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PARITY AND TIME-REVERSAL NON-CONSERVATION IN ATOMS*

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ABSTRACT

We examine the implications of parity and time-reversal non-conservation for atomic physics. We conclude that a determination of Q_W/N to 10% would give an indirect determination of M_Z competitive with that available from high-energy physics. Limits on the electric dipole moments of neutrons and electrons give non-trivial constraints on model building of CP non-conservation.

In this talk I would like to examine the implications of parity and time-reversal non-conservation in high energy elementary particle theory for atomic physics. These effects are liable to be tiny. Never-the-less because QED, which governs the dynamics of atoms, is T and P invariant there is a discriminant which can be used to extract them from the morass of atomic structure.

Parity non-conservation (PNC) is the statement that a physical process and its mirror-image process might proceed at different rates. In some cases certain mirror-image particles may not even exist. For example, although left-handed neutrinos (spin anti-parallel to direction of motion) are emitted in muon decay, the mirror-image particle, the right-handed neutrino (spin parallel to direction of motion) has never been observed.

Time-reversal non-conservation (TNC) implies that the matrix elements of a process and its time-reversed process may have different amplitudes. I emphasize that this has nothing to do with the improbability of the events seen in a 'backwards running movie'; that has to do (in quantum mechanics) with the smaller density of final states of the time-reversed process (imploding gas) relative to the normal one (exploding gas) which leads to an entropy increase.

We first discuss PNC in atoms within the context of the Glashow-Salam-Weinberg standard model of electroweak unification (GSW) based on the group structure $SU(2)_L \times U(1)$. The theory has the particle content indicated in

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Table I.[1] The only undiscovered particles are the Higgs' scalar H and the top quark t.* We assume that strong interactions are given by $SU(3)_{color}$ QCD.

In addition to the particle content, there are some coupling constants which govern the dynamics of the theory. These include

$$\alpha_{em}(0),\ M_W,\ M_Z;\ M_H,\ M_f,\ \theta_{k-m} \tag{1}$$

where $\alpha_{em}(0)$ is the fine structure constant (at $q^2 = 0$) and M_W and M_Z are the masses of the $W^{\pm}$ and Z^0 respectively. M_H is the Higgs' scalar mass and M_f the set of fermion (quark and lepton) masses. θ_{k-m} are some quark mixing angles. We will return to these when discussing TNC effects.

We must use the very best input data available and will now eliminate M_W in favor of the muon decay lifetime τ_μ. We <u>calculate</u> τ_μ as a function of the data (1) with the resultant formula for muon decay.[2]

$$M_W^2/M_Z^2 = \frac{1}{2} + \frac{1}{2}\left(1 - \frac{4A_0^2}{M_Z^2}\right)^{1/2} \tag{2a}$$

$$A_0^2 = \frac{\pi\alpha_{em}(0)}{\sqrt{2}\,G_\mu} = (37.281\ \mathrm{GeV})^2 \tag{2b}$$

with $G_\mu = (1.16634 \pm .00002) \times 10^{-5}\ \mathrm{GeV}^{-2}$ the Fermi constant. We use (2) to eliminate M_W as a free parameter and thus the theory is completely defined in terms of

$$\alpha_{em}(0),\ \tau_\mu,\ M_Z;\ M_H,\ M_f,\ \theta_{k-m} \tag{3}$$

Note that the weak mixing angle θ_W is no longer a free parameter, but must be calculated in terms of the above.

$$\sin^2\theta_W \equiv s_\theta^2 \equiv 1 - M_W^2/M_Z^2 \tag{4}$$

We are now in a position to calculate the coefficients in the effective low energy PNC electron-quark Hamiltonian.[3]

$$\begin{aligned}\mathcal{H}^{e-q}_{PNC} = \frac{G_\mu}{\sqrt{2}}\int d^3x \Big\{ &\bar{e}\gamma_\mu\gamma_5 e\left[C_{1u}\bar{u}\gamma_\mu u + C_{1d}\bar{d}\gamma_\mu d\right] \\ &+ \bar{e}\gamma_\mu e\left[C_{2u}\bar{u}\gamma_\mu\gamma_5 u + C_{2d}\bar{d}\gamma_\mu\gamma_5 d\right] \\ &+ \bar{e}\sigma_{\mu\nu} e\frac{q_\nu}{m_e}\left[C_{3u}\bar{u}\gamma_\mu\gamma_5 u + C_{3d}\bar{d}\gamma_\mu\gamma_5 d\right]\Big\}\end{aligned} \tag{5}$$

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* There are candidate events for the t at CERN which might indicate a mass $M_t = 40 \pm 10$ GeV.

