay asymmetry	"atomic" field	$\sim 290 \cdot 10^{-1}$
p	$-3.7(6.3) \cdot 10^{4}$	Tl F-beam	29.5	~ 0.01
n	< 63 (90% C.L.)	stored neutrons, Ramsay technique	4.5	130

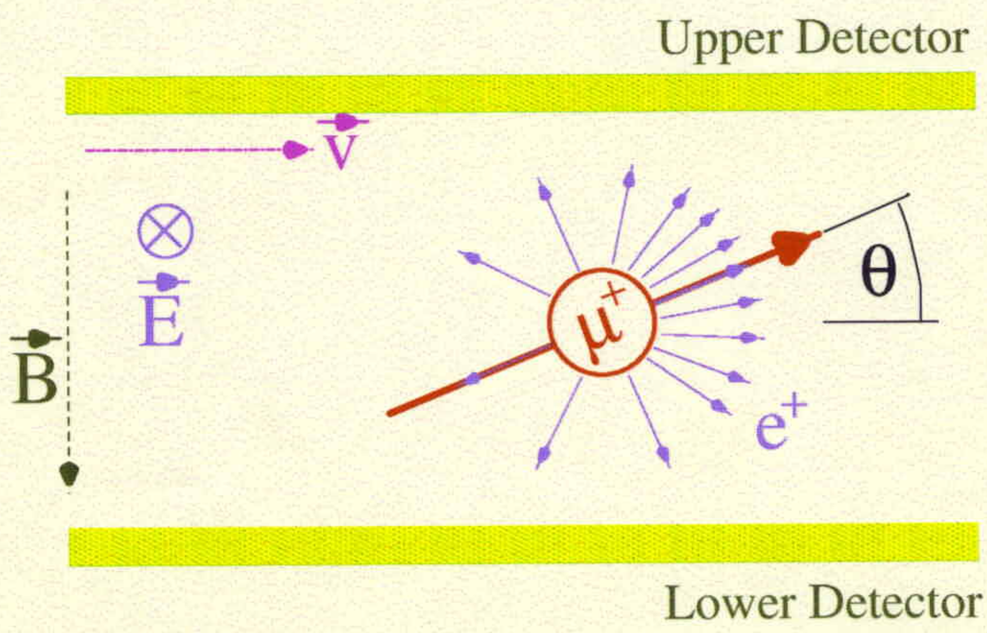


E
v
E
μ+
μ+
θ
μ+
2θ
B
B
0
1
2
Time [arb.]

EDM Experiments in Storage Rings



(a)



(b)

- Possible for muons and nuclei
- Sensitivity better 10^{-24} e cm

$$\vec{\omega} = \frac{q}{M}\Big\{ \underbrace{a\vec{B} - c\left(a - \frac{1}{\gamma^2-1}\right)\vec{\beta}\times\vec{E}}_{R_{g-2}} + \eta\left(\vec{E} + c\,\vec{\beta}\times\vec{B}\right)\Big\}$$

compensation of residual g-2 precession:

$$R_{g-2} = 0$$

$$\boxed{E = \frac{a\,v\,B}{1-(1+a)\left(\frac{v}{c}\right)^2}}$$

$\vec{E} \perp \vec{B}$

$\vec{E} \perp \vec{\beta}$

$\rightarrow \vec{E}$ radial

proposed muon edm experiment

$\gamma = 5 \rightarrow \frac{v}{c} = 0.98$; $a = \frac{\alpha}{2\pi} = 0.00116\ldots$; $B = 0.2$

$$E \cong 2\,\frac{MV}{m} = \frac{20\,kV}{cm}$$

$\Longrightarrow$ technically achievable E constrains possible a and β

Candidate Nuclei

	J	μ/μ_K	a	τ_{y}
$^{139}_{57}La$	$7/2$	$+2.783$	-0.0305	
$^{123}_{51}Sb$	$7/2$	$+2.550$	-0.1215	
$^{75}_{33}As$	$3/2$	$+1.4395$	0.0905	
$^{6}_{3}Li$	1	$+0.8220$	-0.1779	
$^{171}_{70}Yb$	$1/2$	$+0.49367$	0.2060	
$^{2}_{1}H$	1	$+0.8574$	0.1426	
$^{31}_{16}S$	$1/2$	± 0.4880	0.055	2.
$^{75}_{32}Ge$	$1/2$	$+0.510$	0.195	82.
$^{157}_{69}Tm$	$1/2$	$+0.476$	0.083	3.
$^{137}_{55}Cs$	$7/2$	$+2.8413$	0.0119	30.
^{223}Fr	$3/2$	$+1.17$	< 0.02	22

Possible Experiment @ GSI

J state preparation → Interaction with $\vec{E}$ field → Analysis of state

J state preparation

- polarized nuclei source
- optical pumping?
- cooling in ESR
- $\frac{v}{c} \approx 75\%$ (> 10%)
- $N_N \approx 10^5 \ldots 10^6 / \text{sec}$
- $\frac{\Delta p}{p} \leq 10^{-4}$

$\frac{\Delta p}{p} \sim 10^{-6}$ possible!

Interaction with $\vec{E}$ field

- special storage ring
- $r \approx 2\,m$
- $B \approx 1 \ldots 1.5\,T$
- Interaction time $\tau_i \lesssim 1\,\text{sec}$
- Spin rotation angle @ $d_N \approx 10^{-24}\,e\,cm$ $\vartheta_e \approx 2\,mrad$

Analysis of state

- scattering analyzing power

or

- β-asymmetry
  - counters in r
  - counters aft extraction

Sensitivity

$$d_N = \eta \cdot 5 \cdot 10^{-15} \, e\,cm$$

$$\curvearrowright \; d_N = 10^{-24} \, e\,cm \;\hat{=}\; \eta = 2 \cdot 10^{-10}$$

Error in η:

$$\sigma_\eta = \frac{1}{\gamma \cdot \beta \cdot P_{beam} \cdot \varepsilon_{detector} \cdot \mu_K \cdot B \cdot \sqrt{2 \cdot N_N} \cdot \tau}$$

$\beta = 0.5$; $\gamma = 1.15$

$\tau_i = 150 \, ms$

$P_{beam} \approx 0.5$

$\varepsilon_{detector} \approx 0.05$

$B = 1.5 \, T$

$\mu_K = 7.66 \, \frac{MHz}{T}$

$$\Rightarrow \sigma_\eta = \frac{2.9}{\sqrt{N_N}} \cdot 10^{-5}$$

$\Rightarrow$ need ~10^{10} nuclei to compete with neutron edm!

Conclusions

- Fundamental Interactions/Symmetries Research well motivated and important
- Various Possibilities exist with atomic physics methods at accelerators
- Experiments should be conducted at most suited accelerator world wide
- GSI has unique possibilities through
  - Highly charged heavy ions
  - High velocities
  - Combination of facilities (accelerator(s), storage rings, Lasers, cool beams..
- Take advantage of unique chances!