Chapter II PHYSICS MOTIVATION[1]

A. Introduction and Background

The present proposal, with its potential for measuring the neutron EDM d_n with a sensitivity of 10^{-27} e·cm is one of a class of new-generation experiments aiming to search for new physics in the CP violating sector. A focus on CP violation is suggested by the critical importance which symmetry has assumed in constructing theories of modern particle physics. More broadly, it acknowledges the importance of CP violation in shaping our understanding of the origins and evolution of the Universe. Empirical evidence for physics beyond the standard model of electroweak interactions (SM) is provided by recent experimental results on neutrino oscillations.

The role of symmetry, including the observed breaking of the discrete symmetries of parity P and CP, has been particularly significant for the construction of the SM. Parity violation, which has been measured in many systems, is well represented in the SM through a definitive chiral *V-A* coupling of fermions to gauge bosons. The information available on CP violation, while much more limited, still has had a profound impact; e.g., the decay of neutral kaons anticipated the three-generation structure of the SM as we now know it. Although neither P nor CP violation has been understood at a deep level in the SM, CP violation is arguably the less understood of the two, appearing tentatively through the complex phase $e^{i\delta_{\mathrm{CKM}}}$ characterizing $\Delta S = 1$ transitions in the CKM matrix. Because of the limited information available and the many open questions, searching for new sources of CP violation has become an attractive focus in the quest for New Physics.

The observation of CP violation also implies time-reversal symmetry T violation (and vice-versa) through the CPT theorem. This theorem asserts that field theories with local, Lorentz invariant, and hermitian Lagrangians (believed to be the only acceptable ones [3]) must be invariant under the combined transformation C, P, and T. In the absence of degeneracy, the energy of a spin-1/2 particle, say a neutron, in an electric field **E** is related to d_n by $E_n = d_n \sigma \cdot \mathbf{E}$ where σ is its Pauli spin matrix. Since this expression is odd under T (and P), measuring a non-vanishing d_n is also a unique signature for CP violation. The same arguments apply to d_e for the electron, whose value is determined from measurements of the EDM of paramagnetic systems (those having unpaired electrons), such as atomic *Tl*. The current experimental bounds on the neutron and electron EDMs are $d_n < 0.63 \times 10^{-25}$ e·cm (90% CL) and $d_e = (0.18 \pm 0.16) \times 10^{-26}$ e·cm, respectively [3a].

[1] Two excellent resources are Refs. [1] and [2].

In the SM, there are actually two sources of CP violation. In the electroweak sector it appears, as already mentioned, through δ_{CKM}. The other is a term in the QCD Lagrangian itself, the so-called θ-term,

$$L_{\text{eff}} = L_{\text{QCD}} + \frac{\theta g_s^2}{32\pi^2} G_{\mu\nu}\tilde{G}^{\mu\nu} \ , \qquad \text{(II.1)}$$

which explicitly violates CP symmetry because of the appearance of the product of the gluonic field operator G and its dual $\tilde{G}$. Since G couples to quarks but does not induce flavor change, d_n is much more sensitive to θ than it is to δ_{CKM}; additionally, the θ-term is practically irrelevant to d_e and kaon decays. Thus, measurement of d_n would uniquely determine an important parameter of the SM. Calculations [4,4a] have shown that $d_n \sim O(10^{-16}\theta)\ e\cdot$cm.

Although the value of the strength θ is unknown, the observed limit on d_n allows one to conclude that $\theta < 10^{-9\pm1}$ [2]. A comparable limit on θ comes from the EDM of the *Hg* atom. However, the natural scale apparent in Eq. (II.1) suggests rather that $\theta \sim O(1)$. The extreme smallness of θ (The so-called strong CP problem) begs for an explanation. One attempt [5] augments the SM by a global U(1) symmetry (referred to as the Peccei-Quinn symmetry), imagined to be spontaneously broken and to give rise to Goldstone bosons called axions. The θ-term is then essentially eliminated by the vacuum expectation value of the axion. Subsequently, much experimental effort and millions of dollars have been spent on the search for axions. The fact that axions have not been observed is, however, not in conflict with the empirical limit on the θ because other proposals exist [5a] to explain the small value of θ. For example, if CP violation is implemented spontaneously, $\theta = 0$ as the leading effect arises naturally. Clearly, an experimental determination of d_n has the potential to lead to a new paradigm for CP violation.