The results for the electron-quark coefficients C_{iq} follow (at tree-level $\sim$ 10%) from examination of the Feynman diagram with Z^o exchange between electrons and quarks (inside the nucleus) in GSW.

$$C_{1u} = \frac{1-2V_\theta}{6} \qquad C_{1d} = \frac{V_\theta - 2}{6} \tag{6a}$$

$$C_{2u} = -C_{2d} = \frac{V_\theta}{2} \tag{6b}$$

$$C_{3u} = C_{3d} = 0 \tag{6c}$$

$$V_\theta = 4S_\theta^2 - 1 \tag{7}$$

with S_θ^2 defined in eqns. (4) and (2); they are thus functions only of M_Z (to 10%).

Lets imagine that an accurate experiment might be done in PNC in atoms and that we want to calculate the C_{iq} to better than 1%. Electroweak calculations (like QED) may be written as a power series in $\alpha_{em} \simeq (137.026)^{-1}$ and so corrections of this order come from 1-loop Feynman diagrams (like the Lamb shift). We must re-calculate the set (3) including all one-loop diagrams. When we re-calculate the C_{iq} including all one-loop diagrams and express them in terms of the re-calculated set (3), the results are UV and IR finite although some non-physical parameters appearing in intermediate steps of the calculation (used as bookkeeping devices) are not. The theory is renormalizable! The results of this long and thankless task will be to add corrections (with hundreds of terms) of order a few percent to the formulae[3] (6). For example

$$C_{1u} = \left(\frac{1-2V_\theta}{6}\right)(1-\Delta r) + \Delta C_{1u} \tag{8a}$$

$$S_\theta^2 = \frac{1}{2} - \frac{1}{2}\left(1 - \frac{4A_0^2}{M_Z^2(1-\Delta r)}\right)^{1/2} \tag{8b}$$

with the definitions (4) and (7) still enforced to this accuracy. Here Δr (from corrections to muon decay)[2] and ΔC_{1u} are complicated functions (of order α_{em}) of the parameters (3). Of these parameters, only M_Z, M_H, θ_{k-m} and M_t (top quark mass) are unknown; the dependence on all but M_Z is weak because it occurs only in Δr and ΔC_{iq} and so will be suppresssed by a factor of α_{em}/π.

We now know C_{iq} to 1% and would like to upgrade these coefficients of the PNC electron-quark interaction into coefficients C_{1p}, C_{1n}, C_{2p}, C_{2n}, C_{3p}, C_{3n} (p for proton, n for neutron) in an electron-nucleon PNC interaction Hamiltonian analogous to (5). To do this, we need to know something about the dynamics of quarks inside nucleons at $q^2 = 0$.

To deal with C_{1p}, C_{1n} we need use only global chiral $SU_2 \times SU_2$ symmetry (between protons and neutrons) and the CVC (conserved vector current) hypothesis. This is the best known symmetry of hadrons in nature (good to 1%) and so we may calculate C_{1p} and C_{1n} and, with the PCAC (partially conserved axial vector current) hypothesis, C_{3p} and C_{3n} to 1%.

C_{2p} and C_{2n} are not so easily gotten. This is because they involve an axial vector hadronic current at tree level and the chiral $SU_3 \times SU_3$ symmetry (of the lowest baryon octet) needed to deal with this is known to develop isoscalar currents, and is really only reliable to 10-20%. Also, PNC interactions within the nucleus can make their way out to the electrons in an atom via a short-ranged PNC force carried by photons. In the end, we may trust C_{2p} and C_{2n} to 10-20% but this situation could be improved with further work, especially if an experimental determination of C_{2p} were forthcoming.

