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CP Violation and Rare Decays

Chris Quigg

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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CP VIOLATION AND RARE DECAYS

Chris Quigg*
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510 USA

ABSTRACT

After a brief essay on the current state of particle physics and possible approaches to the opportunities before us, I summarize the contributions to the Third Workshop on Physics and Detectors for DAΦNE that deal with CP Violation and Rare Decays.

1 Prologue

This is my first visit to Frascati, and it has been thrilling for me to be in this laboratory of such great significance to the development of electron–positron colliding beams. I have greatly enjoyed the engagement between theory and experiment in the laboratory, the spirit of this week's workshop, and the sense of anticipation for the DAΦNE physics program.

I am delighted that our hosts have arranged a post-workshop visit to the Vatican Museums and the Sistine Chapel. In February of 1988, I brought my children to Rome during their school vacation. In the course of our visit to the Vatican Museums, we came across a temporary exhibition in which a panel displayed a passage that struck me as so remarkable and perceptive that I copied it down in my notebook:

* E-mail address: quigg@fnal.gov.

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Italiano	English
Il *De Rerum Natura* di Lucrezio è la prima grande opera di poesia in cui la conoscenza del mondo diventa dissoluzione della compattezza del mondo, percezione di ciò che è infinamente muto e mobile e leggero. Lucrezio vuole scrivere il poema della materia ma ci avverte subito che la vera realtà di questa materia è fatta di corpuscoli invisibili. È il poeta della concretezza fisica, vista nella sua sostanza permanente e immutibile, ma per prima cosa ci dice che il vuoto è altrettanto concreto che i corpi solidi. La più grande preoccupazione di Lucrezio sembra quella di evitare che il peso della materia ci schiacci. Italo Calvino, "Leggerezza," in *Lezioni Americane* (1988)	The *De Rerum Natura* of Lucretius is the first great work of poetry in which knowledge of the world tends to dissolve the solidity of the world, leading to a perception of all that is infinitely minute, light, and mobile. Lucretius set out to write the poem of physical matter, but he warns us at the outset that this matter is made up of invisible particles. He is the poet of physical concreteness, viewed in its permanent and immutable substance, but the first thing he tells us is that emptiness is just as concrete as solid bodies. Lucretius' chief concern is to prevent the weight of matter from crushing us . . . Italo Calvino, "Lightness," in *Six Memos for the Next Millennium*

The text is taken from the Charles Eliot Norton Lectures that Calvino prepared to deliver at Harvard.[1] Back in Berkeley, I found a copy of the American translation, *Six Memos for the Next Millennium,* one of the great short works of literary analysis and appreciation. 1) In the translation, I found that the passage on a panel in the Vatican Museums concludes, "The poetry of the invisible, of infinite unexpected possibilities—even the poetry of nothingness—issues from a poet who had no doubts whatever about the physical reality of the world." For us who have no doubts whatever about the physical reality of the world, who experience daily the poetry of the invisible, of infinite unexpected possibilities—even of nothingness—it is inspiring to see our passion and our confidence in Nature reflected in Calvino's scan of Lucretius. I hope that each of you will have a similar epiphany in the Vatican Museums tomorrow.

2 What Strange Particles Have Been Telling Us . . . (When We Have Known How to Listen)

For half a century, the strange particles have offered us important clues to the nature of matter and the character of the forces that shape the world. It is interesting to consider some of the phenomena that pointed the way to our current picture of constituents and interactions, and the lessons we drew—or could have drawn—from them.

[1] He died on September 19, 1985, just before departing for Cambridge.

- *Strangeness.*

  At a time when the significance of isospin was incompletely appreciated, the K mesons and hyperons showed us the importance of an imperfectly conserved quantum number, and of the notion that different interactions can respect different symmetries.

  As our understanding of internal symmetries matured, strange particles pointed the way to $SU(3)_{\mathrm{flavor}}$ as a classification symmetry for the hadrons. The observation in the 1960s that all mesons fit into $SU(3)_{\mathrm{flavor}}$ singlets and octets, and that all baryons fit into $SU(3)_{\mathrm{flavor}}$ singlets, octets, and decimets, pointed to the quark model, with its rule that mesons are composed of $q\bar{q}$ and baryons of qqq. It is important to note that the quark model gives us a new view of additive quantum numbers, not as quantities carried by particles—to be loaded and unloaded—but as defining attributes of the fundamental constituents, the quarks.

  The conflict between the symmetric sss wave function of the Ω^- and the Pauli principle led to the introduction of color as a hitherto unobserved quantum number and, eventually, to the development of quantum chromodynamics as the theory of the strong interactions.

- *Kaon Decays*

  The τ/θ puzzle challenged the implicit notion that the fundamental interactions are invariant under parity, and set in motion the chain of investigations that gave us the $V - A$ theory of the (charged-current) weak interactions.

  The identification of K_S and K_L provided the opportunity to observe quantum-mechanical superposition effects over macroscopic distances and focused attention on CP eigenstates.

  The very different rates for the decays $K_S \to \pi^+\pi^-$ and $K^+ \to \pi^+\pi^0$ gave evidence for the $\Delta I = \frac{1}{2}$ rule in nonleptonic weak decays. Though we saw it only in retrospect, the nonleptonic "octet" enhancement that accounts for the $\Delta I = \frac{1}{2}$ rule requires colored quarks and the short-distance effects of the strong interaction.

  The notion of Cabibbo universality gave rise to the idea of mixing between quark generations and laid the foundation for a theory of weak interactions based (in part) on $SU(2)_L$ symmetry, which gives the framework for a connection between quarks and leptons.

- *Rare Decays*

  The suppression of the strong decay $\phi \to \pi^+\pi^-$ gave us clues about the character of the strong interaction, embodied in the Okubo–Zweig–Iizuka rule, and offered a template for understanding the inhibited decays of J/ψ and Υ into hadrons.

  The absence of flavor-changing neutral currents inspired the second coming of charm and the Glashow–Iliopoulos–Maiani mechanism.

  The agreement between the observed rate for the decay $K_L \to \mu^+\mu^-$ and conventional expectations indicated that the charmed quark could not be arbitrarily heavy, and permitted an estimate $m_c \approx 1.5$ GeV/c^2.

- CP *Violation*

  The observation of the CP-violating decay $K_L \to \pi^+\pi^-$ suggested the need for at least three doublets of quarks (therefore of leptons) and gave us reason to explore scenarios for cosmic baryogenesis.

  The discovery that the direct CP-violating parameter $\varepsilon' \neq 0$ demonstrates that a superweak interaction is not the (only) source of CP violation, and supports the phase in the quark-mixing matrix as the dominant origin of CP violation.

- K^0–$\bar{K}^0$ *Mixing*

  The degree of K^0–$\bar{K}^0$ mixing, which is to say the K_L–K_S mass difference, together with the value of the CP-violating parameter ε, offered a hint that the mass of the top quark was quite large.

Not all of these items represent finished business. What clues have we missed? What is to come?

3 Our Picture of Matter

Twenty-five years after the November Revolution, our understanding of physical phenomena is grounded in the identification of fundamental constituents, at the current limits of resolution of about 10^{-18} m, and a few fundamental forces. The constituents—our elementary particles—are the pointlike quarks

$$\begin{pmatrix} u \\ d \end{pmatrix}_L \quad \begin{pmatrix} c \\ s \end{pmatrix}_L \quad \begin{pmatrix} t \\ b \end{pmatrix}_L \tag{1}$$

and leptons

$$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L \qquad \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L \tag{2}$$

with strong, weak, and electromagnetic interactions specified by $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ gauge symmetries.

It is instructive to consider the agenda of particle physics today under four rubrics:

- *Elementarity.* Are the quarks and leptons structureless, or will we find that they are composite particles with internal structures that help us understand the properties of the individual quarks and leptons?

- *Symmetry.* One of the most powerful lessons of the modern synthesis of particle physics is that (local) symmetries prescribe interactions. Our investigation of symmetry must address the question of which gauge symmetries exist (and, eventually, why). We must also understand how the symmetries are hidden from us in the world we inhabit. For the moment, the most urgent problem in particle physics is to complete our understanding of electroweak symmetry breaking by exploring the 1-TeV scale. This is the business of the experiments at LEP2, the Tevatron Collider, and the Large Hadron Collider.

