Theoretical Issues in Flavor Physics

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Quark and lepton flavor physics presents us with a basic question: Can we understand the pattern of masses and mixings of the known quarks and leptons, and how do present and proposed measurements help to advance that goal? Topics discussed include the apparent suppression of new flavor-changing effects, the status of quark and lepton mixing, the implications of new measurements of CP asymmetries in heavy quark decays, the implications of forthcoming experiments on the muon’s anomalous magnetic moment and its transitions to an electron, and what we can hope to learn from electric dipole moments.

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1 Introduction

An outstanding puzzle in particle physics is the pattern of quark and lepton masses and mixings. Does it point the way to a deeper structure, or is it governed by random effects? In Section 2, we discuss this pattern, including the status of mixings, the apparent suppression of new flavor-changing effects, and new measurements of CP violation in heavy quark decays.

Some measurements to discern the mass and mixing pattern are noted in Section 3. These include a forthcoming experiment to obtain a more precise value of the muon anomalous magnetic moment, proposed searches for various forms of $\mu \to e$ transitions, and searches for electric dipole moments.

The big unknown player in this question is dark matter, five times as abundant as the matter we know. It is evident in the behavior of galaxies, clusters, large-scale structure, and gravitational lensing. Trying to guess the pattern of the known quarks and leptons without accounting for dark matter may be like trying to guess the structure of the periodic table knowing only Li, Be, and their relatives. Some remarks on the dark matter “elephant in the room” are offered in Sec. 4, while Sec. 5 concludes.

2 Masses and mixings of quarks and leptons

The Cabibbo-Kobayashi-Maskawa matrix describing charge-changing transitions among quarks has the hierarchical form

$$V_{CKM} = \begin{pmatrix}
0.974 & 0.225 & 0.0035e^{-i(70^\circ)} \\
-0.224 & 0.973 & 0.042 \\
0.0088e^{-i(22^\circ)} & -0.041 & 0.999
\end{pmatrix},$$

suggesting that its elements might be correlated with quark masses. (The approximate relations $V_{us} \simeq \sqrt{m_d/m_s}$, $V_{cb} \simeq m_s/m_b$ were noted long ago.) Underlying dynamics might involve logarithms of quark masses. In Randall-Sundrum models [2], for instance, fermions could be localized along a fifth dimension, with mixing related to proximity in this variable. The mixing pattern is illustrated in Fig. 1.

Lepton mixings are a different story, exhibiting a more “democratic” pattern [3]:

$$U_{PMNS} = \begin{pmatrix}
0.82 & 0.55 & 0.155e^{-i\delta} \\
-0.44 - 0.08e^{i\delta} & 0.65 - 0.05e^{i\delta} & 0.61 \\
0.35 - 0.10e^{i\delta} & -0.52 - 0.07e^{i\delta} & 0.78
\end{pmatrix}. $$

Aside from the small 13 element, this is not far from

$$\begin{pmatrix}
2/\sqrt{6} & 1/\sqrt{3} & 0 \\
-1/\sqrt{6} & 1/\sqrt{3} & 1/\sqrt{2} \\
1/\sqrt{6} & -1/\sqrt{3} & 1/\sqrt{2}
\end{pmatrix} = \begin{pmatrix}
0.82 & 0.58 & 0 \\
-0.41 & 0.58 & 0.71 \\
0.41 & -0.58 & 0.71
\end{pmatrix}. $$
Figure 1: The quarks and charge-changing transitions among them. Relative magnitudes of transition amplitudes are $\mathcal{O}(1)$ (black solid lines), $\mathcal{O}(0.2)$ (blue dashed lines), $\mathcal{O}(0.04)$ (red dot-dashed lines), and $<0.01$ (green dotted lines).

With a sign change in the last row, this is “tribimaximal” mixing, in which the columns are eigenvectors of a $3 \times 3$ matrix with all 1’s.

So, what’s the difference between quark and lepton mixings? The answer could lie in the seesaw mechanism, a candidate for understanding the tiny neutrino masses. The differences between elements of $U_{PMNS}$ and a tribimaximal $U$ are all less than $\mathcal{O}(0.1)$ in magnitude, suggesting that one look for tribimaximal mixing as a first approximation.