The results for the electron-nucleon PNC couplings are:

$$C_{1p} = -\frac{V_\theta}{2}(1-\Delta r) + \Delta C_{1p} \tag{9a}$$

$$C_{1n} = -\frac{1}{2}(1-\Delta r) + \Delta C_{1n} \tag{9b}$$

$$C_{2p} = \frac{g_A}{g_V}\frac{V_\theta}{2}(1-\Delta r) + \Delta C_{2p} \tag{9c}$$

$$C_{2n} = -\frac{g_A}{g_V}\frac{V_\theta}{2}(1-\Delta r) + \Delta C_{2n} \tag{9d}$$

$$C_{3p} = -C_{3n} = \frac{g_A}{g_V}\frac{\alpha_{em}}{\pi}\frac{V_\theta}{8}(1-\Delta r) \tag{9e}$$

Here $g_A/g_V = 1.255 \pm .006$ is the ratio of axial vector to vector couplings[4] in neutron Beta decay and everything with a 'Δ' in its name is order α_{em}. Note that $\Delta r \simeq .07$ so that the coefficients receive a 7% renormalization from the one-loop radiative corrections to muon decay alone as well as radiative corrections to the coefficients ΔC_{iN} (N = n, p) themselves. Radiative corrections are important!

The numerical results in Table II show the dramatic dependence of the coefficients on the precise value of M_Z within the allowed UA1/UA2 range 90 GeV $\le M_Z \le$ 98 GeV. We have for M_H = 100 GeV, M_t = 36 GeV.

Table II Values of PNC Coefficients in GSW [3]

M_Z (GeV)	C_{1p}	C_{1n}	C_{2p}	C_{2n}
90	.017	-.490	.016	-.013
94	.073	-.488	.083	-.079
98	.118	-.485	.137	-.132

C_{2p} is the object of present experiments in PNC in hydrogen. We note that it (along with C_{1p}, C_{2n}) changes by an order of magnitude over the allowed range of M_Z. This is because it is proportional to $V_\theta = 4\,S_\theta^2 - 1$ with S_θ^2 near 1/4 so small changes in S_θ^2 in eqn. (8b) affect C_{1p}, C_{2p} and C_{2n} dramatically.

The implications of Table II for PNC in heavy atoms are startling. These experiments measure the quantity

$$Q_W = 2\left(Z C_{1p} + N C_{1n}\right) \tag{10}$$

and are all done in atoms (Cs, T_ℓ, Pb, Bi) where $\frac{Z}{N} \simeq \frac{2}{3}$. Thus we may characterize all experiments in heavy atoms by one parameter η

$$\eta = -2\left(C_{1n} + \frac{2}{3} C_{1p}\right) \tag{11a}$$

$$Q_W/N = -\eta + \zeta \simeq -\eta \tag{11b}$$

$$\zeta = 2\left(\frac{Z}{N} - \frac{2}{3}\right) C_{1p} < .01 \tag{11c}$$

Thus we have the predictions (good to 2 - 3%) of Table III* and it is possible to compare the results of experiments on PNC in different heavy atoms ($55 \leq Z \leq 83$) via the parameter η.

Table III PNC Q_W/N in Heavy Atoms [3]

M_Z (GeV)	$S_\theta^2 = 1 - M_W^2/M_Z^2$	$\eta \simeq -Q_W/N$
90	.2432	.958
94	.2154	.880
98	.1929	.813

* S_θ^2 is correct to better than 1%

Note that η changes by 18% over the allowed UA1/UA2 range of M_Z. We conclude that a 10% (total theoretical plus experimental error) determination of Q_W/N in PNC in heavy atoms would give an indirect determination of M_Z (within GSW) which was competitive with results from CERN! It is interesting to compare the results of Table III, in which we have tabulated the one-loop prediction for S_θ^2 as well, with the determination of S_θ^2 from neutrino-hadron scattering. We have [5]

$$S_\theta^2 = .215 \pm .015 \text{ (theoretical)} \pm .015 \text{ (experimental)} \tag{12}$$

so that PNC in heavy atoms is competitive with ν data as well.

