ERRATA and ADDENDUM

THE NEUTRON ELECTRIC DIPOLE MOMENT

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There are several typing errors in this paper which we would like to correct in these errata. We would like to use this opportunity to summarize some new developments related to the neutron EDM.

The typing errors and their corrections are as follows:

- (1) The result of D_n in the standard model should be $1.4 \times 10^{-32} \text{ ecm} < |D_n| < 1.6 \times 10^{-31}$. Corrections should be made on pages 5011 (abstract (i)), 5018 (19th line), 5021 (Eq. (3.19)) and 5043 (conclusion (i)).
- (2) “become” on page 5011 on the 5th line from bottom should be “became”.
- (3) “week” on page 5020 on the 14th line should be “weak”.
- (4) Ref. 12 on page 5020 on the 15th line should be Ref. 15.
- (5) Ref. 20 on page 5020 on the 17th line should be Ref. 22.
- (6) Ref. 56 on page 5039 on the 2nd line should be Ref. 57.

- (7) The expression $D_\mu = \partial_\mu + iQA_\mu$ in Eq. (3.7) should be written as

$$D_\mu M = \partial_\mu M + ieA_\mu[Q, M],$$

$$\text{with } Q = \begin{pmatrix} 2/3 & 0 & 0 \\ 0 & -1/3 & 0 \\ 0 & 0 & -1/3 \end{pmatrix}.$$

- (8) The third term of Eq. (3.13) should be $D_{\Sigma p} \bar{\Sigma}^+ i\sigma_{\mu\nu} q^\nu \gamma_5 p^\mu$.

- (9) The 4th line of page 5020 should be

$$D_{n,2}^{(II)} = -2.7 \times 10^{-29} s_2 s_3 s_\delta \text{ ecm (Pauli coupling to neutral baryons).}$$

- (10) Equation (5.1) should be

$$L_Y = 2^{3/4} G_F^{1/2} \sum_i \bar{U} \left[V_{KM} M_d \frac{1+\gamma_5}{2} X_i + M_u V_{KM} \frac{1-\gamma_5}{2} Y_i \right] D H_i^+ + \text{H.C.}$$

- (11) G_{Fg_s} in the denominator of Eq. (5.13) should be $G_F g_s$.

- (12) The function g_a in Eqs. (6.12) and (6.13) should be g_b .

- (13) Equation (8.8) should be written as

$$L_{\pi NN} = -\pi \cdot \bar{N} \tau (i\gamma_5 g_{\pi NN} + f_{\pi NN}) N,$$

$$f_{\pi NN} = -2(m_\Xi - m_\Sigma) \frac{m_u m_d}{F_\pi (m_u + m_d)(2m_s - m_u - m_d)} \theta. \quad (8.8)$$

- (14) On page 5042, the numerical values given for $f_{\pi NN}, f_{\Lambda n K}, f_{\eta nn}, f_{\Sigma n K}$ by the second of the equations should be multiplied by θ .

- (15) $D_{n,I}^2$ on the left hand side of Eq. (8.14) should be $D_{n,2}^{(I)}$.

We summarize some recent developments related to the neutron EDM:

- (1) The experimental upper bound on the neutron EDM at the 90% confidence level is now 1.2×10^{-25} ecm.¹

- (2) The lower bound on the top quark mass is now 89 GeV.² Since the upper bound on D_n in the standard model is related to the lower bound of the top quark mass, the upper bound for D_n will change accordingly. Using $m_t = 89$ GeV, we have $|D_n| < 10^{-31}$ ecm and the lower bound on D_n is not changed.

- (3) In the Weinberg model of CP violation due to Higgs exchange, if CP violation only comes from spontaneous symmetry breaking then D_n from charged Higgs exchange is predicted to be larger than the upper bound on the neutron EDM in our paper. Recently it has been shown that if one uses an improved treatment of $\eta - \eta'$ mixing and of the $K - \eta_0$ transition, the model can be made consistent with the experimental data on ε'/ε and D_n .³ There is another problem with spontaneous CP violation. Spontaneous CP violation requires complex vacuum expectation values (VEVs). These complex VEVs will generate imaginary quark masses and therefore a non-zero θ -term.⁴ Using the constraint on θ from the neutron EDM, one finds that the VEV phases are constrained to be too small to explain the CP violation

in the neutral kaon system. This problem can be solved if one considers a model in which CP violation arises not only from spontaneous symmetry breaking, or if one considers models of spontaneous CP violation with Peccei-Quinn symmetry.⁵ In a model in which CP violation occurs both in the charged current due to W exchange (the KM phase) and Higgs exchange, the contribution to the neutron EDM from the charged Higgs exchange is $< 2 \times 10^{-25}$ ecm. This is because CP violation in the neutral kaon mixing is dominated by the contribution from the KM phase and the CP-violating parameters involving charged Higgs exchange are weakly constrained from ϵ compared with the constraint from ϵ'/ϵ . Using the new experimentally measured bound $\epsilon'/\epsilon = (-5 \pm 14 \pm 6) \times 10^{-4}$,⁶ at 90% confidence level we obtain $|D_n| < 2 \times 10^{-25}$ ecm.

