Neutron Physics at the Precision Frontier

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Lecture 1: on the symmetries of the Standard Model (SM) and the role β-decay played in their elucidation

Lecture 2: on β-decay and precision tests of the SM at the quantum level

Lecture 3: on difficulties with the SM and how neutron observables open windows to their resolution

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The Standard Model as a Low-Energy, Effective Theory

There is much theoretical "evidence" that the Standard Model is incomplete — *it leaves many questions unanswered.* Here are a few.

- Where is gravity? [It does not include it by design.]
- What are dark matter, dark energy?
- Why are there 3 generations? What explains the observed pattern of fermion masses and mixings?
- Why is the weak mass scale $\mathcal{O}(100\,\mathrm{GeV})$?

  [The Planck scale is $M_P = (G_N)^{-1/2} \approx 10^{19}$ GeV – why this "hierarchy"?]
- Why is neutron electric dipole moment so small?

  [QCD has its own source of CP violation – but it doesn't operate! Why?]
- What makes the baryon asymmetry of the Universe its observed value?

Most notably, the Standard Model only explains 5% of the known Universe.

There is much observational evidence for dark matter.

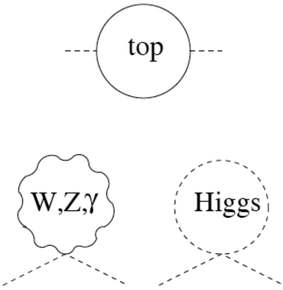
[Clowe et al., astro-ph/0608407]

The Trouble with Scalars...

The Standard Model is theoretically consistent to arbitrarily high energy scales. However, its incompleteness makes us think that new physics – i.e., physics not included in the SM – must enter at some energy scale Λ.

Theories with fundamental scalars (the Higgs) are particularly sensitive to the value of Λ. Let's look at the quantum corrections to the Higgs mass M_H.

$$V_{\rm Higgs} = -\mu^2 \phi^\dagger \phi + \frac{\lambda}{4!}(\phi^\dagger \phi)^2$$



[Schmaltz, hep-ph/0210415]

The λ term, e.g., yields

$$\delta\mu^2 \propto \lambda \int^\Lambda d^4k \frac{1}{k^2 - M_H^2} \sim +\lambda\Lambda^2$$

thus $\Longrightarrow M_H^2 = \mu^2 - \lambda c \Lambda^2$

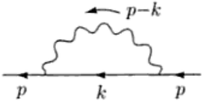
For perturbation theory to make sense λ cannot be too large; this limits M_H to few $\times$ 100 GeV. [Dicus, Mathur, Phys. Rev. D7, 3111 (1973); Lee, Quigg, Thacker, Phys. Rev. D16, 1519 (1977)]

For $\Lambda \sim M_{GUT}$ the required tuning of μ is to 1 part in 10^{26}!!

There is no Fine Tuning in QED

The fine tuning we have seen is *special* to the Higgs sector of the SM.
Such fine tuning appears *unnatural*. [K. Wilson, see Susskind, Phys Rev D20, 2619 (1979)]
These effects do not appear in QED because of its symmetries.
Let's see how this works.

The leading radiative correction to the electron mass is



[Peskin and Schroeder]

Naively $\delta M_e \propto \int^{\Lambda} \frac{d^4k}{\not{k} k^2} \propto \Lambda$

However $\mathcal{L}_{\rm QED}$ has a chiral symmetry if $M_e^{\rm bare} = 0$.

δM_e must then vanish if $M_e^{\rm bare} = 0$.

By dimensional analysis:

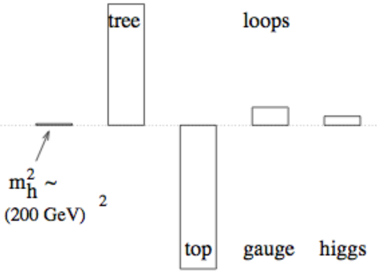
$\delta M_e \propto M_e \log\left(\frac{\Lambda}{M_e}\right)$

Thus chiral symmetry "protects" the electron mass from large radiative corrections. Similarly gauge symmetry protects the photon mass.