If we move out of the context of GSW with light t-quark even more interesting things can happen. For very heavy top quarks (or sequential quark doublets with large top-bottom splitting) for M_t = 230 GeV we get an additional[3] shift $\delta\eta \simeq -.04$. If, within the context of minimal supersymmetric (SUSY) $SU_2 \times U_1$, this is accompanied by a similar top-bottom squark splitting[6] we have $\delta\eta \simeq -.08$. A class of SUSY models proposed by Fayet ('D term' models) give an extra gauge group U(1) factor (as a means of breaking SUSY) with an extra neutral vector boson with $M_u \lesssim$ 18 GeV with PNC couplings. This could change the results of PNC atomic physics experiments substantially (because they are done at low $|q^2| \lesssim M_u^2$) while affecting high energy experiments (done at high $|q^2| >> M_u^2$) only slightly.

We conclude that PNC in heavy atoms is still in a position to test fundamental physics (even if GSW is right) if the total error can be brought down to 10% (or better?). This is a feasible reasonable goal as can be inferred from the lectures of PGH Sandars and M. Bouchiat at this Conference and can be done at a fraction of the cost of high energy accelerator physics.

We now turn to the discussion of time-reversal non-conservation (TNC). It should be noted that while there is abundant evidence for CP non-conservation, there is none as yet for TNC. In a relativistic local field theory CP and T non-conservation are equivalent and we will assume the CPT theorem in what follows.

TNC has so far only been observed in the $K_L^0 - K_S^0$ system.[7] K_L^0 normally decays to 3 pions (CP = -1) while K_S^0 normally decays to 2 pions (CP = +1). Sometimes though K_L^0 decays to 2 pions as well, so there is TNC. If we form the ratios of cross sections

$$\eta_{ij} = \frac{\sigma(K_L^0 \to \pi^i \pi^j)}{\sigma(K_S^0 \to \pi^i \pi^j)} \tag{13}$$

the experimental data gives $\eta_{+-} \simeq \eta_{00} \simeq 2 \times 10^{-3}$ where the two final-state pions are always in a total isospin I = 0 state. An important discriminant among models of TNC is whether $|\eta_{+-}| = |\eta_{00}|$ and a measurement of

$$\frac{\epsilon'}{\epsilon} \sim \frac{\sigma(K_L^0 \to 2\pi, I=2)}{\sigma(K_L^0 \to 2\pi, I=0)} \tag{14}$$

is very important. We shall see however that setting more stringent upper bounds (or seeing the effect!) on electric dipole moments (edm) of elementary particles also serves as a very important constraint on model building.

We list below some experimental tests for TNC.

high energy physics	low energy physics
$K_S^o \to 3\pi$	d_e^n neutron edm
$\Lambda \to p\pi^-$	d_e^e electron edm
$\Lambda \to n\pi^o$	d_e^N nucleus edm
$K_L^o \to \pi^o e^+ e^-$	C_S
$K^+, K_L^o \to \pi\nu\mu_{pol}$	C_T
$K_L^o \to 2\pi$ (I = 2)	
Charmed particle decays	
b quark decays	

C_S and C_T are the coefficients of a short-ranged TNC scalar-pseudoscalar and tensor-pseudo tensor interaction between electrons and quarks (in the nucleus) in atoms.

All of these experiments are designed to answer the question "What is the origin of CP non-conservation or TNC?" It must be admitted that there is no good answer to this question and so we are reduced to model building. We will examine below a number of the more interesting models--relativistic field theories of elementary particle interactions--which appear in the literature. These models can be divided into four classes:

i) $SU(3)_{color} \times SU(2)_L \times U(1)$ standard GSW model of strong and electroweak interactions with the particle content of Table I.

ii) Models which add new particles to the soup of GSW but do not change the gauge structure of interactions.

iii) Models which add new interactions (new gauge group structure) such as left-right symmetric theories, grand unified theories (GUT) or theories with vector bosons which mediate fermion generation-changing (horizontal) interactions.[8]

iv) Models which have new principles such as supersymmetry[9] (SUSY) or attempt to use gravity as the origin of CP non-conservation like supergravity (SUGRA).

Typical predictions for TNC parameters from the various models are tabulated in Table V. We begin with class i).