- *Unity.* In the sense of developing explanations that apply not to one individual phenomenon in isolation, but to many phenomena in common, unity is central to all of physics, and indeed to all of science. At this moment in the development of particle physics, the quest for unity takes several forms. First, we have the fascinating possibility of gauge coupling unification, the idea that all the interactions we encounter have a common origin and thus a common strength at suitably high energy. Second, there is the imperative of anomaly freedom in the electroweak theory, which urges us to treat quarks and leptons together, not as completely independent species. Both of these ideas are embodied, of course, in unified theories of the strong, weak, and electromagnetic interactions, which imply the existence of still other forces—to complete the grander gauge group of the unified theory—including interactions that change quarks into leptons. The third aspect of unity is the idea that the traditional distinction between force particles and constituents might give way to a unified understanding of all the particles. The gluons of QCD carry color charge, so we can imagine quarkless hadronic matter in the form of glueballs. Beyond that breaking down of the wall between messengers and constituents, supersymmetry relates fermions and bosons. Finally, we desire a reconciliation between the powerful outsider, gravity, and the forces that prevail in the quantum world of our everyday laboratory experience.

- *Identity.* We do not understand the physics that sets quark masses and mixings. Although we are testing the idea that the phase in the quark-mixing matrix lies behind the observed CP violation, we do not know what determines that phase. The accumulating evidence for neutrino oscillations presents us with a new embodiment of these puzzles in the lepton sector. At bottom, the question of identity is very simple to state: What makes an electron and electron, and a top quark a top quark?

One aspect of the problem of identity is the origin of mass. In particle physics, we know the challenge of explaining many different kinds of mass. The masses of the hadrons are (in principle, and with increasing precision in practice) understood from QCD in terms of the energy stored to confine a color-singlet configuration of quarks in a small volume. [2)] We also have an excellent understanding of the masses of the electroweak gauge bosons $W^{\pm}$ and Z^0 as consequences of electroweak symmetry breaking, in terms of a single weak mixing parameter, $\sin^2\theta_W$.[2] When we get to the question of quark and (charged) lepton masses, however, our understanding is considerably more primitive. For each of these, we require not just the scale of electroweak symmetry breaking, but a distinct and apparently arbitrary Higgs-fermion-antifermion Yukawa coupling to reproduce the fermion mass. For neutrinos, which may be their own antiparticles, there are still more possibilities for new physics to enter, and, for the moment, more room for bafflement.

4 The Problems of Mass, and of Mass Scales

As we have just remarked, electroweak symmetry breaking sets the values of the W- and Z-boson masses. At tree level in the electroweak theory, we have

$$M_W^2 = g^2v^2/2 = \pi\alpha/G_F\sqrt{2}\sin^2\theta_W, \quad (3)$$

$$M_Z^2 = M_W^2/\cos^2\theta_W, \quad (4)$$

where the electroweak scale is $v = (G_F\sqrt{2})^{-\frac{1}{2}} \approx 246$ GeV. But the electroweak scale is not the only scale. It seems certain that we must also consider the Planck scale,

[2] Although for the moment we take this parameter from experiment, we understand how it arises in a unified theory. Indeed, in a unified theory we can hope to understand the parameter $\Lambda_{\rm QCD}$ that sets the scale of the hadron masses.

derived from the strength of Newton's constant,

$$M_{\text{Planck}} = (\hbar c / G_{\text{Newton}})^{\frac{1}{2}} \approx 1.22 \times 10^{19}\ \text{GeV}\ . \tag{5}$$

It is also probable that we must take account of the $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ unification scale around 10^{15-16} GeV. And, as we heard on the first day of the workshop from Antonio Masiero, [3)] there may well be a distinct flavor scale. The existence of other scales is behind the famous problem of the Higgs scalar mass: how to keep the distant scales from mixing in the face of quantum corrections, or how to stabilize the mass of the Higgs boson on the electroweak scale.

It is because G_{Newton} is so small (or because M_{Planck} is so large) that we normally consider gravitation irrelevant for particle physics. The graviton-quark-antiquark coupling is generically $\sim E/M_{\text{Planck}}$, so it is easy to make a dimensional estimate of the branching fraction for a gravitationally mediated rare kaon decay: $B(K_L \to \pi^0 G) \sim (M_K/M_{\text{Planck}})^2 \sim 10^{-38}$, which is truly negligible!

We know from the electroweak theory alone that the 1-TeV scale is special. Partial-wave unitarity applied to gauge-boson scattering tells us that unless the Higgs-boson mass respects

$$M_H^2 < \frac{8\pi\sqrt{2}}{3G_F} \approx 1\ \text{TeV}^2\ , \tag{6}$$

new physics is to be found on the 1-TeV scale. To stabilize the Higgs-boson mass against uncontrolled quantum corrections, and to resolve the mass-hierarchy problem, we consider electroweak physics beyond the standard model. The most promising approaches are to generalize $SU(3)_c \otimes SU(2)_L \otimes U(1)_Y$ to a theory with a composite Higgs boson in which the electroweak symmetry is broken dynamically (technicolor and related theories) or to a supersymmetric standard model.

Let us look a little further at the problem of fermion masses. In the electroweak theory, the value of each quark or charged-lepton mass is set by a new, unknown, Yukawa coupling. Taking the electron as a prototype, we define the left-handed doublet and right-handed singlet

$$\mathsf{L} = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L , \qquad \mathsf{R} \equiv e_R. \tag{7}$$

Then the Yukawa term in the electroweak Lagrangian is

$$\mathcal{L}^{(e)}_{\text{Yukawa}} = -\zeta_e[\bar{\mathsf{R}}(\varphi^\dagger \mathsf{L}) + (\bar{\mathsf{L}}\varphi)\mathsf{R}]\ , \tag{8}$$

where φ is the Higgs field, so that the electron mass is $m_e = \zeta_e v/\sqrt{2}$. Inasmuch as we do not know how to calculate the fermion Yukawa couplings ζ_f, I believe that *we should consider the sources of all fermion masses as physics beyond the standard model.*

Note that the values of the Yukawa couplings are vastly different for different fermions: for the top quark, $\zeta_t \approx 1$, for the electron $\zeta_e \approx 3\times10^{-6}$, and if the neutrinos have Dirac masses, presumably $\zeta_\nu \approx 10^{-10}$.[3] What accounts for the range and values of the Yukawa couplings? Our best hope until now has been the suggestion from unified theories that the pattern of fermion masses simplifies on high scales. The classic intriguing prediction of the $SU(5)$ unified theory involves the masses of the b quark and the τ lepton, which are degenerate at the unification point for a simple pattern of spontaneous symmetry breaking. The different running of the quark and lepton masses to low scales then leads to the prediction $m_b \approx 3m_\tau$, in suggestive agreement with what we know from experiment.

The conventional approach to new physics has been to extend the standard model to understand why the electroweak scale (and the mass of the Higgs boson) is so much smaller than the Planck scale. [3)] A novel approach that has been developed over the past two years is instead to *change gravity* to understand why the Planck scale is so much greater than the electroweak scale. Now, experiment tells us that gravitation closely follows the Newtonian force law down to distances on the order of 1 mm. Below about a millimeter, the constraints on deviations from Newton's inverse-square law deteriorate rapidly, so nothing prevents us from considering changes to gravity even on a small but macroscopic scale. For its internal consistency, string theory requires an additional six or seven space dimensions, beyond the $3+1$ dimensions of everyday experience. Until recently it has been presumed that the extra dimensions must be compactified on the Planck scale, with a compactification radius $R_{\mathrm{unobserved}} \approx 1/M_{\mathrm{Planck}} \approx 1.6\times10^{-35}$ m. The new wrinkle is to consider that the $(SU(3)_c \otimes SU(2)_L \otimes U(1)_Y)$ standard model gauge fields, plus needed extensions, reside on $3+1$-dimensional branes, not in the extra dimensions, but that gravity can propagate into the extra dimensions.

How does this hypothesis change the picture? The dimensional analysis (Gauss's law, if you like) that relates Newton's constant to the Planck scale changes. If gravity propagates in n extra dimensions with radius R, then

$$G_{\mathrm{Newton}} \sim M_{\mathrm{Planck}}^{-2} \sim M^{\star\,-n-2} R^{-n} \ , \tag{9}$$

where $M^\star$ is gravity's true scale. Notice that if we boldly take $M^\star$ to be as small as 1 TeV, then the radius of the extra dimensions is required to be smaller than

[3] I am quoting the values of the Yukawa couplings at a low scale typical of the masses themselves.

about 1 mm, for $n \geq 2$. What we know as the Planck scale is then a mirage that results from a false extrapolation: treating gravity as four-dimensional down to arbitrarily small distances, when in fact—or at least in this particular fiction—gravity propagates in $3+n$ spatial dimensions. The Planck mass is an artifact, given by $M_{\text{Planck}} = M^{\star}(M^{\star}R)^{n/2}$.