Can some new symmetry resolve the fine-tuning problem we have found? At what energy scale should it appear?

"Naturalness" Suggests New Physics at a TeV...

Once again we suppose Standard Model is an effective theory, valid for scales $E \leq \Lambda$. What is Λ? At one-loop level, we have found large corrections to the tree-level Higgs mass μ.

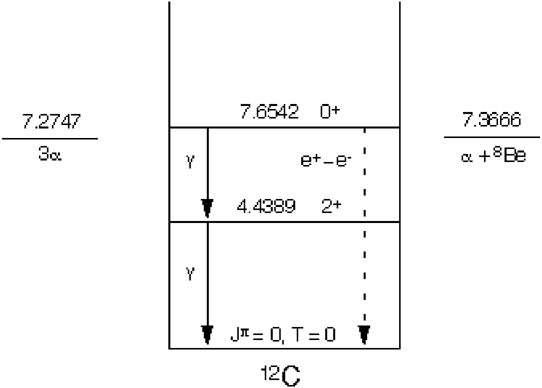


[Schmaltz, hep-ph/0210415]

N.B. fermion and boson loop contributions have *opposite sign*.
As Λ is reduced from the Planck (or GUT) scale, the fine tuning required to yield the Higgs mass required by perturbative arguments mitigates.
At $\Lambda = 10$ TeV, μ must be tuned to merely one part in 100.
Thus we have a theoretical argument for new physics at $\Lambda \sim \mathcal{O}(1\,TeV)$

New physics can make the cancellations natural. Thus we stabilize the numerical value of M_H under radiative corrections, even if we cannot answer why $M_H \ll M_P$.

"Fine-Tuning" does exist in Nature



[Hoyle, 1953; Dunbar, Pixley, Wenzel, Whaling, 1953]

Resolving the Hierarchy Problem with New Physics

N.B. we focus on solutions which make the weak scale "technically natural".

- **Supersymmetry**
  makes a one-to-one correspondence between the boson and fermion content of the theory, and the quadratic divergences cancel exactly to all orders in perturbation theory.
- **Technicolor**
  makes the Higgs a composite built of heavy "technifermions", aping chiral dynamics in QCD.
- **A Strongly Coupled Higgs Sector**
  makes the perturbative bounds on the Higgs mass moot.
- **"Extra" Dimensions**
  models let gravity see spacetime dimensions which other particles cannot, explaining why gravity is weak at the TeV scale.
- **Little Higgs**
  models give new gauge bosons couplings arranged so that the quadratic divergences cancel to one loop order.

All predict new phenomena at the TeV scale.

Theoretical Arguments for Supersymmetry

That supersymmetry should eventually appear as $\Lambda \to M_P$ is a very appealing idea.

We distinguish boson and fermion field operators on the basis of their commutation relations. A generator of supersymmetry, which changes a boson to a fermion or vice versa, is thus a spacetime operator.

This was once thought impossible, but a generator of supersymmetry is itself a fermionic operator (of spin $1/2$) and evades the conditions of the proof!

[Coleman and Mandula, Phys Rev D159, 1251 (1967)]

If supersymmetry is imposed as a local gauge symmetry general relativity (gravity) emerges automatically!

Thus a theory of everything is most likely to be supersymmetric, as superstring theory is.

But whether supersymmetry will manifest itself in phenomena at the TeV scale is an open question.

On the eve of the LHC era weak-scale supersymmetry is the least problematic of our suggested resolutions to the hierarchy problem.

Indirect Support for Weak-Scale Supersymmetry

The Baryon Asymmetry of the Universe (BAU):

We live in a known Universe of matter.

Confronting the observed abundance of the light elements (^{2}H, ^{4}He, ^{7}Li) with big-bang nucleosynthesis yields $\eta = \frac{n_{\rm baryon}}{n_{\rm photon}} = (5.21 \pm 0.5) \times 10^{-10}$ (95%CL)

This reflects the excess of baryons over anti-baryons when the Universe was a $\sim$ 100 seconds old.

Why else do we think this?