B. Previous Measurements of CP Violation and Future Possibilities

A CP violation signal has now been observed in both the decay of neutral K and B mesons. The CP violation signal observed in the decay of neutral kaons into two pions is characterized by parameters ε and ε'. The parameter ε', signifying *direct* CP violation, indicates a channel-dependent effect in $\pi^0\pi^0$ and $\pi^+\pi^-$ decay. The parameter ε characterizes *indirect* CP violation, an asymmetry in the $\Delta S = 2$ mixing of the neutral kaon with its anti-particle, equivalent to $K_0 - \overline{K}_0$ oscillation. The early data [6] gave

$\varepsilon = 0.002$ and $\varepsilon' = 0$. A possible explanation was given by the superweak (SW) theory of Wolfenstein [7], implying purely indirect CP violation. The most recent experimental results [8–10] are:

$$\mathrm{Re}\frac{\varepsilon'}{\varepsilon} = (21.6 \pm 3.0)\times 10^{-4} \ . \qquad \text{(II.2)}$$

These results show quite convincing evidence for the existence of $\varepsilon' \neq 0$, implying a mixture of both direct and indirect CP violation. Additionally, time-reversal violation in the neutral kaon system has been observed by the *CPLEAR* collaboration [11].

Typical predictions of the SM using the complex CKM phase are [12,13]:

$$\begin{gathered} -2.1\times 10^{-4} \leq \frac{\varepsilon'}{\varepsilon} \leq 13.3\times 10^{-4} \\ -0.5\times 10^{-4} \leq \frac{\varepsilon'}{\varepsilon} \leq 25.2\times 10^{-4} \end{gathered} \qquad \text{(II.3)}$$

depending, among other things, upon the mass taken for the strange and charmed quarks. Thus, while it appears that Refs. [8–10] have definitely opened a new window on CP violation, the interpretation of the observed signal is far from settled. It could represent another success of the CKM ansatz, but it also leaves considerable room for New Physics.

In any case, since CP violation as represented in the CKM matrix, embodies flavor mixing, d_n is very small in the SM: calculations predict it to be 10^{-32} to 10^{-31} e·cm [14] (10^{-30} e·cm [15]) well beyond the reach of any experiment being considered at present. An estimate in the superweak theory gives d_n (SW) ~ 10^{-29} e·cm [16], beyond the range of our proposed EDM measurement. Because of the experimental evidence indicating the presence of direct CP violation, a pure $\Delta S = 2$ interaction is now known to be insufficient, and the SW prediction for d_n is no longer relevant. As d_e cannot originate in the SM even from three-loop diagrams, the prediction of the SM, d_e (SM) < 10^{-40} e·cm [17], is also well beyond current experimental capabilities.

As will be discussed in Sect. II.D, models of New Physics, including left-right symmetric models, non-minimal models in the Higgs sector, and supersymmetric models, allow for CP violating mechanisms not found in the SM, including terms that do not change flavor. For this reason searches for d_n and d_e, which are particularly insensitive to flavor-changing parameters (such as δ_{CKM}), have been significant for the development of such models. The models allow for effects that might be observed in a variety of experiments including the new searches for d_n and d_e, B-meson decay, transverse polarization of muons in $K_{\mu 3}$ decay; decays of hyperons; decays of τ leptons; and CP violation in charmed hadron decays.