Although the idea that extra dimensions are just around the corner—either on the submillimeter scale or on the TeV scale—is preposterous, it is not ruled out by observations. For that reason alone, we should entertain ourselves by entertaining the consequences. Many authors have considered the gravitational excitation of a tower of Kałuza–Klein modes in the extra dimensions, which would give rise to a missing (transverse) energy signature in collider experiments. [4)] We call these excitations *provatons,* after the Greek word for a sheep in a flock.[4]

"Large" extra dimensions present us with new ways to think about the exponential range of Yukawa couplings. Arkani-Hamed, Schmaltz, and collaborators [5)] have speculated that if the standard-model brane has a small thickness, the wave packets representing different fermion species might have different locations within the extra dimension. On this picture, the Yukawa couplings measure the overlap in the extra dimensions of the left-handed and right-handed wave packets and the Higgs field, presumed pervasive. Exponentially large differences might then arise from small offsets in the new coordinate(s). True or not, it is a completely different way of looking at an important problem.

5 CP Violation in the Standard Model

In the standard electroweak theory, the charged-current interactions may be represented as

$$\begin{pmatrix} \bar{u} & \bar{c} & \bar{t} \end{pmatrix}_L \mathsf{V} \begin{pmatrix} d \\ s \\ b \end{pmatrix}_L , \tag{10}$$

where the (Cabibbo–Kobayashi–Maskawa [6, 7)]) quark-mixing matrix is

$$\mathsf{V} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} . \tag{11}$$

Within the framework of the standard model, the elements of V originate in the Yukawa couplings of the quarks to the Higgs field; accordingly, they offer a link to

[4] I thank Maria Spiropulu for instructing me in the difference between $\pi\rho\acute{o}\beta\alpha\tau o\nu$ and $\alpha\rho\nu\grave{\iota}$.

physics beyond the standard model. For three generations of quarks, the mixing matrix depends on three real angles and one phase; the phase is the source of CP violation. [8, 9, 10]

The quark-mixing matrix is unitary: $\mathsf{V}\mathsf{V}^\dagger = \mathsf{I}$. Consequently the product of any row or column of the matrix with the complex conjugate of another must vanish. For a 3×3 matrix, each such equation may be depicted as a closed triangle in the complex plane. There are six distinct unitarity triangles. [11] In a convenient parametrization, [12] we can express the quark-mixing matrix in terms of three real quantities and one imaginary quantity as

$$\mathsf{V} = \begin{pmatrix} 1-\frac{1}{2}\lambda^2 & \lambda & A\lambda^3(\rho - i\eta) \\ -\lambda & 1-\frac{1}{2}\lambda^2 & A\lambda^2 \\ A\lambda^3(1-\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix} + \mathcal{O}(\lambda^4)\;, \tag{12}$$

The phases lie in the extreme off-diagonal elements; they are designated by

$$\begin{pmatrix} 1 & 1 & e^{-i\gamma} \\ 1 & 1 & 1 \\ e^{-i\beta} & 1 & 1 \end{pmatrix}\;. \tag{13}$$

A third angle is defined by the triangle constraint $\alpha \equiv \pi - \beta - \gamma$.

One way to characterize the task of testing the hypothesis that all CP violation (among the known particles) arises from the phase in the quark-mixing matrix is to try to overconstrain the unitarity triangle(s), by measuring the sides and angles in many different ways. The bd triangle is shown twice in Figure 1. On the left, I show the triangle schematically, and indicate the kinds of measurements that give us information about the various sides and angles. On the right, I show a summary of what we currently know about the shape of the bd triangle. [13] The sources of our knowledge were reviewed in Frascati by Ahmed Ali, [9] Guido Martinelli, [10], and Gerhard Buchalla [14]. Our most important objectives for the near future are the measurements of the quantity $\sin 2\beta$ in $B^0 \to J/\psi\ K_S$ decays and the rate of B_s–$\bar{B}_s$ mixing, and pushing on to measure the rates for the *rarissime* decays $K^+ \to \pi^+\nu\bar{\nu}$ and $K_L \to \pi^0\nu\bar{\nu}$.

Before leaving these generalities, I want to offer a few comments about CP violation and the matter asymmetry of the Universe. We learned long ago from Andrei Sakharov [15] that three criteria must be fulfilled to generate a matter asymmetry in a universe that begins from neutral initial conditions. We require

1. Microscopic CP violation, such as Christenson, *et al.* first observed in the decay $K_L \to \pi\pi$. [16]

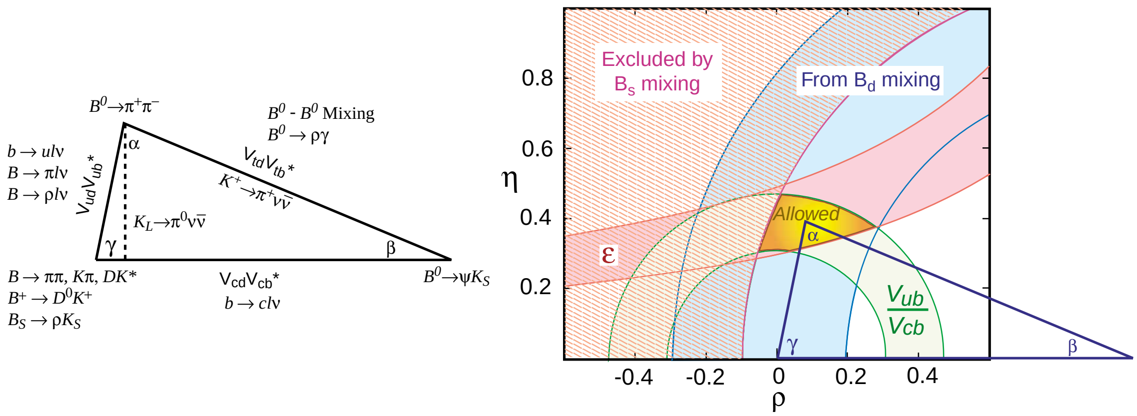

Figure 1: *The bd unitary triangle. On the left, the angles α, β, and γ are defined and some of the decay modes that allow measurements of the sides, angles, and altitude are indicated. On the right, the normalized unitary triangle is depicted in the ρ-η plane, and the current experimental constraints are indicated.*

2. Baryon- (lepton-) number violating processes, of the kind implied by unified theories of the strong, weak, and electromagnetic interactions.

3. A universe that evolves out of thermal equilibrium during baryogenesis, a condition natural in the hot big-bang scenario.

According to our current understanding of baryogenesis, [17)] the observed baryon excess in the Universe, characterized by the baryon-to-photon ratio $n_B/n_\gamma \approx 4\times10^{-10}$, cannot be reproduced within the standard model by the CP violation that arises from the quark-mixing phase. It is just barely possible to generate the observed baryon density at the electroweak scale within the minimal supersymmetric extension of the standard model, but this requires that the lightest Higgs boson lie within reach of LEP experiments, $M_h \lesssim 105$ GeV/c^2, *and* that the lighter top squark be less massive than the top quark, $m_{\tilde{t}_1} \lesssim m_t$. These two requirements do not yet conflict with experiment, but it is likely that we need new sources of CP violation to account for the matter excess. It is important that we speak precisely when we tell the world what we expect to learn from the detailed study of CP violation in the B mesons: it is unlikely that we shall unlock the secrets of primordial baryogenesis, although the increased understanding we gain into CP violation in the quark sector may give us new insights into what it would take to explain the matter excess. We should not promise what we do not expect to deliver!

6 Workshop Headlines

6.1 $\varepsilon' \neq 0$!

The most significant result of this year for the study of CP violation is the conclusion from the KTeV experiment at Fermilab and the NA48 experiment at CERN that CP invariance is violated directly in the decay $K_L \to \pi\pi$. Let us recall for a moment the phenomenological setting of these new experimental results.

In a CPT-invariant theory, we can write the neutral kaons of definite mass and lifetime as

$$|K_S\rangle = p|K^0\rangle + q|\bar{K}^0\rangle \ , \quad |K_L\rangle = p|K^0\rangle - q|\bar{K}^0\rangle \ . \tag{14}$$

If CP invariance holds, then $p = q = 1/\sqrt{2}$, and $(|K_S\rangle, |K_L\rangle)$ is a CP eigenstate with CP $= (+1, -1)$. A small CP impurity can be represented by the parameter ε, through the connection

$$\frac{p}{q} = \frac{(1+\varepsilon)}{(1-\varepsilon)} \ ; \tag{15}$$

the observed $K_L \to \pi\pi$ decay rate fixes $|\varepsilon| \approx 2.28 \times 10^{-3}$. A direct CP violation in the decay amplitude leads to unequal rates for the charged and neutral decay modes that is expressed through the parameter ε', as [18]

$$\begin{aligned} \eta_{+-} = & \ \frac{A(K_L \to \pi^+\pi^-)}{A(K_S \to \pi^+\pi^-)} = \varepsilon + \varepsilon' \ , \\ \eta_{00} = & \ \frac{A(K_L \to \pi^0\pi^0)}{A(K_S \to \pi^0\pi^0)} = \varepsilon - 2\varepsilon' \ . \end{aligned} \tag{16}$$

The parameter ε, which measures the CP-impurity in the $|K_L\rangle$ and $|K_S\rangle$ states, arises in the standard model from box diagrams, whereas the parameter $\varepsilon' \ll \varepsilon$, which measures direct CP violation, arises from penguin diagrams. In the standard model, $\mathrm{Re}(\varepsilon'/\varepsilon) \approx 10^{-3}$; in the superweak phenomenology, [19] $\mathrm{Re}(\varepsilon'/\varepsilon) = 0$.