- The composition of cosmic rays, note $\overline{p}/p \sim 10^{-4}$.
- No evidence for diffuse γ's from $p\overline{p}$ annihilation....

The particle physics of the early universe can explain this asymmetry if B, C, and CP violation exists in a non-equilibrium environment. [Sakharov, JETP Lett 1967]

Estimates of the baryon excess in the Standard Model are much too small, $\eta < 10^{-26}$!! [Farrar and Shaposhnikov, PRL 70, 2833 (1993); Gavela et al., Mod. Phys. Lett. A9, 795 (1994); Huet and Sather, PRD51, 379 (1995).]

SUSY models are generically rich in new sources of CP violation, and can produce a BAU in the electoweak phase transition much more efficiently than in the SM....

Indirect Support for Weak-Scale Supersymmetry

Dark Matter:

Much of the matter in the Universe is of an unknown form.

It has been long thought that a dark-matter candidate, if produced as a thermal relic, ought be a Weakly Interacting Massive Particle or WIMP.

[Jungman, Kamionkowski, Griest, Phys. Rept. 1996]

In SUSY models the WIMP is a *neutralino*: it carries neither electric nor color charge, and it can be the lightest supersymmetric particle.

If we impose an additional discrete symmetry, *R*-parity, it is also stable.

A single species of WIMP with mass $M_{\rm WIMP} \sim \mathcal{O}(100)$ GeV can reproduce the relic density!

Such candidates can be established in scattering expts through the identification of anomalous nuclear recoils....

However, it is possible to reproduce the relic density with lighter particles with stronger (weak but not weak scale!) mutual interactions. [Feng and Kumar, PRL 2008]

Neither the BAU nor dark matter need be generated by weak scale physics....

The Minimally Supersymmetric Standard Model

To build a phenomenologically viable theory we must break supersymmetry.
In doing so we must not generate new quadratic divergences!
This is *possible*, and in this event we say supersymmetry is broken "softly".
Let us build a gauge field theory with global supersymmetry. To realize the Minimally Supersymmetric Standard Model (MSSM), we

- choose the SM gauge group: $\mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$
- augment the matter content of the SM, so that for each fermion of a given chirality there is a new scalar particle. We call the scalar and its left-chiral partner a "superfield". Consistency requires *two* superfield Higgs doublets.
- choose the superpotential which describes the superfield interactions and forbid baryon and lepton number violation by R-parity.
- include all soft supersymmetry breaking terms explicitly.

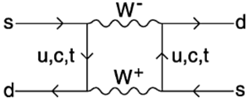
The SM contains 19 free parameters. The MSSM contains 178 free parameters, but 153 of them are associated with soft supersymmetry breaking – and are reducible?

The SUSY Flavor and CP Problems

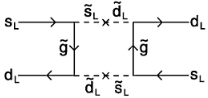
The MSSM is weakly coupled at the TeV scale and thus confronts precision electroweak measurements well if the superpartners are at the weak scale.
However, there are severe constraints from flavor and CP studies....

Flavor-Changing Neutral Current (FCNC) Constraints:

Note, e.g., $K_L - K_S$ mass difference: [Baer and Tata]

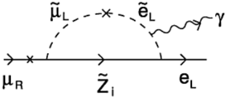


Standard Model



Additional effects from the MSSM

Constraints come from the mass differences from $B - \bar{B}$ and $D - \bar{D}$ mixing, too, as well as $b \to s\gamma$, $\mu \to e\gamma$, $\tau \to e\gamma$,....



Note the change in fermion *chirality*.
Constraints on chirality-changing effects also come from $(g-2)_\mu$.

All place constraints on the scalar masses and mixings in the soft breaking terms.

Can remove systematically through degeneracy or alignment or decoupling....

The SUSY CP Problem

The MSSM generically has many additional sources of CP violation because all the soft breaking terms can be complex.