If the origin of CP violation is essentially correctly described in the SM through δ_{CKM}, large characteristic CP asymmetries are predicted for B-decay [2]. Recent results from the *Belle* and *BaBar* collaborations present compelling evidence for CP violation in the neutral B meson system roughly consistent with these expectations [17a]. However, the large, CP violating effects in B decay arising in the SM could be obscuring signals of New Physics that would be manifest otherwise in these decays. In this case, the fact that CP violation arising from the CKM matrix is very small in d_n leaves open the possibility that measurable effects will be found in d_n even if further analysis finds no deviation from the SM in B decays.

More generally, models of New Physics contain sources of CP violation that affect both flavor-changing and flavor-conserving sectors with a relative weighting characteristic of the model. Correlations between flavor-changing and flavor-non-changing observables (such as between B decay and EDMs) can provide important clues to distinguish among competing theories. Of course, if no CP asymmetries had been found in B decays on a measurable level, we would know immediately that the CKM ansatz is not a significant factor in neutral kaon decays and that physics beyond the SM drives these reactions. Here again, measurement of d_n would narrow the possible sources of New Physics.

C. CP Violation and the Baryon Asymmetry of the Universe (BAU)

One of the great puzzles of physics is the fact that the Universe contains any matter at all. The naïve expectation is rather that matter and antimatter in the universe should balance out, i.e. that the baryon asymmetry $\Delta n_{\mathrm{Bar}} / (n_{\mathrm{Bar}} + n_{\overline{\mathrm{Bar}}})$, where $\Delta n_{\mathrm{Bar}} = n_{\mathrm{Bar}} - n_{\overline{\mathrm{Bar}}}$ is the difference in the abundances of baryons and antibaryons, should have vanished in the creation of the Universe.

The baryon asymmetry can be quantified in terms of estimates of the number of baryons in the Universe today, $n_{\mathrm{Bar}}|_{today}$, and the number of photons in the cosmic background n_γ. One observes that the ratio $r_{Bar} \equiv n_{\mathrm{Bar}}|_{today} / n_\gamma$ is just a few 10^{-10}, i.e., that the Universe is strikingly dilute, containing just a single baryon for every 10^9 or so photons.

Of course, $n_{\rm Bar}$ changes over time. During an earlier epoch, when the temperature was above the threshold for production of nucleons and anti-nucleons ($T \sim 10^{13}$K), both species were plentiful and were in thermal equilibrium with the photons. At this time, $\Delta n_{\rm Bar} \approx n_{\rm Bar}\ |_{today}$, and $n_{\rm Bar} + n_{\overline{\rm Bar}} \cong n_\gamma$, ($n_\gamma$ is roughly constant in time) [18]. The baryon asymmetry at this earlier epoch is therefore approximately equal to the value of $r_{\rm Bar}$,

$$\frac{\Delta n_{\rm Bar}}{n_{Bar} + n_{\overline{Bar}}} = r_{\rm Bar} \approx \ \sim \text{few } 10^{-10}. \qquad \text{(II.4)}$$

The basic question is: how could this BAU result from physical processes happening since the birth of the Universe in the Big Bang some $\tau_U \sim 10^{10}$ years ago?

In a seminal paper, A. Sakharov [19] raised the definite possibility of calculating the BAU from basic principles. He identified three criteria that, if satisfied simultaneously, will lead to a baryon asymmetry: (1) reactions that change baryon number have to occur; (2) these reactions must be CP violating; and (3) they must occur in non-equilibrium processes. Attempts to understand the BAU from this point of view has focused on two distinct eras of Big Bang evolution. One, the era of grand unified theory (GUT) baryogenesis, occurred when the temperature of the Universe was $T \approx 10^{29}$K , corresponding to the mass $M_x \approx 10^{16}$ GeV expected of a GUT gauge particle. The other, the era of electroweak baryogenesis, corresponds to $T \approx 10^{15}$K or energies of about 100 GeV comparable to the mass of a *W* or *Z* gauge boson. For us, the important point is that a quantitative characterization of CP violation is an essential element for achieving an understanding of $r_{\rm Bar}$ along the lines suggested by Sakharov.