A comparison of the charged and neutral decay rates yields a measure of ε'/ε as

$$|\eta_{+-}|^2/|\eta_{00}|^2 \approx 1 + 6\mathrm{Re}(\varepsilon'/\varepsilon) \ . \tag{17}$$

The decisive new results on $\mathrm{Re}(\varepsilon'/\varepsilon)$ reported within the past year are

KTeV [20, 21]: $(28.0 \pm 4.1) \times 10^{-4}$, and
NA48 [22, 23]: $(18.5 \pm 7.3) \times 10^{-4}$,

which are in good agreement with each other, and with the earlier CERN result from NA31, [24] $\mathrm{Re}(\varepsilon'/\varepsilon) = (23 \pm 6.5) \times 10^{-4}$. The KTeV measurement in particular is not in close agreement with the earlier measurement from Fermilab experiment

E731, [25] $\mathrm{Re}(\varepsilon'/\varepsilon) = (7.4 \pm 5.9) \times 10^{-4}$. Taken together, all the results lead to a world average

$$\mathrm{Re}(\varepsilon'/\varepsilon) = (21.3 \pm 2.8) \times 10^{-4} , \tag{18}$$

which is convincingly different from zero. We can therefore draw the important conclusion that *the superweak picture does not explain all* CP *violation.*

In my view, these two experiments are among the most beautiful we have in particle physics today. As we heard in the talks by Elliott Cheu [20] and Jean Duclos, [22], both aim in the future for a precision of $\pm 1 \times 10^{-4}$. That same level of precision is the target for KLOE, in its special setting at the $\phi(1019)$ resonance, and we saw in the presentation by Matteo Palutan [26] a clean CP-violating signal from the KLOE shakedown cruise. We look forward with anticipation to the first high-luminosity running of DAΦNE. The Budker Institute in Novosibirsk has its own designs on a ϕ factory with a luminosity of $2.5 \times 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$, and for VEPP-2000, which is intended to investigate particle production up to 2 GeV in regions not exhaustively studied. [27]

What more can we make of the value of ε'/ε now in hand, and of the exquisitely precise results to come? It is fair to say that the new KTeV result seemed at first sight shockingly large; the expectation in nearly everyone's head was for a number no longer than 10 (in 10^{-4} units). Perhaps while awaiting the new results we had all become mesmerized by the dependence of ε'/ε upon m_t and the threat that a heavy top quark might mean little discrimination between the three-generation electroweak theory and the superweak hypothesis. Surely we should have taken more note (before the event) of the m_s^{-2}-sensitivity of (the usual parametrization of) ε'/ε and the trend in modern lattice determinations toward smaller strange-quark masses. [28] Perhaps hearing similar predictions year after year for ε'/ε we lost a sense of how difficult is the step from quarks to hadrons and accorded too much respect to the central values. In any event, the KTeV value provoked many reexaminations of how well we can predict ε'/ε in the standard model, [29, 30, 31, 32, 33, 34, 35] as well as searches [36] for evidence of new physics in the value of ε'/ε. A new lattice study by the Brookhaven–Columbia–RIKEN group [37] that yields a sign opposite to other calculations (and the data!) has not settled the matter. Guido Martinelli's conclusion is apt: Calculating ε'/ε "requires control of strong-interaction dynamics at a level of accuracy still not reached by the theory." [10]

6.2 CDF's Measurement of $\sin 2\beta$

We do not yet have a definitive observation of CP violation in B decays, but the CDF Collaboration has made impressive progress toward that goal. [38] In their 110-pb^{-1} Run 1 at the Tevatron Collider, they have reconstructed a sample of 395 ± 31 $B^0 \to \psi K_S$ events. To construct the CP-violating asymmetry for the decay rates of B^0 and $\bar{B}^0$ into this common decay mode, it is necessary to tag the flavor of the neutral B meson at the moment of its birth. CDF has employed both an opposite-side tag, using the charge of a soft lepton or a jet-charge algorithm to identify the flavor of the b or $\bar{b}$ produced in association with the state that decays into ψK_S. They have also used the charge of a nearby hadron to tag the decaying object itself. Combining all their tagging methods, they arrive at a measurement

$$\sin 2\beta = 0.79^{+0.41}_{-0.44} , \tag{19}$$

which is non-negative at 93% CL. This does not constitute a proof that CP is violated in B decays, nor a precision measurement of $\sin 2\beta$, but it is a proof of the method and the harbinger of things to come. In Run 2 of the Tevatron Collider, a 2-fb^{-1} exposure to begin in March 2001, they expect to reconstruct about 10^4 $B^0 \to \psi K_S$ events, and to measure $\sin 2\beta$ with an uncertainity $\delta \sin 2\beta \lesssim 0.08$. Other improvements—beyond their longer silicon vertex detector and the increased luminosity—may make possible a still better determination. The DØ experiment will have a silicon vertex detector for the first time in Run 2. They project an uncertainty of $\delta \sin 2\beta \approx 0.15$.

The next run of CDF should also yield our first measurement of the frequency of B_s - $\bar{B}_s$ mixing. In experiments carried out so far (ALEPH, CDF, DELPHI, OPAL, and SLD), the oscillations are too rapid to be observed. The combined results give the mass difference between the two B_s - $\bar{B}_s$ mixtures as $\Delta m_s > 14.3$ ps^{-1} at 95% CL, or $x_s \equiv \tau_s \Delta m_s > 22$. We currently project the standard-model value for the oscillation frequency to be no more than about 20 ps^{-1}. In Run 2, CDF expects to reconstruct about 20 000 examples of $B_s \to D_s(\pi, 3\pi)$. They should be sensitive to $x_s \lesssim 63$, or to $\Delta m_s \lesssim 41$ ps^{-1}.

In Run 2 of the Tevatron and beyond, CDF and DØ anticipate a very rich harvest of B physics,[5] including detailed studies of B_s, B_c, and b-baryons. To quote one simple figure of merit, in an extended run of $(20, 30)$ fb^{-1}, CDF expects $\delta \sin 2\beta = (0.03, 0.02)$.

[5] Consult the web pages of the ongoing Run 2 b Workshop at Fermilab, for which links may be found at http://www-theory.fnal.gov.

Table 1: *Precision expected in one year's running*

Experiment	$\delta \sin 2\beta$
ATLAS	0.021
CMS	0.025
LHCb	0.015
BTeV	0.021

Prospects are very bright for the hadron collider B experiments that will succeed CDF and DØ, as we heard in detail from Ramon Miquel. [39] Again to give a simple measure of the power of these experiments, I show in Table 1 the quality of the $\sin 2\beta$ measurements anticipated in one year of running. I refer to Miquel's talk for the capabilities of these experiments to measure α, γ, and other quantities. As the new hadron collider experiments prepare, the extremely challenging (fixed-target) HERA-B Experiment gives a preview of LHC-like running conditions. [40]

6.3 CLEO Observes $B^0 \to \pi^+\pi^-$

After several years of publishing ever smaller upper bounds to the branching ratio for the rare decay $B^0 \to \pi^+\pi^-$, the CLEO Collaboration now reports the definitive observation of this potentially important mode. [41] The branching fraction

$$B(B^0 \to \pi^+\pi^-) = (4.3 \pm 1.5 \pm 0.5) \times 10^{-6} \tag{20}$$

is smaller than hoped, which will complicate both the observation and the interpretation of CP violation in the $\pi\pi$ channel. CLEO has also reported the first observation, at about the 10^{-5} level, of the rare decays $B^+ \to K^+\pi^0$ and $B^0 \to K^0\pi^0$.

CLEO has also made a new measurement of B^0–$\bar{B}^0$ mixing, determining

$$\Delta m_d = (0.519 \pm 0.025 \pm 0.032)\ \mathrm{ps}^{-1}\ , \tag{21}$$

in excellent agreement with the world average. Finally, to search for unexpected sources of CP violation that might be needed to account for the baryon number of the Universe, CLEO has looked for CP-violating asymmetries in eight rare decays. The experimental uncertainties are larger than the asymmetries expected if the phase of the quark-mixing matrix is the source of the CP violation, and no significant asymmetries are observed.