Many constraints come from the non-observation of flavor-changing CP-violating effects beyond those of the SM:

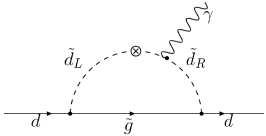
in K's:
$\Gamma(K_L \to 2\pi)$ (ϵ_K) and from the pattern of isospin-breaking in $\Gamma(K_L, K_S \to \pi^+\pi^-, \pi^0\pi^0)$ (ϵ').

in B's:
$A_{CP}(b \to s\gamma)$, $\Gamma(B, \bar{B}(t)) \to \psi K_S, \ldots$, $B_s \to \mu^+\mu^-$

We can study flavor-conserving, CP-violating processes also.
$\Longrightarrow$ Enter the EDM of the neutron, electron,....

In the case of the μ, this is the "complex", i.e., CP-violating, analogue of the study of $(g-2)_\mu$. We can compute $(g-2)_\mu$ in the SM.
We cannot employ the measurement of the anomalous magnetic moment of the neutron to similar use because lattice QCD techniques are too primitive.

The leading contribution to the neutron EDM in the MSSM:



on the Electric Dipole Moment

The electric dipole moment d and magnetic moment μ of a nonrelativistic particle with spin S is defined via $\mathcal{H} = -d\frac{\mathbf{S}}{S}\cdot\mathbf{E} - \mu\frac{\mathbf{S}}{S}\cdot\mathbf{B}$

Assuming CPT invariance, the relativistic generalization is:

$\mathcal{L} = -d\frac{i}{2}\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi F_{\mu\nu} - \mu\frac{i}{2}\bar{\psi}\sigma^{\mu\nu}\psi F_{\mu\nu}$

Thus through the EDM d, a P-odd, T-odd observable, we probe CP-violating effects in the Lagrangian (of everything?).

Both d and μ can be computed from spin-flip matrix elements of the nucleon.

In principle, we can test for CPT invariance by checking whether $d_N = d_{\bar{N}}$ or $d_{e^-} = d_{e^+}$ or $d_{\mu^-} = d_{\mu^+}$.

In the MSSM we compute $d_d = \langle n|\bar{\psi}_d\sigma^{\mu\nu}\gamma_5\psi_d F_{\mu\nu}|n\rangle$ and note $d_n \approx d_d$.

On dimensional grounds, under SU(2)$_L\times$ U(1) gauge invariance

[de Rujula et al., Nucl Phys B 357, 311 (1991)]

$d_d \sim 10^{-3} e\frac{m_d(\text{MeV})}{\Lambda(\text{TeV})^2} \sim 10^{-25}/\Lambda(\text{TeV})^2$ e-cm.

Λ is the scale CP is broken.

Thus $|d_n^{\text{expt}}| < \mathcal{O}(2.9\times 10^{-26})$ e-cm at 90%CL [Baker et al., PRL 97, 131801 (2006)] implies that the $\Lambda \sim 1$ TeV.

This makes the n EDM a sensitive probe of TeV-scale physics.

N.B. our estimate is not special to the MSSM (nor to the n)!!

The Effective CP-Violating Lagrangian at $\Lambda \sim 2$ *GeV*

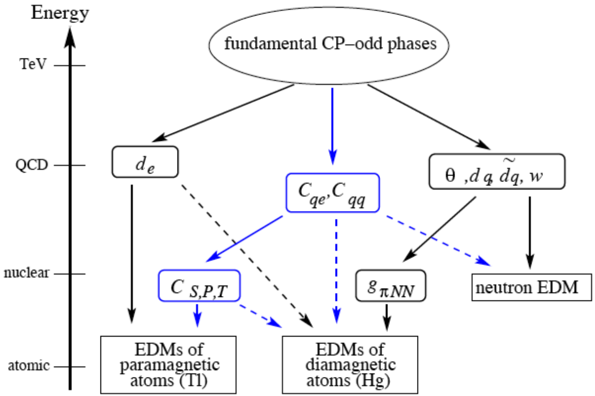
Here we organize the expected contributions to the low-energy $\mathcal{L}$ in terms of the mass dimension of the possible operators. We choose $\Lambda \sim m_c$ so that we can use QCD perturbation theory.
Note a mass dimension of $d - 4 > 0$ enters with a suppression factor of $\Lambda_{\rm CP}^{4-d}$, where $\Lambda_{\rm CP}$ is presumably not less than ~ 1 TeV.
Aside: $[\mathcal{L}] = 4$ so that $\int d^4x\mathcal{L}$ is dimensionless.
Thus $[A] = 1\,, [\psi] = 3/2\,, [\partial_\mu] = 1\,, [\phi] = 1$.
We have

