Electric Dipole Moment Goals and "New Physics"

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d_p with 10^{-29}e-cm sensitivity! Why is it important?

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d_p not "just" complementary to d_n

Outstanding Discovery Potential! $\rightarrow$ Baryogenesis!

(**why do we exist?**)

☐Potential sensitivity an order of magnitude **better** than d_n!

Probes New Physics(NP) at $(1\text{TeV}/\Lambda_{NP})^2 \tan\phi_{NP} \leq 10^{-7}$!

or for $\phi_{NP} \sim O(1) \rightarrow \Lambda_{NP} \sim$ 3000TeV! (**well beyond LHC**)

Paves the way for a **new generation** of storage ring experiments $d_p \rightarrow d_D$, d(^{3}He), d(radioactive nuclei), d_μ

Baryogenesis

- **1928 The Dirac Equation**

  QM+Special Rel.+Spin+EM Gauge Invariance

  $$i(\partial_\mu - ieA_\mu(x))\gamma^\mu\psi(x) = m_e\psi(x)$$ First Order

  Mag. Moment: $\mu = g_e Qe/2m_e s$ $g_e = 2$!

  Great Success-Cornerstone of Modern Physics

Later realized→AntiMatter→positron!

Why is the Universe Matter-Antimatter Asymmetric?

(1964-CP Violation Discovered-Not Strong Enough)

"New Physics" Source of CP Violation Needed!

Baryogenesis & New Physics CP Violation

Examples of New Physics Models with potentially large CP Violation: Supersymmetry, Multi-Higgs, L-R Models, 4th Generation, Extra Dimensions…

- Generic Manifestation - **Electric Dipole Moments**

What is the "New Physics"?

Look for EDMs!

No Standard Model Background (too small)

1947 Small Anomalous Atomic Fine Structure Effects

We could add extra terms to the Dirac Equation

$$e/4m_e a_e F_{\mu\nu}(x)\sigma^{\mu\nu}\psi(x) + i/2 d_e \gamma_5 F_{\mu\nu}(x)\sigma^{\mu\nu}\psi(x)$$

Anomalous Mag. Mom.	Electric Dipole Mom.
$g_e=2(1+a_e)$	(Violates P&T(CP)
Electron $g_e=2.002$	Not Observed
Proton $g_p=5.59$	$\|d_e\|<2\times10^{-27}$e-cm
	But It Must Exist!

1948 Schwinger Calculates: $a_e=\alpha/2\pi\approx$0.00116

Agreed with measurement of Kusch & Foley!

Great Success of QED -Quantum Field Theory

General Formalism (Spin1/2 Form Factors)

$$\langle f(p')|J_\mu^{em}|f(p)\rangle = \bar{u}_f(p')\Gamma_\mu u_f(p)$$

$$\Gamma_\mu = F_1(q^2)\gamma_\mu + iF_2(q^2)\sigma_{\mu\nu}q^\nu - F_3(q^2)\gamma_5\sigma_{\mu\nu}q^\nu \ \ldots$$

$F_1(0)=Q_f e$ electric charge

$F_2(0)=a_f Q_f e/2m_f$ anom. mag. mom.

$F_3(0)=d_f Q_f$ el. dipole mom.

Effective Dim. 5 Dipole Operators

$$H_{dipole}=-1/2[F_2\ \bar{f}(x)\sigma_{\mu\nu}f(x)+iF_3\ \bar{f}(x)\sigma_{\mu\nu}\gamma_5 f(x)]F^{\mu\nu}(x)$$

F_2&F_3 Real, Finite & Calculable in Ren. QFT

Complex Formalism: $F_D=F_2+iF_3$

$$H_{dipole}=-1/2[F_D\ \bar{f}_L\sigma_{\mu\nu}f_R+F_D^*\ \bar{f}_R\sigma_{\mu\nu}f_L]F^{\mu\nu}$$

$F_D=|F_D|e^{i\phi}$ (Relative to m_f)

$|F_D|=(F_2^2+F_3^2)^{1/2}$, $\tan\phi=F_3/F_2$

$\tan\phi$= Relative Degree of CP Violation

egs. $|\tan\phi_e|^{SM}\approx 10^{-24}$ $|\tan\phi_n|^{SM}\approx 10^{-20}$

Anomalous Magnetic Dipole Moments

fermion	a_f^{exp}	$\lvert d_f(e/2m_f)^{exp}\rvert$
e	0.00115965218073(28)	$<1\times10^{-16}$
μ	0.00116592089(63)	$<3\times10^{-6}$
p	1.792158142(28)	$<3\times10^{-12}$ (new d_{Hg})
n	-1.9130427(5)	$<1\times10^{-13}$

"New Physics" expected to scale as $(m_f/\Lambda)^2$

$(m_\mu/m_e)^2\approx43000$ Muon only a_f sensitive to high $\Lambda\sim2$TeV!