6.4 BaBar and BELLE Are Coming

I should perhaps entitle this paragraph, "BaBar and BELLE Are Here!", for KEK-B and BELLE and PeP-II and BaBar have completed their construction and commissioning in very rapid and impressive fashion. The performance of these two asymmetric B factories and their detectors, summarized here at DAΦNE99 by Ida Peruzzi, [40] has been inspiring, and gladdens the heart of every particle physicist. Both experiments are already producing quasi-physics plots, and we can reasonably hope for new physics by the 2000 summer conferences.

The PeP-II collider [42] has already reached half its design luminosity, with

$$\mathcal{L}_{\mathrm{peak}} = 1.35 \times 10^{33}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ . \tag{22}$$

The BaBar detector has already logged more than 1 fb^{-1}, and the experimenters will try to accumulate 10 fb^{-1} by next summer. The PeP-II designers are planning for a threefold luminosity increase in 2002, and are beginning to work toward a tenfold increase in 2005. The KEK-B machine has also made a good beginning, [43] and luminosity is improving there. The plan at KEK is now to run BELLE continuously for about ten months.

6.5 $K \to \pi\nu\bar{\nu}$

One of the outstanding recent results was the observation at Brookhaven of the first candidate—a superb candidate, at that—for the rare decay $K^+ \to \pi^+\nu\bar{\nu}$ in Experiment 787. [44] As I wrote at the time, "What is most impressive to me is not the one beautiful candidate event, but the extremely low level of background: the event occurs on an empty field." [45] Given the sensitivity at the time, that one event led to a branching fraction $\Gamma(K^+ \to \pi^+\nu\bar{\nu})/\Gamma(K^+ \to \mathrm{all}) = (4.2^{+9.7}_{-3.5}) \times 10^{-10}$, consistent with the standard-model expectation [14] of $(0.8 \pm 0.3) \times 10^{-10}$, but tantalizingly large. As we heard in Frascati from Takahiro Sato, [46] a trebled data set has led to no new candidate events, still with an admirable absence of background near the signal region. The new (and preliminary) branching fraction is

$$B(K^+ \to \pi^+\nu\bar{\nu}) = 1.5^{+3.5}_{-1.3} \times 10^{-10}\ , \tag{23}$$

which could hardly agree better with the standard model.

Because of the clean theoretical interpretation of the $K^+ \to \pi^+\nu\bar{\nu}$ mode and its potential sensitivity to new physics, it is clearly of interest to subject the standard model to a more incisive test. There are plans at Brookhaven for an evolution of

E787 to a project known as E949, which promises a single-event sensitivity $B(K^+ \to \pi^+\nu\bar{\nu}) = 1.4 \times 10^{-11}$, with an expected background of 0.7 event. By adding the kinematic region below the $K^+ \to \pi^+\pi^0$ line, the E949 experimenters project an ultimate sensitivity $B(K^+ \to \pi^+\nu\bar{\nu}) = 0.8 \times 10^{-11}$. [47] An experiment currently under study at Fermilab as an R&D project, CKM, aims for a 10% measurement of $B(K^+ \to \pi^+\nu\bar{\nu})$. [48, 49]

The neutral analogue decay, $K_L \to \pi^0\nu\bar{\nu}$, for which the standard-model branching fraction is $(2.8 \pm 1.1) \times 10^{-11}$, [14] directly measures the altitude η of the *bd* unitarity triangle. Three experiments plan to take on the very considerable challenge of detecting $K_L \to \pi^0\nu\bar{\nu}$. At KEK, Experiment E391 will begin in 2001 at the existing 12-GeV proton synchrotron, where a sensitivity at the 10^{-10} level is anticipated. If all goes well, it would evolve into a more sensitive experiment at the Japanese Hadron Facility. Brookhaven has approved, but not yet secured funding for, E926, or KOPIO, which would record about 50 events at the standard-model rate. [50, 51] At Fermilab, the next phase of the KTeV program would be the KAMI (Kaons At the Main Injector) experiment, currently an R&D project. [52] Its goal is a 10% measurement of η and sensitivity to other rare decays at the 10^{-13} level. [48]

Both K^+ and K_L experiments are fantastically challenging, but they promise indispensable tets of the three-generation electroweak theory. [3, 14, 53, 54, 55] To balance the world's research portfolio—so heavily invested in the B sector—we need to pursue the $K \to \pi\nu\bar{\nu}$ channels vigorously.

6.6 Persistent Electric Dipole Moments

The electric dipole moment of a particle or structure is defined in terms of its charge distribution $\rho(\vec{x})$ as

$$\vec{D} = \int d^3\vec{x}\ \vec{x}\rho(\vec{x})\ , \tag{24}$$

which must be directed along (or opposite to) the spin direction $\vec{s}$, because the spin is the only directional reference the particle carries. Under the action of a parity inversion, P, the electric dipole moment is reversed ($\vec{D} \to -\vec{D}$), while the spin (pseudo)vector is unchanged ($\vec{s} \to \vec{s}$). Under time reversal, T, the electric dipole moment is unchanged ($\vec{D} \to \vec{D}$), while the spin direction is reversed ($\vec{s} \to -\vec{s}$). Accordingly, the persistent electric dipole moment must vanish unless both P and T are violated. A nonvanishing electric dipole moment therefore implies T violation and, in a CPT-invariant world, CP violation.

Since the discovery of CP violation in K_L decays in 1964, the neutron electric dipole moment has been the target of many experiments, first with neutron beams and later with ultracold neutrons. [56] As Mike Pendlebury reminded us, [57] the experimental upper bounds have dropped steadily, sweeping away a number of theoretical speculations. Whether or not persistent electric dipole moments exist, we can be grateful for the persistent experimenters who are hunting them down. An improved limit reported this year from the Institut Laue-Langevin, Grenoble, [58]

$$|d_n| < 6.3 \times 10^{-26}\ e\ \text{cm at } 90\%\ \text{CL}, \tag{25}$$

is still about six orders of magnitude greater than the standard-model expectation, but menaces multi–Higgs-boson models for CP violation, and approaches the predictions of supersymmetric models. The ILL group anticipates an improvement by a factor of 3 over about three years; an improvement by two orders of magnitude may be possible over a decade.

The past decade has brought remarkable progress in the search for an electric dipole moment of the electron. The most sensitive measurement is obtained using the amplification of d_e in atomic thallium, [59]

$$d_e = (1.8 \pm 1.2 \pm 1.0) \times 10^{-27}\ e\ \text{cm}\ , \tag{26}$$

which leads to an upper limit of

$$|d_e| \lesssim 4 \times 10^{-27}\ e\ \text{cm}\ . \tag{27}$$

That is impressive in absolute terms, but—because of the electron's small mass—at least ten orders of magnitude greater than the range predicted in the standard model. The good news, of course, is that a lot of terrain is open for an important discovery. A new technique using the YbF molecule to amplify the effect of d_e may lead to a tenfold increase in sensitivity over three years, and perhaps another order of magnitude beyond that is in prospect.

The current published limit on the muon's electric dipole moment dates to the classic $(g-2)_\mu$ experiment at CERN. [60] That number,

$$|d_\mu| \lesssim 7 \times 10^{-19}\ e\ \text{cm}\ , \tag{28}$$

should be improved by about a factor of twenty in the $(g-2)_\mu$ experiment under way at Brookhaven. [61] A proposed dedicated experiment at Brookhaven [62] could improve the sensitivity to

$$|d_\mu| \approx 10^{-24}\ e\ \text{cm}. \tag{29}$$

That would be as sensitive, in relative terms, as the current limit on the electron's electric dipole moment, since we expect $|d_\mu| \approx (m_\mu/m_e)|d_e|$.