Electroweak baryogenesis [20] is currently one of the most actively pursued scenarios since electroweak dynamics is fairly well understood. Shaposhnikov [21] has analyzed this in the SM. In the SM and other non-Abelian gauge theories there exist multiple and topologically distinct vacuum states distinguished by their baryon number *B* (and lepton number *L*). Although baryon current conservation strictly forbids transitions among states of different *B* at the classical level, one finds quantum mechanically that the divergence of the baryon current is subject to triangle anomalies that signify symmetries broken at a quantum mechanical level but conserved classically. Thus, *B*-violating transitions are no longer forbidden, and the corresponding probability may be expressed in terms of instanton-like gauge field configurations [22], sometimes called sphalerons. This probability is extremely small for $T \approx 0$ as in the Universe today (the proton lifetime τ_p (> 10^{32} yr.) >> τ_U); however, when $T > 10^{17}$K , sphalerons are easily excited, in which case anomalous B violation may be extremely rapid [23]. In this way the first Sakharov condition is satisfied in the SM. The second Sakharov condition is satisfied in the SM through the explicit CP violation present in the CKM matrix. Finally, if conditions of supercooling prevail at electroweak-scale temperatures, then the third Sakharov condition would be satisfied in the first-order transition, occurring as droplets of the broken phase began to nucleate out. Supercooling refers to the situation where the universe cools (through expansion) beyond the point at which a phase change would already have occurred under equilibrium conditions.

However, Shaposhnikov [21] was unable to describe r_{Bar} quantitatively in the SM. The SM has two shortcomings. First, the SM does not supply enough CP violation. Secondly, it is now believed that a single Higgs doublet as incorporated into the SM would not support a first-order electroweak phase transition. This is because a single Higgs doublet with mass, M_H, greater than 70 GeV is known, from Lattice Gauge calculations [24], to be insufficient for supercooling and because LEP measurements suggest that M_H exceeds 100 GeV. Clearly, some physics beyond the SM, including new sources of CP violation that may lead to a measurable value for d_n, must exist if the observed BAU is to be understood.

One such source might be found in the minimal supersymmetric extension of the SM (MSSM). It has been shown recently [25] that small values of the CP violating phases (consistent with constraints from d_n) can provide values of r_{Bar} comparable to the empirical value given in Eq. (II.1).

Another such source could be GUT physics. It is generally believed that GUT physics would easily satisfy the three Sakharov conditions, with baryon number being generated in most GUTs through C- and CP-violating asymmetries in the decays of particles of masses near M_X. However, the following concerns have been raised about GUT baryogenesis [23,26]. The first problem is that the physics involved, is not likely to be directly testable in the foreseeable future. The second is the erasure of symmetry, meaning that the thermal sphaleron-mediated B-changing reactions discussed in connection with baryogenesis during the electroweak era, would be capable of undoing any $B + L$ production having arisen prior to or during Grand Unification.

However, there is yet another possibility for generating BAU. If at some temperature, well above the electroweak phase transition, an excess of leptons over anti-leptons is generated, sphaleron mediated processes, which conserve $B - L$, can communicate this asymmetry to the baryon sector [27]. The simplest way this can be realized is by adding a heavy right-handed Majorana neutrino to the SM. Since such a neutrino is its own CPT image, its decay necessarily violates lepton number conservation, which can be translated into a lepton asymmetry through a CKM analog to the neutrino mass matrix. The resulting lepton asymmetry is transferred into a baryon number through the sphaleron-mediated processes in the unbroken high energy phase of $SU(2)_L \times U(1)$. Whether this would have an observable impact on d_n would depend on the actual scenario by which CP violation is realized in the lepton-number violating processes.