All d_f sensitive to "New Physics" if $\tan\phi^{NP}$ not too small

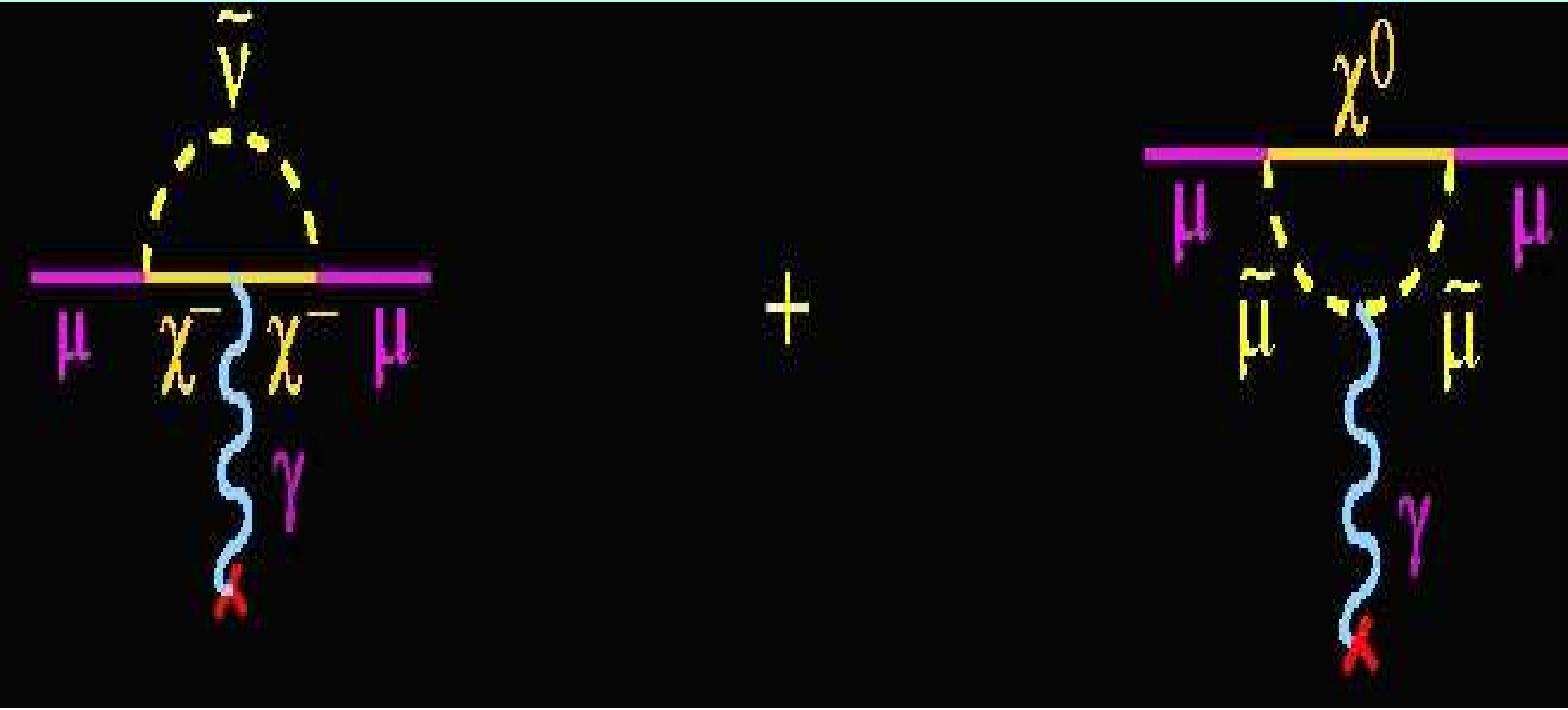
Nucleon edms Isovector or isoscalar? Mixed?

Both d_n and d_p need to be measured!

“New Physics” Effects

SUSY 1 loop a_μ Corrections

(Most Likely Scenario)



- <u>SUSY Loops are like EW, but depend on:</u>

- 2 spin 1/2 χ- (charginos)
- 4 spin 1/2 χ^0 (neutralinos) including dark matter!
- spin 0 sneutrinos and sleptons with mixing

Enhancement $\tan\beta = \langle\phi_2\rangle / \langle\phi_1\rangle \sim 3\text{-}40$!

- **Potentially large CP Violating Phases**

$\Delta a_\mu = a_\mu^{exp} - a_\mu^{SM} = 255(63)(49)\times10^{-11}$ **(3.2σ!)**

- New Physics? Nearly 2xStandard Model EW!

  Most Natural Explanation: **SUSY Loops**

Generic 1 loop SUSY Conribution:

$\mathbf{a_\mu^{SUSY} = (sgn\mu)130\times10^{-11}(100GeV/m_{susy})^2 tan\beta}$

$\tan\beta \approx 3\text{-}40$, $\mathbf{m_{susy} \approx 100\text{-}500GeV}$ Natural Explanation

Other Explanations: Hadronic? $\tau \to \pi^- \pi^0 \nu_\tau$ +isospin data

($\Delta a_\mu = \sim 157(63)(52)\times10^{-11}$ (2σ))

Other New Physics ≤ 2TeV

eg Extra Dimensions

If SUSY is responsible for g_μ-2 **Happy Days**

Implications: sgnμ>0 (dark matter searches easier)

SUSY at LHC very likely

edms, $\mu \rightarrow e\gamma$, … Good Bets

All chiral changing amplitudes L⇔R

Enhanced by tanβ ~ 3-40 factor

But, why haven't we seen edms if susy is correct?