6.7 The Search for Lepton Flavor Violation

The observation of lepton flavor violation would be a clear sign of physics beyond the standard electroweak theory. High-sensitivity experiments provide access to high mass scales for the particles that might mediate lepton flavor violation. Although these two facts are reason enough to pursue the search for lepton flavor violation, the experimental evidence for neutrino oscillations has renewed interest in LFV searches, although it must be said that the connection is highly model dependent. [63]

For more than four decades, the upper bounds on a variety of lepton-flavor-violating decay modes have decreased by a factor of ten every seven years. [64] In the realm of kaon physics, the decay $K_L \to \mu^\pm e^\mp$ is sensitive to axial and pseudoscalar LFV operators, while the decays $K^+ \to \pi^+\mu^\pm e^\mp$ and $K_L \to \pi^0\mu^\pm e^\mp$ probe vector and scalar LFV operators. Brookhaven experiment E871's current limit on the purely leptonic decay mode, [65]

$$B(K_L \to \mu^\pm e^\mp) < 4.7 \times 10^{-12} \text{ (90\% CL)}, \tag{30}$$

is the smallest limit on the branching fraction of a hadron. Experiment E865 at Brookhaven has improved its limit on the $K^+ \to \pi^+\mu^\pm e^\mp$ branching fraction to

$$B(K^+ \to \pi^+\mu^\pm e^\mp) < 2.9 \times 10^{-11} \text{ (90\% CL)}. \tag{31}$$

With five times more data accumulated in 1998, they project a 90%-CL sensitivity of 6×10^{-12}. The corresponding neutral-kaon branching fraction, reported by Fermilab experiment E799 (KTeV), [66] is

$$B(K_L \to \pi^0\mu^\pm e^\mp) < 3.1 \times 10^{-9} . \tag{32}$$

Many experiments have now used natural sources of neutrinos, neutrino radiation from fission reactors, and neutrino beams generated in particle accelerators to look for evidence of neutrino oscillation. The positive indications for neutrino oscillations fall into three classes: [67]

1. Five solar-neutrino experiments report deficits with respect to the predictions of the standard solar model: Kamiokande and Super-Kamiokande using water-Cherenkov techniques, SAGE and GALLEX using chemical recovery of germanium produced in neutrino interactions with gallium, and Homestake using radiochemical separation of argon produced in neutrino interactions with chlorine. These results suggest the oscillation $\nu_e \to \nu_x$, with $|\Delta m^2|_{\mathrm{solar}} \approx 10^{-5}$ eV^2 and $\sin^2 2\theta_{\mathrm{solar}} \approx 1$ or a few$\times 10^{-3}$, or $|\Delta m^2|_{\mathrm{solar}} \approx 10^{-10}$ eV^2 and $\sin^2 2\theta_{\mathrm{solar}} \approx 1$.

2. Five atmospheric-neutrino experiments report anomalies in the arrival of muon neutrinos: Kamiokande, IMB, and Super-Kamiokande using water-Cherenkov techniques, and Soudan II and MACRO using sampling calorimetry. The most striking result is the zenith-angle dependence of the ν_μ rate reported last year by Super-K [68, 69]. These results suggest the oscillation $\nu_\mu \to \nu_\tau$ or ν_s, with $\sin^2 2\theta_{\mathrm{atm}} \approx 1$ and $|\Delta m^2|_{\mathrm{atm}} = 10^{-3}$ to $10^{-4}\ \mathrm{eV}^2$.

3. The LSND experiment [70] reports the observation of $\bar{\nu}_e$-like events is what should be an essentially pure $\bar{\nu}_\mu$ beam produced at the Los Alamos Meson Physics Facility, suggesting the oscillation $\bar{\nu}_\mu \to \bar{\nu}_e$. This result has not yet been reproduced by any other experiment. The favored region lies along a band from $(\sin^2 2\theta_{\mathrm{LSND}} = 10^{-3}, |\Delta m^2|_{\mathrm{LSND}} \approx 1\ \mathrm{eV}^2)$ to $(\sin^2 2\theta_{\mathrm{LSND}} = 1, |\Delta m^2|_{\mathrm{LSND}} \approx 7 \times 10^{-2}\ \mathrm{eV}^2)$.

A host of experiments have failed to turn up evidence for neutrino oscillations in the regimes of their sensitivity. These results limit neutrino mass-squared differences and mixing angles. In more than a few cases, positive and negative claims are in conflict, or at least face off against each other. Over the next five years, many experiments will seek to verify, further quantify, and extend these claims.

Groups at Berkeley, Brookhaven, CERN, Fermilab, and KEK are investigating the feasibility of using muon decay rings as intense neutrino sources. Studies directed toward the eventual construction of $\mu^+\mu^-$ colliders suggest that it may be possible to accumulate approximately a millimole of muons per year. What is a bug for the muon colliders—the decay $\mu^- \to e^-\nu_\mu\bar{\nu}_\mu$—becomes a feature for a neutrino factory.[6] With a stored muon beam with an energy of tens of GeV, it may be practical to illuminate a distant detector virtually anywhere on Earth and to have an event rate useful for oscillation studies. [71] Under rather special circumstances, it may be possible to observe CP violation in neutrino oscillations. [72] The prospect of intense high-energy beams of electron neutrinos and antineutrinos is very intriguing. For now, the principal questions are whether a neutrino factory is feasible and whether it is the right instrument to address the next-generation questions in neutrino mass and mixing. I expect useful first-order answers to these questions within a year.

6.8 T Violation in K Decays

About a year ago, the CPLEAR Collaboration at CERN reported on the first observation of time-reversal symmetry violation through a comparison of the probabilities

[6] For an overview, see the web site for NuFact '99, the ICFA/ECFA Workshop, "Neutrino Factories based on Muon Storage Rings," held last summer in Lyon, at http://lyoinfo.in2p3.fr/nufact99/.

for $\bar{K}^0 \leftrightarrow K^0$ oscillations as a function of the neutral-kaon proper time. [73] The strangeness of the neutral kaon at the moment of its creation, $t = 0$, was tagged by observing the kaon charge in the formation reaction $\bar{p}p \to K^{\pm}\pi^{\mp}(K^0, \bar{K}^0)$ at rest, while the strangeness of the neutral kaon at the time of its semileptonic decay, $t = \tau$, was tagged by the charge of the final-state lepton. The time-average decay-rate asymmetry, measured over the interval $1 \times \tau_s < \tau < 20 \times \tau_s$, is

$$\left\langle \frac{\Gamma(\bar{K}^0|_0 \to e^+\pi^-\nu|_\tau) - \Gamma(K^0|_0 \to e^-\pi^+\bar{\nu}|_\tau)}{\Gamma(\bar{K}^0|_0 \to e^+\pi^-\nu|_\tau) + \Gamma(K^0|_0 \to e^-\pi^+\bar{\nu}|_\tau)} \right\rangle = (6.6 \pm 1.3_{\mathrm{stat}} \pm 1.0_{\mathrm{sys}}) \times 10^{-3}. \quad (33)$$

This asymmetry is a direct manifestation of T-violation: [74] If CPT is a good symmetry in semileptonic decays and the $\Delta S = \Delta Q$ rule is exact, then the observed asymmetry (33) is identical to

$$\frac{\mathcal{P}(\bar{K}^0 \to K^0) - \mathcal{P}(K^0 \to \bar{K}^0)}{\mathcal{P}(\bar{K}^0 \to K^0) + \mathcal{P}(K^0 \to \bar{K}^0)}, \quad (34)$$

where $\mathcal{P}$ is a probability for strangeness oscillation. The observed result is in good agreement with the theoretical expectation, $4\,\mathrm{Re}(\varepsilon) = (6.63 \pm 0.06) \times 10^{-3}$.

At the same time, the KTeV Collaboration at Fermilab reported their observation of a large T-odd effect in 1822 ± 42 examples of the formerly rare $K_L \to \pi^+\pi^-e^+e^-$ decay mode. [75] An asymmetry of $(13.6 \pm 2.5 \pm 1.2)\%$ is seen in the angular distribution between the e^+e^- and $\pi^+\pi^-$ decay planes, in the K_L rest frame. This is the largest integrated CP-violating effect yet observed, and is in excellent agreement with theoretical predictions. [76, 77]

In Frascati we learned that the NA48 Collaboration has now identified 458 ± 22 $K_L \to \pi^+\pi^-e^+e^-$ events and observed the expected T-odd asymmetry of about 14%. [78] In a CPT-invariant world, the observation of this T-odd correlation would constitute direct evidence for T noninvariance. However, the right sort of CPT violation could induce an asymmetry in the angular correlation without the need to invoke T violation. [79]

6.9 New Limits on Charm Mixing

Because the standard-model contributions to D^0 - $\bar{D}^0$ mixing and to CP violation in D decays are so minute, there are many opportunities to observe new physics. [81, 82] The large number of fully reconstructed charmed mesons available in CLEO, the LEP experiments, and Fermilab fixed-target experiments make possible incisive searches, reviewed here by Jeff Appel. [80] We can now contemplate experiments to reconstruct 10^8 charms, and it is worth thinking about how to pursue those opportunities. In particular, with Fermilab's 800-GeV fixed-target program at an end, we need to consider how to exploit dedicated B experiments for charm. A novel possibility, recently noticed, is that a 4-kg-year exposure at a neutrino factory could lead to a tagged sample of a million semileptonic D decays.