The most relevant conclusion to be drawn from the above discussion is the following: to explain the BAU through GUT or electroweak baryogenesis, substantial New Physics in the CP violating sector is required. As we have indicated, identifying the new source is subject to scrutiny through a variety of new experiments—and the value of d_n may well play an important role in quantifying it. Identification of any new source of CP violation, beyond that presently represented in the SM, may have a significant impact on our understanding of baryogenesis.

D. Models of New Physics

As we have mentioned, the evidence that the SM adequately represents CP violation is clearly not compelling, leading to the somewhat obvious conclusion that finding any new measure of CP violation would be enormously significant. To anticipate how hard we would have to look to find it by a measurement of d_n, and what we might conclude from such a measurement, we turn to models embodying New Physics. The models provide a natural and reasonable expectation that that the values of d_n may lie at levels just beyond current empirical limits. Additionally, these models clearly show that significant correlations among different CP measurements can be expected, and that knowledge of these correlations is essential to unraveling the origin of the effects once they are found. If d_n is *not* seen at levels just beyond current empirical limits, one would arrive at the important conclusion that something quite special is going on.

In the following discussion of models we focus on d_n, but it is perhaps worth noting that the EDM of atoms (see below) and of the electron are also relevant. In many models d_e is predicted to lie at least an order of magnitude below d_n. The reasons for this are the smaller chirality flip and weaker gauge couplings for leptons [28]. However, there is a great deal of model dependence and in the absence of experimental information, d_e or d_n may be favored by the specific choice of parameters. In parallel to our efforts to improve the experimental sensitivity to d_n, ambitious attempts to improve on the electron EDM measurements are being vigorously pursued (see e.g., [29] in which a factor of 10^4

improvement in statistical sensitivity is being sought in a measurement on an excited metastable state of PbO). Based on experience with these theoretical models, and the current empirical limits, one may infer that new experiments to measure d_e or d_n would have to exhibit about the same improvements in sensitivity over existing measurements to be competitive.

Left-right symmetric gauge models [30] have many intriguing features such as the highly symmetric starting point that motivates them. Although many potential dynamical sources of CP violation exist, the EDM in these models is driven by $W_L - W_R$ mixing, the scale of which is set by the mass of the W_R. These models are interesting for us because they show that it is possible, through $W_L - W_R$ mixing, to have ε' agree with neutral kaon decay, yet have d_n large enough to be observable (at the level of O(10^{-27}) e·cm [2]). The electron EDM can be naturally in the range of 10^{-26} to 10^{-28} e·cm [28]. The most strict limits on the relevant parameters in these models [31] have been determined from measurement of the EDM of diamagnetic atoms (atoms with paired electrons such as ^{129}Xe and ^{199}Hg). Diamagnetic systems are sensitive to *CP* violating effects predominantly through the nuclear force rather than through d_e (see, *e.g*., Eq. (II.6), below).

CP violation in the CKM matrix of the SM is envisioned to occur "minimally" via the complex couplings of the Higgs to the fermions. A class of non-minimal models arises in the Higgs sector through CP violation generated from spontaneous symmetry breaking. There is considerable latitude in constructing these models, since the Higgs sector represents the largest area of unknown physics of the SM and lacks direct experimental support. One may discuss the EDM in these models in terms of the following classification: (1) Higgs exchanges which generate an EDM for individual quarks d_q or leptons. Such direct one-loop contributions with charged Higgs, tend to give a large d_n incompatible with experimental upper limits, if one insists that the empirical value of ε also originates entirely within this sector [32]. Thus, for these models to be viable, one must arrange for ε to arise in part (or entirely) from other sources (such as the CKM phase). (2) CP odd gluonic operators which induce a d_n. Since the contribution of these operators is suppressed by successively higher powers of M_H with increasing operator dimension, the operator most likely to give the dominant contribution to d_n (excluding $G\tilde{G}$, which is related to θ as discussed earlier) is $G^2\tilde{G}$. Estimates for the resulting d_n suggest values $d_n \sim \mathrm{O}(10^{-26})$ e·cm [33,34]. (3) Quark color-electric dipole moments, d_q^{QCD}, (two-loop effects) that lead to large d_n with values close to the current upper bound [33,35,36]. The corresponding two-loop contribution to d_e is obtained by replacing gluons in the color-electric dipole operator by electroweak gauge bosons and attaching them to a lepton. This yields d_e ~ few 10^{-27} [33,35-38] which is just at the present experimental bound. Recognizing that this classification is actually quite general and applicable in particular to supersymmetric theories [38a], the EDM of the neutron and the paramagnetic atom *Tl* can be expressed in terms of quantities appearing in this classification as [39]