Flavor-changing processes are suppressed in the CKM framework. New fermions, scalars, and gauge bosons in loops can upset this suppression, but so far no effects of this sort have been seen. It appears that whatever new physics may be hiding in loops, it either respects the CKM pattern (“Minimal Flavor Violation”) or is associated with a mass scale (e.g., $>10^5$ TeV) far beyond the reach of present accelerators. As A. Pais used to say, “Where’s the joke?”

Similar considerations were associated with the attempt to endow the neutral partner of the Cabibbo current with physical meaning. A charged current leading to $(d \cos \theta + s \sin \theta) \to u$ would have a neutral partner in an SU(2) with a flavor-changing part. The introduction of the charm quark participating in a transition $(-d \sin \theta + s \cos \theta) \to c$ canceled tree-level flavor-changing neutral currents (FCNC) and led to definite predictions for loop-level FCNC, e.g., in the transitions $K^+ \to \pi^+ \nu \bar{\nu}$ and $K_L \to \pi^0 \nu \bar{\nu}$. 
3 Present and proposed measurements

3.1 Processes related by Minimal Flavor Violation

In Minimal Flavor Violation (MFV), loop-induced FCNC can generate nonstandard effects, but they are often correlated with one another. For example, in MFV one expects \( \Gamma(B_s \rightarrow \ell^+\ell^-)/\Gamma(B_d \rightarrow \ell^+\ell^-) = |V_{ts}/V_{td}|^2 \simeq 34 \). The Standard Model (SM) predictions for branching fractions are

\[
B(B_s \rightarrow \ell^+\ell^-) = (3.7 \pm 0.4) \times 10^{-9}, \quad B(B_d \rightarrow \ell^+\ell^-) = (1.1 \pm 0.15) \times 10^{-10}.
\]

A combination of results from CMS and LHCb \cite{10} gives

\[
B(B_s \rightarrow \ell^+\ell^-) = (2.9 \pm 0.7) \times 10^{-9}, \quad B(B_d \rightarrow \ell^+\ell^-) = (3.6^{+1.6}_{-1.4}) \times 10^{-10},
\]

consistent with the SM predictions but still leaving room for a deviation from the ratio predicted by MFV.

The predicted \( K^+ \rightarrow \pi^+\nu\bar{\nu} \) and \( K_L \rightarrow \pi^0\nu\bar{\nu} \) rates are also correlated in MFV \cite{11}. In the SM the predicted branching fractions are

\[
B(K^+ \rightarrow \pi^+\nu\bar{\nu}) \simeq 8.5 \times 10^{-11}, \quad B(K_L \rightarrow \pi^0\nu\bar{\nu}) \simeq 2.4 \times 10^{-11}.
\]

3.2 CP violation in heavy quark decays

Observations by CDF \cite{12}, Belle \cite{13}, and LHCb \cite{14} suggest that direct CP asymmetries \( A_{CP} \) in \( D^0 \rightarrow K^+K^- \) and \( D^0 \rightarrow \pi^+\pi^- \) could be as large as several tenths of a percent. These asymmetries could be due to non-SM physics, or simply to an enhanced CP-violating \( c \rightarrow u \) penguin amplitude \cite{15}. If the latter, one expects fractional-percent CP asymmetries in other singly-Cabibbo-suppressed two-body decays such as \( D^0 \rightarrow \pi^0\pi^0 \) and \( D^+ \rightarrow K^0\pi^+ \). In Ref. \cite{16} we noted that such fractional-percent asymmetries can shift the apparent weak phase \( \gamma \) extracted from \( B \rightarrow DK \) decays by up to several degrees.