$$\begin{aligned}\mathcal{L}_\Lambda \quad = \quad & \frac{\alpha_s\bar{\theta}}{8\pi}\epsilon^{\alpha\beta\mu\nu}F^a_{\alpha\beta}F^a_{\mu\nu} \\ & -\frac{i}{2}\sum_i d_i\bar{\psi}_i F_{\mu\nu}\sigma^{\mu\nu}\gamma_5\psi_i - \frac{i}{2}\sum_i \tilde{d}_i\bar{\psi}_i F^a_{\mu\nu}t^a\sigma^{\mu\nu}\gamma_5\psi_i \\ & +\frac{1}{3}wf^{abc}F^a_{\mu\nu}\epsilon^{\nu\beta\rho\delta}F^b_{\rho\delta}F_\beta^{\;\mu,c} + \sum_{i,j}C_{ij}(\bar{\psi}_i\psi_i)(\bar{\psi}_j i\gamma_5\psi_j) + \ldots\end{aligned}$$

with $i, j \in u, d, s, e, \mu$
and we neglect terms higher than dimension 6.

EDMs of Complex Systems

There is a hierarchy of scales to consider:



[Pospelov and Ritz]

At $\Lambda \sim 1$ MeV we have $\mathcal{L}_\Lambda = \mathcal{L}_{\mathrm{edm},\Lambda}(e,p,n) + \mathcal{L}_{\pi NN} + \mathcal{L}_{eN}$

All terms act as sources of CP violation.

EDMs in neutrons, nuclei, atoms, and molecules are broadly complementary.

EDMs in the Standard Model

There are two CP-violating parameters in the SM:
$\bar{\theta}$ in QCD and $\delta_{\rm KM}$ (η) in the CKM matrix.

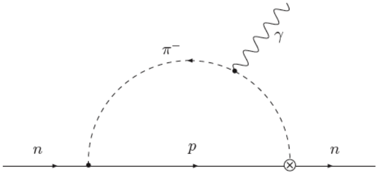
The Strong CP Problem

Since $\bar{\theta}$ accompanies a term of mass dimension 4,
it is not suppressed by a large scale!

$\mathcal{L}_{\rm CP} = \frac{\alpha_s \bar{\theta}}{8\pi} \epsilon^{\alpha\beta\mu\nu} F^a_{\alpha\beta} F^a_{\mu\nu}$ can be rewritten as a total divergence, but it contributes in QCD nonetheless.

The needed matrix element $\langle n | \bar{q} i \gamma_5 q | n \rangle$ [Baluni, Phys Rev D19, 2227 (1979)]
can be estimated using chiral Lagrangian techniques.

As $M_\pi \to 0$ limit one expects



to dominate, yielding $5.2 \cdot 10^{-16} \bar{\theta}$ e-cm.

[Crewther, Di Vecchia, Veneziano, Witten, PLB88, 123 (1979); PLB91, 487 (1980)]

Comparing to the exptl limit on d_n at 90%CL (Baker et al., ILL, 2007) yields $\bar{\theta} < 10^{-10}$.

Why is $\bar{\theta}$ so small?? Perhaps there is a spontaneously broken symmetry [Peccei and Quinn, 1979] (enter the axion) or $\Lambda_{\rm CP} \gg \Lambda_{\rm SUSY}$. [Hiller and Schmaltz, 2001]

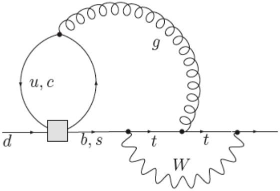
EDMs in the Standard Model

EDMs sourced from $\delta_{\rm KM}$

The structure of the CKM matrix guarantees that d_q is zero at two-loop order.