SU(3)color

There have been a number of attempts to understand TNC within the strong interaction theory of 3 colors of quarks and an octet of gluons (QCD) based on $SU(3)_{color}$.[7,10] These all involve the so-called θ vacuum. TNC can indeed arise this way but once one has set $\theta \lesssim 10^{-9} - 10^{-10}$ so as not to violate the known limits on the neutron edm (d_e^n) it is not possible to get TNC in the $K_L^o - K_S^o$ anywhere near as large as 10^{-3}. Thus, $SU(3)_{color}$ alone cannot give a complete theory of TNC. Furthermore there is the question of why θ should be 'naturally' so small. It's smallness could be due to some extra continuous symmetry but this would induce a Goldstone boson (axion) when the symmetry was broken to give $\theta \neq 0$. The light axion has not been observed to date.

Kobayashi-Maskawa (KM) Mixing[7,10]

It seems to be a fact of nature that quarks and leptons come in generations such as the first generation listed in Table I. The second generation is

$$\begin{pmatrix} c \\ s \end{pmatrix}_L, \; c_R, \; s_R, \; \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L, \; \mu_R, \; (\nu_{\mu R}?) \tag{14}$$

We know experimentally however that the weak eigenstates in the quark sector for the first two generations u, d, c, s are not mass eigenstates but rather combinations of them are. Thus, a 2 x 2 unitary (Cabibbo) mixing matrix makes its way into the charged currents while the neutral currents automatically re-diagonalize when these currents are written in terms of the mass eigenstates (GIM mechanism). No complex phase appears and thus the theory is CP conserving with only 2 generations of quarks.

For 3 generations of quarks we have the weak eigenstates

$$\Psi_u = \begin{bmatrix} u \\ c \\ t \end{bmatrix}, \qquad \Psi_d = \begin{bmatrix} d \\ s \\ b \end{bmatrix} \tag{15a}$$

and a 3 x 3 mixing matrix appears. The most general such[10] KM (Kobayashi-Maskawa) mixing matrix may be written, (eqn. 15b)

$$\mathcal{U}_q = \begin{bmatrix} c_{\theta_1} & -s_{\theta_1}c_{\theta_3} & -s_{\theta_1}s_{\theta_3} \\ s_{\theta_1}c_{\theta_2} & c_{\theta_1}c_{\theta_2}c_{\theta_3} - s_{\theta_2}s_{\theta_3}e^{i\delta} & c_{\theta_1}c_{\theta_2}s_{\theta_3} + s_{\theta_2}c_{\theta_3}e^{i\delta} \\ s_{\theta_1}s_{\theta_2} & c_{\theta_1}s_{\theta_2}c_{\theta_3} + c_{\theta_2}s_{\theta_3}e^{i\delta} & c_{\theta_1}s_{\theta_2}s_{\theta_3} - c_{\theta_2}c_{\theta_3}e^{i\delta} \end{bmatrix}$$

after absorbing as many phases as possible into the quark fields with $\theta_1 = \theta_C$ the Cabibbo angle. This matrix has a CP non-conserving complex phase $e^{i\delta}$ whose magnitude is set to account for the observed CP non-conservation in the $K_L^o - K_S^o$ system. The KM theory then gives a very small neutron edm. In the leptonic sector, there is no analogous mixing matrix to U_q because neutrinos are presumed massless and therefore one can re-absorb all phases (including TNC) into the leptons. Thus the electron edm is zero in the KM model as are C_S and C_T.

The KM theory does not attempt to answer the question 'why TNC?" but rather gives only a reasonable parametrization of the problem. It does set the general trend of CP non-conservation theories; induce a complex phase into the theory via a mixing matrix.

Other models

We now turn to class (ii) theories. The simplest would be to add more quarks and leptons to GSW with more KM complex phases. It has been shown that in order to induce a maximum electron edm, $d_e^e < 10^{-27}$ e-cm, this way one needs at least two generations of leptons with very heavy ($\sim M_W$) massive neutrinos.[8] Weinberg has proposed another variation on the standard model in which there are 3 rather then 1 Higgs doublets;[11] a scenario which could come from technicolor. These have mixings which induce complex phases into the quark currents but one must then be careful to avoid $\Delta S \neq 0$, $\Delta Q = 0$ currents. This model tends to give relatively large $d_e^n \simeq 5 \times 10^{-26}$ e-cm and it is possible that it would also induce $C_T \simeq 5 \times 10^{-11} G_\mu$.[12]

Class iii) models add new interactions to the soup. The most attractive of these is the left-right symmetric $SU(2)_L \times SU(2)_R \times U(1)$ with Higgs' triplets.[7,10] In this model, P and T are good symmetries of the fundamental Lagrangian but are broken spontaneously (in contrast to GSW where PNC and TNC are put in by hand). Thus the magnitudes of PNC and TNC are related to each other. Another attractive feature of this model is that ν_L (ν_R) are naturally light (heavy) and heavy ν_R help develop reasonably large d_e^n and d_e^e.