Large direct CP asymmetries have been reported by the LHCb Collaboration in certain three-body \( B \) decays to charged hadrons \cite{17}. Even larger asymmetries show up in restricted regions of the Dalitz plot, e.g.,

\[
A_{CP}(B^+ \rightarrow \pi^+(\pi^+\pi^-)_{low~m}) = +0.622 \pm 0.075 \pm 0.032 \pm 0.007, \\
A_{CP}(B^+ \rightarrow \pi^+(K^+K^-)_{low~m}) = -0.671 \pm 0.067 \pm 0.028 \pm 0.007,
\]

where “low \( m \)” refers to low effective mass, defined in \cite{17}. We have found \cite{18} that these large CP asymmetries can be interpreted through the interference of SM tree and penguin amplitudes. Final-state interactions play a crucial role, as do U-spin relations, \( K\bar{K} \) rescattering, and CPT invariance. The last is important in interpreting the nearly equal and opposite values of the above two asymmetries. No new physics need be invoked.
3.3 Muon anomalous magnetic moment

In deep inelastic neutrino scattering, flavor-changing neutral currents are absent at tree level, but flavor-preserving effects were crucial in validating electroweak unification. One might look elsewhere in flavor-preserving processes for signs of new physics. The muon’s anomalous magnetic moment $a_\mu$ is a case in point. Taking the following numbers from Ref. [19], the difference between experiment and theory is

$$a_\mu^{(\text{exp})} - a_\mu^{(\text{th})} = (287)(63)(49) \times 10^{-11},$$

to be compared with

Electroweak [20]: 154(1)(2) \times 10^{-11}; light-by–light: 70 to 140 \times 10^{-11};

$$a_\mu^{\text{SUSY}} \simeq \pm 130 \times 10^{-11} \left(\frac{100 \text{ GeV}}{m_{\text{SUSY}}}\right)^2 \tan \beta$$

(see [21]) which must be larger than the electroweak term if it is to account for the discrepancy. Where else do we see such sensitivity to SUSY? Flavor-diagonal processes can provide unique windows to new physics.

3.4 Muon to electron transitions

In 1962, the muon and electron were seen to be accompanied by separate neutrinos [22]. This explained why the decay $\mu \to e\gamma$ did not proceed with a branching fraction $\mathcal{B}(\mu \to e\gamma) \simeq 10^{-4}$ [23]. Many authors noted the restrictive nature of the apparent suppression of $\mu \to e$ transitions. For example, many types of TeV-scale new physics would be expected to lead to “rates comparable to or within a few orders of magnitude of current rate limits [24].”

The present situation of $\mu \to e$ transitions has been reviewed in Ref. [25]. Light-neutrino mixing leads to the prediction

$$\mathcal{B}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \left| \sum_{i=2,3} U_{\mu i}^* U_{ei} \frac{\Delta m_{i1}^2}{M_W^2} \right|^2 < 10^{-54}$$

which is incredibly tiny, but can easily exceed present limits if you substitute your favorite mixings, $\Delta m^2$, and replace $M_W^2$ by $\Lambda^2$ where $\Lambda$ is a cutoff. New physics can induce a dipole operator (inducing $\mu \to e\gamma$) and/or a four-fermion contact term ($\bar{q}q\gamma\gamma\bar{q}q$). The present upper limit of the conversion rate of $< 7 \times 10^{-13}$ in Au limits the scale $\Lambda$ to at least $10^3$ TeV [26] (quoted in [27]). Improvement of this limit to $< 10^{-16}$ in Al will raise the limit on $\Lambda$ by a factor of 7 for this contact term [28].
3.5 Electric dipole moments

Standard Model contributions to electric dipole moments are below the level of current experiments by several orders of magnitude, but many scenarios of new physics can give rise to effects observable at present levels or with various foreseen improvements. The following values are taken from Refs. [29, 30].

If the strong CP phase $\theta$ is zero, CKM contributions to hadron electric dipole moments need to involve all three quark families and three-loop Feynman diagrams, leading to a predicted range of $10^{-31}$ to $10^{-32} \, e\cdot cm$ for the neutron electric dipole moment $d_n$, and $10^{-33} \, e\cdot cm$ for $^{199}\text{Hg}$. To generate lepton electric dipole moments in the SM one needs an additional loop, leading to the predicted range $10^{-39 \pm 1} \, e\cdot cm$ for the electron moment $d_e$.