6.10 Other Rare Kaon Decays

There is much work in progress on other rare—and formerly rare—kaon decays. NA48 has used 74 examples of the double-Dalitz decay $K_L \to e^+e^-e^+e^-$ to verify the CP-odd assignment of K_L. [78] Let us note their plan for a future intense K_S beam, with a goal of measuring the CP-violation parameter η_{000} in the $K_S \to \pi^0\pi^0\pi^0$ decay rate. As for KTeV, [83] they have lowered the upper bounds

$$B(K_L \to \pi^0 e^+ e^-) < 5.6 \times 10^{-10} \; , \tag{35}$$

and

$$B(K_L \to \pi^0 \mu^+ \mu^-) < 3.4 \times 10^{-10} \tag{36}$$

to near the background levels. They hope to triple their rare-decay data sets in current running. For other evidence of progress on rare and radiative decays, see the talks by D'Ambrosio [84] and Kettell. [85]

6.11 Tests of CPT and Quantum Mechanics

Finally, we heard brief reports on searches for violations of CPT invariance and failures of quantum mechanics in kaon decays. [86] We need to test these fundamental elements of physical theory, but it is difficult to know how to characterize deviations and what constitutes a viable theoretical framework. [87, 88] I would caution that the link between string theory and observable deviations from quantum mechanics and CPT invariance is metaphorical at best. It seems to me just slightly delusional to believe that in looking for violations of CPT and quantum mechanics one is testing the essentials of string theory in any direct way.

7 Parting Thoughts

The physics of CP Violation and rare decays is in an exciting state: We have new results to consider, we eagerly anticipate incisive new information in the near future, and we have ambitious long-term prospects. BaBar and belle, which are running now, and CDF and DØ, which will run again in about a year, are ready to produce important results on B mixing and decays. The physics of neutrino masses, neutrino oscillations, and lepton flavor violation will soon join the physics of quark mixing as we seek to define and address the problem of identity. Beginning next year, we expect great things from KLOE on CP violation and rare decays, and we wish DAΦNE a long and rich life!

8 Acknowledgments

I wish to compliment our hosts and organizers for the rich and varied program that brought many of us together for the first time, and for our warm reception in Frascati. I particularly want to acknowledge the hospitality of Giorgio Capon, Franco Fabbri, Lia Pancheri, Juliette Lee-Franzini, and Paolo Franzini. I thank the scientific secretaries and members of the secretariat for their very efficient work in scanning and photocopying transparencies from the presentations, and for making them available so quickly on the conference web site at http://wwwsis.lnf.infn.it/dafne99/, which greatly aided me in preparing this summary. Fermilab is operated by Universities Research Association Inc. under Contract No. DE-AC02-76CH03000 with the United States Department of Energy.

References

1. Italo Calvino, *Lezioni americane : sei proposte per il prossimo millennio* (Garzanti, Milano, 1988); *Six Memos for the Next Millennium* (Harvard University Press, Cambridge, 1988).

2. See the accessible essay on the problem of hadron mass by Frank Wilczek, "Mass without Mass I: Most of Matter," *Phys. Today* **52** (11) 11 (November, 1999).

3. Antonio Masiero, "Looking for New Physics in CP Violation and Rare Decays," *These Proceedings.*

4. For a sampling of work, see G. Giudice, R. Rattazzi, and J. Wells, "Quantum Gravity and Extra Dimensions at High-Energy Colliders," *Nucl. Phys.* **B544**, 3 (1999), hep-ph/9811291. Eugene A. Mirabelli, Maxim Perelstein, Michael E. Peskin, "Collider Signatures of New Large Space Dimensions," *Phys. Rev. Lett.* **82**, 2236 (1999), hep-ph/9811337. JoAnne L. Hewett, "Indirect Collider Signals for Extra Dimensions," *Phys. Rev. Lett.* **82**, 4765 (1999), hep-ph/9811356.

5. Nima Arkani-Hamed and Martin Schmaltz, "Hierarchies without Symmetries from Extra Dimensions," hep-ph/9903417; Eugene A. Mirabelli and Martin

Schmaltz, "Yukawa Hierarchies from Split Fermions in Extra Dimensions," hep-ph/9912265.

6. N. Cabibbo, *Phys. Rev. Lett.* **10**, 531 (1963).

7. M. Kobayashi and T. Maskawa, *Prog. Theoret. Phys.* **49,** 652 (1973).

8. For informative surveys of our subject, see A. J. Buras, "CP Violation and Rare Decays of K and B Mesons," hep-ph/9905437. R. D. Peccei, "CP Violation and Weak Decays," hep-ph/9904456; "Overview of Kaon Physics," hep-ph/9909236. Y. Nir, "CP Violation in and Beyond the Standard Model," hep-ph/9911321. A. Falk, "B Decays, the Unitarity Triangle, and the Universe," hep-ph/9908520. J. Lee-Franzini and P. Franzini, "CP Violation in the K System," hep-ex/9709007.

9. Ahmed Ali, "CP Violation and Quark Mixing," *These Proceedings.*

10. G. Martinelli, "CP Violation," *These Proceedings.*

11. I. I. Bigi and A. I. Sanda, "On the Other Five KM Triangles," hep-ph/9909479.

12. L. Wolfenstein, *Phys. Rev. Lett.* **51**, 1945 (1983).

13. S. Stone, "Future of Heavy Flavour Physics: Experimental Perspective," from Heavy Flavours 8, Southampton, hep-ph/9910417.

14. G. Buchalla, "Theoretical Update on Rare K Decays," *These Proceedings.* See also "CP Violation and Rare Decays," plenary talk at EPS–HEP99, hep-ph/9912369.

15. A. Sakharov, *ZhETF Pis'ma* **5,** 32 (1967) [English translation: *Sov. Phys. – JETP Lett.* **5,** 24 (1967)].

16. J. H. Christenson, J. Cronin, V. Fitch, and R. Turlay, *Phys. Rev. Lett.* **13**, 138 (1964).

17. Antonio Riotto and Mark Trodden, "Recent Progress in Baryogenesis," *Ann. Rev. Nucl. Part. Sci.* **49**, 35 (1999); hep-ph/9901362.

18. T. T. Wu and C. N. Yang, "Phenomenological analysis of violation of CP invariance in decay of K^0 and $\bar{K}^0$," *Phys. Rev. Lett.* **13**, 380 (1964).

19. L. Wolfenstein, "Violation of CP invariance and the possibility of very weak interactions," *Phys. Rev. Lett.* **13**, 562 (1964).

20. E. Cheu, "ε'/ε Measurements at KTeV," *These Proceedings.*

21. A. Alavi-Harati, *et al.* (KTeV Collaboration), *Phys. Rev. Lett.* **83**, 22 (1999), hep-ex/9905060.

22. J. Duclos, "ε'/ε Measurements at NA48," *These Proceedings.*

23. V. Fanti, *et al.* (NA48 Collaboration), *Phys. Lett.* **B465**, 335 (1999), hep-ex/9909022.

24. G. D. Barr, *et al.* (NA31 Collaboration), *Phys. Lett.* **B317**, 233 (1993).

25. L. K. Gibbons, *et al.* (E731 Collaboration), *Phys. Rev. Lett.* **70**, 1203 (1993).

26. M. Palutan, "KLOE Prospects for ε'/ε," *These Proceedings.* For other information about KLOE and DAΦNE, see S. Dell'Agnello, "The KLOE Detector," *These Proceedings,* and C. Milardi, "Status of DAΦNE," *These Proceedings.*

27. I. Koop, "Status of VEPP–2M collider, its upgrade plans and Novosibirsk ϕ factory project," *These Proceedings.*

28. S. Ryan, "Lattice determinations of the strange quark mass," from KAON 99, hep-lat/9908386.

29. S. Bosch, *et al.*, "Standard Model Confronting New Results for ε'/ε," hep-ph/9904408.

30. A. J. Buras, "Theoretical Status of ε'/ε," from KAON 99, hep-ph/9908395.

31. U. Nierste, "Theoretical Status of ε'/ε," hep-ph/9910257.

32. M. Fabbrichesi, "Estimating ε'/ε. A user's manual," hep-ph/9909224.

33. S. Bertolini, "ε'/ε and the $\Delta I = \frac{1}{2}$ Rule," *These Proceedings.*

34. S. Gardner and G. Valencia, "Additional Isospin-Breaking Effects in ε'/ε," hep-ph/9909202.

35. E. J. Paschos, "Rescattering Effects for ε'/ε," hep-ph/9912230.

36. See, for example, H. Murayama, "Can ε'/ε be supersymmetric?" from KAON 99, hep-ph/9908442.

37. T. Blum, *et al.*, "A first study of ε'/ε on the lattice using domain wall fermions," hep-lat/9908025.

38. C. Blocker, "$\sin 2\beta$ measurement at CDF," *These Proceedings.*

39. R. Miquel, "Future prospects for CP violation at hadron machines," *These Proceedings.*

40. I. Peruzzi, "B Factories: Prospects and preliminary experimental results," *These Proceedings.*

41. D. G. Cassel, "$B\ \bar{B}$ Mixing and Rare Decays," *These Proceedings.*

42. T. Himel, "Status of the SLAC B Factory," *These Proceedings.*

43. M. Yoshioka, "Status of the KEK B Factory," *These Proceedings.*

44. S. Adler, *et al.* (E787 Collaboration), *Phys. Rev. Lett.* **79**, 2204 (1997), hep-ex/9708031.

45. C. Quigg, "Perspectives on Heavy Quark 98," in *Heavy Quarks at Fixed Target,* edited by H. W. K. Cheung and J. N. Butler (American Institute of Physics, Woodbury, NY, 1999) p. 485, hep-ph/9812299.