$$d_n = 1.6(\frac{4}{3}d_d - \frac{1}{3}d_u) + O(10^{-1})d_q^{QCD} + O(1)(\theta/10^{-9})d_n^{1995}$$

(II.5)

$$d_{Tl} = -600\,d_e + O(10^{-4})d_q + O(10^{-3})d_q^{QCD} + O(10^{-3})(\theta/10^{-9})\,d_{Tl}^{1995}\ .$$

Corresponding relationships exist for the diamagnetic atoms; a typical result is

$$d_{Xe} = 10^{-3}d_e + O(10^{-4})d_q + O(10^{-3})d_q^{QCD} + O(10^{-1})(\theta/10^{-9})d_{Xe}^{1995}\ . \qquad \text{(II.6)}$$

In these expressions, the contribution from strong CP violation involving the θ-term, has been expressed in terms of the current upper bounds ($d_{Tl}^{1995} \leq 6.6\ 10^{-24}$ e-cm, $d_{Xe}^{1995} \leq 1.4\ 10^{-26}$ e-cm, and $d_n^{1995} \leq 0.8\ 10^{-25}$ e-cm). A recent analysis [40] within the context of the MSSM has shown that the measurement [41] of the EDM of ^{199}Hg may be providing the most reliable constraint on CP violating phases.

Thus, one cannot rule out the possibility that non-minimal Higgs models will lead to values for d_n and d_e that are observable with the improvements in sensitivity planned in next-generation experiments. These models may also make significant contributions to other CP violating observables, such as the transverse polarization in $K_{\mu 3}$ decay, without necessarily having much effect on kaon decays. They are especially worthy of attention since Higgs dynamics also appears to be capable of providing sufficient CP violation to generate the BAU of today's Universe at the electroweak scale.

There is one very elegant theoretical scheme in which scalars such as Higgs arise quite naturally—namely supersymmetry (SUSY). Here, scalars arise as superpartners of fermions. In the MSSM, only two new observable CP-violating phases emerge: one is analogous to the usual CKM phase, whose effect is felt throughout various sectors of the theory, and the other is a phase reflecting soft SUSY breaking. The latter is severely restricted already by the experimental bound on d_n, which makes this phase irrelevant to neutral kaon decay [2]. However, within the broad framework of non-minimal SUSY models, including GUTs, there are numerous new sources of CP violation to be found in complex Yukawa couplings and other Higgs parameters that may have observable effects on d_n and d_e [2,39,42,43]. While large effects emerge in beauty decays, there are sizable deviations from the CKM expectations. Within each scenario there can be numerous non-trivial correlations among the CP observables, rare decay rates, and gross features of the particle spectrum; for example, in the SO(10) GUT, d_n and d_e scale as $1/m^2$ with the scale *m* of supersymmetry breaking, whereas the $\mu \to e\gamma$ rate scales as $1/m^4$ [42].

E. Summary and Conclusions

We have seen that there is ample reason to expect a non-zero value for the neutron electric dipole moment, with many theories predicting values lying within the six-orders of magnitude window between the current limit and the value allowed by the Standard Model. We conclude that experiments able to explore the next two orders of magnitude would make a significant contribution to the search for New Physics.

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