[Shabilin, Sov. J. Nucl. Phys. 28, 75 (1978)]

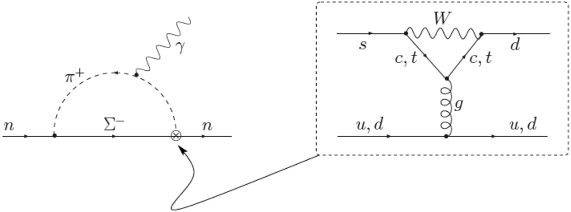
The first non-trivial contributions come at 3 loops, the largest involving a gluon [Khriplovich, PLB 173, 193 (1986)]



In leading logarithmic order at three loops $d_d^{\rm KM} \simeq 10^{-34}$ e-cm.

[Czarnecki and Krause, PRL 78, 4339 (1997)]

The π-loop contributions can be $1/m_\pi$ enhanced



and lead to the estimate $d_n^{\rm KM} \simeq 10^{-32}$ e-cm.

[Gavela et al., PLB 109, 215 (1982); Khriplovich and Zhitnitsky, PLB 109, 490 (1982).]

The estimates are so much smaller than the current experimental limits that the window for new physics is HUGE!

QCD matrix elements

How well can we interpret an EDM limit?

Let compare matrix element calculations for $\bar{\theta}$-QCD:
chiral: $d_n(\bar{\theta}) = 5.2 \cdot 10^{-16}\bar{\theta}$ e-cm [Crewther et al., 1979]
QCD sum rules: [Pospelov and Ritz, PRL 1999]

$$d_n(\bar{\theta}) = (1 \pm 0.5)\frac{\langle \bar{q}q \rangle}{(225\,\mathrm{MeV})^3} 2.5 \cdot 10^{-16}\bar{\theta}\ \text{e-cm}$$

They are crudely comparable, but... [Narison, PL B666, 455 (2008)]

$D_N|_{\exp} \leq 6.3 \times 10^{-26}$ cm ,

one can deduce in units of 10^{-10}:

$$\begin{aligned} \theta &\leq (1.6 \pm 0.4)\ [\text{Chiral}]\ :\ \nu = M_N \\ &\leq (1.3 \sim 11.7)\ [\text{ChPT}]\ :\ M_N/3 \leq \nu \leq M_N \\ &\leq (6.9 \pm 3.5)\ \ [\text{Constituent quark}] \\ &\leq (14.9 \pm 4.9)\ \ [\text{QSSR}]\ . \end{aligned}$$

cf. claimed 50% error in QSR method for CP-violating ops. w/ dimension ≤ 5

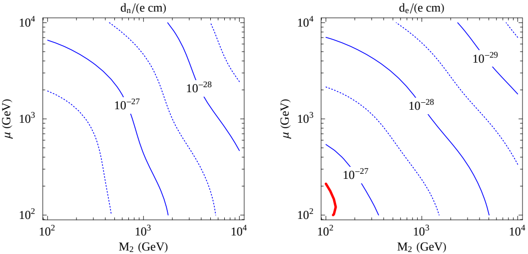
[Pospelov & Ritz, PRL 1999]

N.B. The nucleon matrix element computations needed can be tested by confronting the empirical anomalous moments. [Brodsky, SG, Hwang, PRD 2006]

Electric Dipole Moments in Split Supersymmetry

Can resolve SUSY CP problem by making superpartners heavy or CP phases small....

Models with "split" supersymmetry (heavy scalars!) can still produce significant EDMs at two-loop order: [Chang, Chang, Keung, 2005; Giudice and Romanino, 2006]



n and "e" EDMs are complementary! [see also Pospelov and Ritz]

Both d_e and d_n are expected to improve.

$|d_n| \leq 2.9 \cdot 10^{-26}$ e-cm (90% CL) [Baker et al., PRL 97, 131801 (2006)]

$|d_e| \leq 1.6 \cdot 10^{-27}$ e-cm [Regan et al., PRL 88, 071805 (2002)]

Some supersymmetric models (from "M Theory") realize CP violation only in the quark and lepton Yukawas $\Longrightarrow$ EDMs are SM-like [Kane, Kumar, Shao, arXiv:0905.2986]

Bibliography

The following textbooks and monographs provide helpful background and should aid in assimilating the information found in the journal articles cited throughout.

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