Supersymmetry

None of the above models 'explains' TNC but rather seems to hide our lack of understanding more deeply behind layers of model-building technique. We need a new principle. As Abdus Salam says 'Nature is not jealous of structures (e.g. there are many elements) but very jealous of Principles (QED tells us both their number and properties)'.[1] That principle could be supersymmetry (SUSY); the only new symmetry possible which is compatible with local relativistic field theory.[9]

SUSY is a global symmetry between bosons and fermions. The particle content of minimal N = 1 SUSY $SU(3)_{color} \times SU(2)_L \times U(1)$ is displayed in Table IV. Note that the supermultiplets connect spins ($0 \leftrightarrow \frac{1}{2}$), ($1 \leftrightarrow \frac{1}{2}$) so that the superpartners of quarks, leptons, $W^{\pm}$, Z, A, gluons and Higgs' are squarks, sleptons, $W^{\pm}$ inos, Zinos, photinos, gluinos and shiggs'. TNC complex phases occur naturally in SUSY in the mass matrices for Winos ($\tilde{W}$) and the mixing of left ($\tilde{t}_L$) and right ($\tilde{t}_R$) squarks and sleptons. Further, there is a super GIM mechanism (to suppress $\Delta S \neq 0$, $\Delta Q = 0$ currents) with super K-M mixing which is presumed the largest source of TNC and responsible for TNC in $K_L^o - K_S^o$. We have listed in Table V some typical edm's from SUSY[13] and note that the limit reported at this conference $d_e^n \leq 10^{-25}$ e-cm places non-trivial constraints on SUSY model building already. Further, it is possible that C_S, $C_T \simeq 10^{-11}$ G_μ can arise in SUSY.[12]

One need not stop there. The many parameters (including PNC and TNC) appearing in N = 1 SUSY may be motivated (and related to each other) by coupling the theory to gravity. The crucial observation is that when SUSY is made into a local symmetry (like $SU(2)_L \times U(1)$are in GSW) and 'gauged' the mediating particles (analogous to $W^{\pm}$, Z^o, A) carry spin 2 (graviton) and 3/2 (gravitino) and the theory automatically has general coordinate invariance (Poincaré symmetry). Thus, classical general relativity follows naturally from local SUSY or supergravity (SUGRA) and a real connection is made between planetary motion and PNC in atoms. The upshot of all this is that in the $K^2 = 8\pi G_N \to 0$ limit (G_N is Newton's constant) we have a well defined effective global SUSY model at low energies in which (after use of the super-Higgs' effect) SUSY is naturally broken (e.g. quarks and squarks are split in mass). Models can be made which satisfy all experimental constraints and one side effect of all of this is that CP non-conserving phases occur naturally in SUGRA. The SUSY predictions listed in Table V were actually gotten from SUGRA so that experimental limits on d_e^n (and d_e^e, C_S, C_T) actually constrain supergravity!

We have given in Table V a summary of the TNC properties[14] of the various models considered here. The parameters of the models are first constrained by the limit on neutron edm. One then asks whether the model can still account for ('explain') the observed CP non-conservation in the $K_L^o - K_S^o$ system. Of course these models tend to have tunable parameters in them so d_e^n often just constrains combinations of mixing angles and masses. For example the entry $d_e^n < 4 \times 10^{-22}$ e-cm under "SUSY $\tilde{t}_L - \tilde{t}_R$ mixing" tells us that the neutron edm could be in principle this large but that certain parameters must be constrained to agree with experiment. The entry '0' in the Table indicates either zero or very small.