Experimental upper bounds currently are $d_n < 2.9 \times 10^{-26} \, e\cdot cm$, with a factor of 100 improvement foreseen in five years; $d(^{199}\text{Hg}) < 10^{-27} \, e\cdot cm$, with up to $10^5$ improvement claimed possible; and $d_e < 1.06 \times 10^{-27} \, e\cdot cm$ (90% c.l.), where by using cold molecules (e.g., YbF), a factor of up to $10^4$ improvement may be possible [31].

If they contain CP-violating phases, many models beyond the SM give rise to observable electric dipole moments. As an example [32], CP violation in the decay of a Higgs boson to $\gamma\gamma$ can lead to an electric dipole moment through a diagram in which the Higgs boson and one of the photons interact with a fermion.

4 The elephant in the room: dark matter

The preponderance of dark matter (by a factor of five) over ordinary matter could signify that we are privileged to see only a small subset of gauge interactions in the SM. There could exist a “hidden” gauge sector $G$ with its own exotic charges (see, e.g., Ref. [33]). Ordinary quarks and leptons could be just the tip of a large iceberg (Fig. 2).

4.1 Relevance to the flavor problem

The unseen part of the iceberg could be a clue to the nature of ordinary matter. Like blind men, we may be able to put together a coherent picture of the dark matter “elephant” from several pieces of evidence. It would be most fortunate, for instance, if some particles had charges both in the SM and in $G$, as shown in Table 1.

4.2 Hidden sector and the Higgs boson

The Higgs boson could be a different tip of the same iceberg. Its light mass suggests that the Higgs sector is not a replay of QCD at a scale $v/f_\pi \simeq 2650$, where $v = 246$ GeV and $f_\pi = 93$ MeV. Nonetheless, composite Higgs theories refuse to die. A
Figure 2: Balance between ordinary and dark matter

Table 1: Types of matter and their SM and $G$ properties.

| Type of matter | Std. Model | $G$       | Example(s)       |
|----------------|------------|-----------|------------------|
| Ordinary       | Non-singlet| Singlet   | Quarks, leptons  |
| Mixed          | Non-singlet| Non-singlet| Superpartners   |
| Hidden         | Singlet    | Non-singlet| $E'_8$ of $E_8 \otimes E_8'$ |

key difference from QCD is that whereas the lightest $q\bar{q}$ composites in QCD are pseudoscalar ($J^P = 0^-$), the Higgs boson is at least predominantly a scalar ($0^+$), with upper bounds on its $0^-$ admixture becoming ever more stringent. This could be due to a non-vector-like interaction between constituents of the Higgs boson.

Some questions for the Higgs and hidden sectors: (1) If the Higgs boson is composite, is there one doublet or two? (2) Do Higgs bosons, quarks, and leptons share $Q = \pm 1/2$ components [34, 35, 36]? (3) Does a hidden sector play a role in generating a composite Higgs boson?

4.3 Two familiar patterns

In Fig. 3 we illustrate two familiar patterns. The arrangement of the elements is a triumph of quantum mechanics. Each element has a different nuclear charge; electron shell structure governs chemistry. On the basis of this scheme, the existence of technetium (Tc) was predicted. However, imagine if Mendeleev had only the labeled
elements to work with: he would not have constructed his scheme. We may be in the same situation with regard to ordinary and dark matter.

Titius and Bode saw that the planetary orbits followed a simple regularity, with semi-major axes obeying the law $a(AU) = 0.4 + 0.3k$, where $k = 0, 1, 2, 4, 8, \ldots$. This law predicted the orbits of Ceres and Uranus, but failed to predict the orbit of Neptune. Pluto is near where Neptune should have been, other dwarf planets don’t fit, and there is no dynamical explanation of the law. Simulations can give similar relations, in analogy to the “anarchy” pattern in quark and lepton masses [37].

5 Conclusions

Is the pattern of quark and lepton masses and mixings more like a periodic table, with an underlying explanation, or like the Titius-Bode description of planetary orbits, just a step away from a roll of the dice? So far, we have no convincing theory. Further progress awaits better neutrino mixing measurements (including of the CP phase), improved understanding of the Higgs sector, and elucidation of the dark sector: What is hidden from us?

We are in a happy situation I have not seen since the 1960s, when the lack of a “Standard Model” didn’t stop us from making progress. I hope the situation is about to repeat itself.

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