46. T. Sato, "BNL E787 results on $K^+ \to \pi^+\nu\bar{\nu}$," *These Proceedings.*

47. M Aoki, *et al.* "P949: An experiment to measure the branching ratio $B(K^+ \to \pi^+\nu\bar{\nu})$," available at http://www.phy.bnl.gov/e949/.

48. R. E. Ray, "Future experiments on rare K decays at Fermilab," *These Proceedings.*

49. E. Coleman, *et al.* (CKM Collaboration), "P905: Charged Kaons at the Main Injector, A Proposal for a Precision Measurement of the Decay $K^+ \to \pi^+\nu\bar{\nu}$ and Other Rare K^+ Processes at Fermilab Using the Main Injector," available at http://www.fnal.gov/projects/ckm/Welcome.html.

50. D. Bryman, "Future measurements of $K_L^0 \to \pi^0\nu\bar{\nu}$," *These Proceedings.*

51. I-Hung Chiang, *et al.*, "P926: Measurement of $K_L \to \pi^0\nu\bar{\nu}$," available at http://sitka.triumf.ca/e926/.

52. E. Cheu, *et al.* (The KAMI Collaboration), "An Expression of Interest to Detect and Measure the Direct CP Violating Decay $K_L \to \pi^0 \nu \bar{\nu}$ and Other Rare Decays at Fermilab Using the Main Injector," hep-ex/9709026, available at http://fnalpubs.fnal.gov/archive/proposals/KAMI.html.

53. Y. Nir and M. P. Worah, "Probing the Flavor and CP Structure of Supersymmetric Models with $K \to \pi \nu \bar{\nu}$ Decays," hep-ph/9711215.

54. A. J. Buras, *et al.*, "Connections between ε'/ε and Rare Kaon Decays in Supersymmetry," hep-ph/9908371.

55. G. Isidori, "Standard Model *vs* New Physics in Rare Kaon Decays," hep-ph/9908399.

56. C. Caso *et al.* (Particle Data Group), *Euro. Phys. J.* **C3,** 1 (1998) and 1999 off-year partial update for the 2000 edition available on the PDG WWW pages at http://pdg.lbl.gov/.

57. M. J. Pendlebury, "Review of particle electric dipole moments, measurement of neutron electric dipole moment," *These Proceedings.*

58. P. G. Harris, *et al.*, *Phys. Rev. Lett.* **82**, 904 (1999).

59. Eugene D. Commins, Stephen B. Ross, David DeMille, and B. C. Regan, *Phys. Rev. A***50**, 2960 (1994).

60. F. J. M. Farley, *et al.*, *J. Phys. G* **4,** 345 (1978).

61. K. Jungmann, "A new measurement of the muon magnetic anomaly $(g-2)_\mu$," *These Proceedings.*

62. R. Carey, E. Efstathiadis, J. Miller, O. Rind, B.L. Roberts, L. Sulak, R. Larsen, D. Lazarus, W. Morse, R. Prigl, Y. Semertzidis, Y. Orlov, J. Rogers, D. Winn, K. Jungmann, P. Debevec, D. Hertzog, S. Sedykh, P. Cushman, D. Zimmermann, and F. Farley, AGS Letter of Intent, Brookhaven National Laboratory, Upton, USA (1997), available at http://www.physi.uni-heidelberg.de/~muon/g2muon/LOIEDM.PS.

63. Y. Kuno and Y. Okada, For a review of many aspects of lepton flavor violation, see "Muon Decay and Physics Beyond the Standard Model," hep-ph/9909265.

64. Y. Kuno, "Lepton flavour and T violation in K decays," *These Proceedings.*

65. D. Ambrose, *et al.*, *Phys. Rev. Lett.* **81**, 5734 (1998).

66. K. Arisaka, *et al.*, "Search for the lepton-family number violating decays $K_L \to \pi^0\mu^\pm e^\mp$," *Phys. Lett.* **B432**, 230 (1998).

67. For summaries of the current evidence about neutrino oscillations, see J. M. Conrad, in *Proceedings of the 29th International Conference on High Energy Physics,* Vancouver, edited by A. Astbury, D. Axen, and J. Robinson (World Scientific, Singapore, 1999), p. 25 (hep-ex/9811009), and "Where in the World Is the Oscillating Neutrino?" talk at Inner Space / Outer Space 1999 and PANIC99, available at http://portia.fnal.gov/~jconrad/isos.html;
P. Fisher, B. Kayser, and K. S. McFarland, "Neutrino Mass and Oscillation," *Annu. Rev. Nucl. Part. Sci.* **49,** 481 (1999), hep-ph/9906244;
L. DiLella, "Accelerator and Reactor Neutrino Experiments," hep-ex/9912010.

68. Y. Fukuda, *et al.* (Super-Kamiokande Collaboration), *Phys. Rev. Lett.* **81**, 1562 (1998).

69. Y. Hayato, "Super-Kamiokande: Status and Perspectives," *These Proceedings.*

70. C. Athanassopoulos, *et al.* (LSND Collaboration), *Phys. Rev. Lett.* **77**, 3082 (1996); **81**, 1774 (1998); *Phys. Rev. C***58**, 2489 (1998).

71. V. Barger, S. Geer, and K. Whisnant, "Long Baseline Neutrino Physics with a Muon Storage Ring Neutrino Source," hep-ph/9906487; V. Barger, S. Geer, R. Raja, and K. Whisnant, "Long Baseline Study of the Leading Neutrino Oscillation at a Neutrino Factory," hep-ph/9911524.

72. F. Vissani, "Aspects of CP violation in the leptonic sector," *These Proceedings.* See also A. Donini, M.B. Gavela, P. Hernandez, and S. Rigolin, "Neutrino mixing and CP-violation, hep-ph/9909254.

73. A. Angelopoulos, *et al.* (CPLEAR Collaboration), "First direct observation of time-reversal non-invariance in the neutral-kaon system," *Phys. Lett.* **B444**, 43 (1998).

74. André Rougé, "On the direct evidence of time-reversal invariance in the $K^0 - \bar{K}^0$ system," hep-ph/9909205.

75. A. Alavi-Harati, *et al.* (KTeV E799 Collaboration), "Observation of CP Violation in $K_L \to \pi^+\pi^-e^+e^-$ Decays," hep-ex/9908020, to appear in *Phys. Rev. Lett.*

76. L. M. Sehgal, "CP- and T- Violation in the Decay $K_L \to \pi^+\pi^-e^+e^-$ and Related Processes," from KAON 99, hep-ph/9908338.

77. M. J. Savage, "$K_L^0 \to \pi^+\pi^-e^+e^-$ in Chiral Perturbation Theory," hep-ph/9908324.

78. M. Jeitler, "NA48 results on rare K^0 decays," *These Proceedings.*

79. I. I. Bigi and A. I. Sanda, "Has T violation been seen in K decays?" hep-ph/9904484.

80. J. A. Appel, "Charm results on CP violation and mixing," *These Proceedings.*

81. I. Bigi, "The Expected, The Promised and The Conceivable — On CP Violation in Beauty and Charm Decays," hep-ph/9412227.

82. G. Burdman, "Potential for Discoveries in Charm Meson Physics," hep-ph/9508349; "Charm Mixing and CP Violation in the Standard Model," hep-ph/9407378.

83. M. Corcoran, "KTeV results on rare K^0 decays," *These Proceedings.*

84. G. D'Ambrosio, "Radiative rare K decays," *These Proceedings.*

85. S. Kettell, "Experimental results on radiative and nonleptonic K decays," *These Proceedings.*

86. M. Fidecaro, "Tests of CPT and Quantum Mechanics," *These Proceedings.*

87. R. Floreanini, "Theoretical overview of CPT and Quantum Mechanics violations," *These Proceedings.*

88. Alan Kostelecky, "Bounds on CPT and Lorentz violation from experiments with kaons," from KAON 99, hep-ph/9912456.