Electric Dipole Moments: $d_e, d_n, d_p, d_\mu, d_{Hg}$(new)

Many d_n searches, starting with pioneering exp. Purcell & Ramsey

Recent improvement in Atomic edn exps.

- Griffith, Swallows, Loftus, Romalis, Heckel & Fortson PRL102, 101601 (2009)
- **Some Implications of $|d_{Hg}| < 3.1 \times 10^{-29}$ e-cm**

d_p(e-cm)$< 7.9 \times 10^{-25}$ Best

d_n(e-cm)$< 5.8 \times 10^{-26}$ (Direct $d_n < 2.9 \times 10^{-26}$ Best)

d_e(e-cm)$< 3 \times 10^{-27}$ (Tl: $d_e < 1.6 \times 10^{-27}$ Best)

Further factor 3-5 Improvement Expected!

Future Expectations

- $d_n \rightarrow 10^{-27}$-10^{-28}e-cm Spallation Neutron Sources
- **$d_p \rightarrow 10^{-28}$-10^{-29}e-cm Storage Ring Proposal (BNL)**
- $d_D \rightarrow 10^{-29}$e-cm Storage Ring Proposal
- $d_e \rightarrow 10^{-30}$e-cm or better
- $d_\mu \rightarrow 10^{-24}$e-cm Storage Ring Proposal

If SUSY is responsible for Δa_μ deviation, then a susy loop induced observable edm may be right around the corner!

Source of CP Violation in Baryogenesis?

If the same "New Physics" (Λ_{NP}=100-1000GeV) responsible for Δa_μ is also giving edms, we expect (scaling with m_f):

$|d_\mu^{NP}| \sim 3\times10^{-22}\tan\phi_\mu^{NP}$ e-cm

$|d_e^{NP}| \sim 2\times10^{-24}\tan\phi_e^{NP}$ e-cm

$|d_n^{NP}| \sim 10^{-22}\tan\phi_n^{NP}$ e-cm

$|d_p^{NP}| \sim 10^{-22}\tan\phi_p^{NP}$ e-cm

<u>Future Experiments will have sensitivity:</u>

$\phi_\mu^{NP} \sim 10^{-2}\text{-}10^{-3}$

$\mathbf{\phi_e^{NP} \sim \phi_n^{NP} \sim 10^{-6}}$

$\mathbf{\phi_p^{NP} \sim 10^{-7}!}$

d_p & d_n Relationship

Constituent Quark Model: $d_n=4/3d_d-1/3d_u$

$d_p=4/3d_u-1/3d_d$

Roughly $1/4<|d_p/d_n|<4$ Similar Magnitudes

Isovector $(d_p-d_n)/2$ or Isoscalar $(d_p+d_n)/2$?

Need both d_n & $d_p \rightarrow d_d$ & d_u (Relationship?)

$\bar{\theta}_{QCD}$ leading effect isovector (χPT)

$d_n=-d_p \sim 3.6\text{x}10^{-16}\ \bar{\theta}_{QCD}$e-cm

Currently: $d_n \rightarrow \bar{\theta}_{QCD} < 10^{-10}$! Future: 10^{-12}

d_p at 10^{-29}e-cm explores $\bar{\theta}_{QCD} < 10^{-13}$

If a non-zero d_n is discovered, the first thing we want to do is know d_p

Opposite sign? Isovector, $\bar{\theta}_{QCD}$ Interpretation

Same Sign? $\bar{\theta}_{QCD}$ Unlikely

More Likely: strangeness, gluonic, susy…

Both d_n & d_p needed!

Physics Reach of $d_p \sim 10^{-29}$ e-cm

$$d_p \sim 0.01 (m_p/\Lambda_{NP})^2 \tan\phi^{NP} e/2m_p$$

$$\mathbf{\sim 10^{-22} (1TeV/\Lambda_{NP})^2 \tan\phi^{NP} e\text{-}cm}$$

If ϕ^{NP} is of O(1), Λ_{NP}~<u>3000TeV</u> Probed!

If Λ_{NP}~O(1TeV), ϕ_{NP}~10^{-7} Probed!

<u>Unique Capabilities!</u>

Conclusion

1. Measurements of d_n & d_p with similar sensitivity essential to unfold underlying physics. Explain Baryogenesis
2. d_p has potential to do (10x) better than d_n
3. d_p at 10^{-29}e-cm must do exp. if possible.
   Explores physics up to scales O(3000TeV) for ϕ^{NP}~O(1) i.e. beyond LHC or ϕ^{NP}~10^{-7} at LHC discovery scales!
4. Sets stage for $d_D=d_n+d_p+$d(2 body), d(^{3}He)…