CP-violating parameters associated with neutral Higgs scalar exchange are only constrained by the upper bound on the neutron EDM. In our paper we discussed two ways of estimating D_n . It has recently been pointed out that there is a new contribution to the neutron EDM from neutral Higgs exchange.⁷ At the two-loop level a CP-violating dimension 6 operator $O = -\frac{1}{6}C f_{abc} G_{\mu\nu}^a G_{\alpha}^{b\nu} G_{\sigma\gamma}^c \epsilon^{\mu\alpha\sigma\gamma}$ is generated by exchange of neutral Higgs scalars. The parameter C is given by

$$C = \frac{2\sqrt{2}}{(4\pi)^4} G_{Fi} \Sigma X_i Y_i g_s^3 h(m_t/m_{H_i}) ,$$

$$\text{where } h(x) = \frac{x^4}{2} \int_0^1 du \int_0^1 dv \frac{v^3 u^3 (1-u)}{[x^2 u(1-vu) + (1-u)(1-v)]^2} .$$

The operator O can contribute to the neutron EDM. Using “naive dimensional analysis”, one estimates the neutron EDM to be

$$D_n = e\xi \frac{2\sqrt{2}}{(4\pi)^2} G_{Fi} \Sigma X_i Y_i h(m_t/m_{H_i}) ,$$

where⁸ $\xi = 8 \times 10^{-5}$ is a parameter which includes QCD corrections to D_n . This estimate gives the strongest constraint on the CP violation parameters involving neutral Higgs scalar exchange.

Charged Higgs scalar exchange can also generate the operator O .⁹ Using “naive dimensional analysis”, one estimates the contribution from this operator to D_n to be close to the experimental upper bound on D_n . Since CP violation comes from both the KM phase and the Higgs exchange, it is possible to make the theory consistent with experiments.

In our paper we considered two-Higgs-doublet models with discrete symmetries which prevent neutral flavour violation at the tree level due to exchange of neutral Higgs scalars. In these models there is no CP violation due to Higgs exchange. The neutron EDM is predicted to be of the same order of magnitude as that of the standard model prediction. It is possible to introduce soft symmetry breaking terms in the Higgs potential such that CP violation due to Higgs exchange is allowed.^{10,11}

In these models only neutral Higgs exchanges violated CP. The calculation of these new contributions to the neutron EDM is similar to those in the Weinberg model.

(4) In the left-right symmetric model, an operator similar to O can be generated by exchanging $W_{L,R}$ at the two-loop level.¹² The contribution of this operator to D_n is less important than those from valence quark and hadron loop effects.

(5) In the supersymmetric model, gluino exchange at the two-loop level also generates the operator O .¹³ Again this contribution is less important than those already considered in our paper.

(6) Recently a lattice calculation of D_n due to the θ -term in QCD has been carried out. The result is $D_n = -4 \times 10^{-14} \theta$ ecm.¹⁴ This result is about two orders of magnitude larger than that obtained by bag model calculations and current algebra and PCAC calculations. Further study is necessary to resolve these discrepancies.

References

1. K. F. Smith *et al.*, *Phys. Lett.* **B234** (1990) 191.
2. P. Tipton, talk given at "Thinking about the top quark", Feb., 1990, UC Santa Barbara, U.S.A.
3. H. Y. Cheng, preprint IP-ASTP-07-90.
4. X.-G. He and B. McKellar, preprint UM-P-90/04, OZ-P-90/2.
5. X.-G. He and R. Volkas, *Phys. Lett.* **B208** (1988) 261.
6. J. R. Paterson *et al.*, *Phys. Rev. Lett.* **64** (1990) 1491.
7. S. Weinberg, *Phys. Rev. Lett.* **63** (1989) 2333.
8. E. Braaten, C. S. Li and T. C. Yuan, *Phys. Lett.* **64** (1990) 1709.
9. D. A. Dicus, *Phys. Rev.* **D41** (1990) 999.
10. G. C. Branco and M. N. Rebelo, *Phys. Lett.* **160B** (1985) 117; J. Liu and L. Wolfenstein, *Nucl. Phys.* **B289** (1987) 1.
11. S. Weinberg, preprint UTTG-04-90.
12. D. Chang, C. S. Li and T. C. Yuan, NUHEP-TH-90-2.
13. J. Dai, H. Dykstra, R. G. Leigh and S. Paban, UTTG-46-89.
14. S. Aoki and A. Gocksch, *Phys. Rev. Lett.* **63** (1989) 1125.