A glance at Table V shows that different models can give very different predictions for experiments. We sense, however, that '........ none of these models is very convincing; none of them yields the gut reaction: "Now I understand CP violation"!' -L. Wolfenstein & D.Chang [14]

We now summarize the situation for PNC and TNC in atoms. Electric dipole moments of neutrons and electrons can provide very serious constraints on model building (especially in SUSY and SUGRA) of TNC. On the PNC side, if the total error in a determination of $Q_W/N \simeq \eta$ in heavy atoms can be brought down to 10% atomic physics would be competitive with high energy accellerator physics in giving an (indirect) determination of M_Z. C_{1p}, C_{2p} and C_{2n} change by an order of magnitude over the allowed UA1/UA2 range of M_Z but theoretical strong interaction effects are worrisome in C_{2p} and C_{2n}. These effects are not hopeless however and are interesting in their own right. For example $C_{2D} = C_{2p} + C_{2n} = 0$ at tree level in deuterium and, armed with a determination of this quantity from atomic physics, we could study the induced isoscalar currents there (from axial anomalies involving gluons, etc.) with recent models of the quark structure of hadrons which are emerging in lattice gauge theory calculations. Of course from the point of view of electroweak interactions the best possible experiment would be a measurement of C_{1p} (or $C_{1D} = C_{1p} + C_{1n}$) in hydrogen (or deuterium) as this would be free of strong interaction and atomic theoretical uncertainties and would allow us to probe deeply into the structure of electroweak unification.

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TABLE I

Particle Content of GSW $SU(3)_{color} \times SU(2)_L \times U(1)$

1 generation of quarks,leptons (i=1,3 quark colors;k=1,8 gluon colors)

Vector Bosons(S=1)

g^k
$W^{\pm}$
Z
A

quarks, leptons(S=½)

u_{Li}	ν_L
d_{Li}	e_L
u_{Ri}	(ν_R)
d_{Ri}	e_R

Higgs'(S=0)

H^+
H^0

TABLE IV

Particle Content of Minimal N=1 SUSY $SU(3)_{color} \times SU(2)_L \times U(1)$

1 generation of quarks and squarks,leptons and sleptons
(i=1,3 quark and squark colors;k=1,8 gluon and gluino colors)

Vector Bosons(S=1)	Winos(S=½)
g^k	$\tilde{g}^k$
$W^{\pm}$	$\tilde{W}^{\pm}$
Z	$\tilde{Z}$
A	$\tilde{A}$

quarks,	leptons(S=½)	squarks,	sleptons(S=0)
u_{Li}	ν_L	$\tilde{u}_{Li}$	$\tilde{\nu}_L$
d_{Li}	e_L	$\tilde{d}_{Li}$	$\tilde{e}_L$
u_{Ri}	(ν_R)	$\tilde{u}_{Ri}$	$(\tilde{\nu}_R)$
d_{Ri}	e_R	$\tilde{d}_{Ri}$	$\tilde{e}_R$

shiggs'(S=½)	Higgs'(S=0)
$\tilde{H}^+$	H^+
$\tilde{H}^0$	H^0
$\tilde{H}^{-\prime}$	$H^{-\prime}$
$\tilde{H}^{0\prime}$	$H^{0\prime}$

Note All scalars are complex (2 components) and all fermions are chiral L or R (2 components) spinors in both Tables I & IV. Massless vector bosons have 2 components as well.

TABLE V [14]

Predictions of TNC for various Models

Model	'Explains' $K_L^0 - K_S^0$	ϵ'/ϵ	Neutron EDM(e-cm)	Electron EDM(e-cm)
QCD vacuum	No	0	anything you like	0
K-M	Yes	$\gtrsim 2\times10^{-3}$	$< 10^{-30}$	0
Weinbergs' 3-Higgs'	Yes	$> 2\times10^{-2}$	$\sim 5\times10^{-26}$	?
$SU_{2L}\times SU_{2R}\times U_1$	Yes	10^{-2} to 10^{-3}	$\sim 3\times10^{-27}$	?
Horizontal Interactions	Yes	?	$< 10^{-27}$	$< 10^{-27}$
SUSY super K-M	Yes	?	$< 10^{-28}$	$< 10^{-32}$
SUSY Wino Mixing	No	?	$< 10^{-24}$	$< 10^{-25}$
SUSY $\tilde{t}_L-\tilde{t}_R$ mixing	No	?	$< 4\times10^{-22}$	$< 10^{-24}$

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