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OVERVIEW OF THE STANDARD MODEL*

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Introduction

The standard model, with the gauge group $SU(3)_C \times SU(2) \times U(1)$, assignment of fermions to left-handed doublets and right-handed singlets under the electroweak $SU(2)$, and 18 or more parameters, is in excellent shape. Experiment has again and again confirmed its predictions to whatever accuracy they can be predicted and measured in a given situation. With the beginning of experiments at the Z factories in the near future, the one-loop corrections to the electroweak portion of the standard model will be tested to high accuracy.

Instead of reviewing these successes, we will concentrate on a few possible problem areas: the Kobayashi - Maskawa matrix, CP violation in the neutral Kaon system as expressed through the parameters ϵ and ϵ', $B - \bar{B}$ mixing, and τ decays.

The Kobayashi - Maskawa Matrix

The Kobayashi - Maskawa (KM) matrix[1] is defined as the matrix transformation that takes us from the mass eigenstates of the d, s, and b quarks to the weak eigenstates, d', s', and b', the partners in weak doublets of the u, c, and t quarks, respectively, which by convention are unmixed:

$$\begin{pmatrix} d' \\ s' \\ b' \end{pmatrix} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} \begin{pmatrix} d \\ s \\ b \end{pmatrix} . \tag{1}$$

The 1986 Review of Particle Properties[2] gave the following results for the magnitudes of those matrix elements that can be measured up to the present time:

(1) Nuclear beta decay, when compared to muon decay, gave

$$|V_{ud}| = 0.9729 \pm 0.0012 .$$

which included refinements[3] which had lowered $|V_{ud}|$ by 0.13%.

(2) Analysis[4] of hyperon and K_{e3} decays yielded

$$|V_{us}| = 0.221 \pm 0.002 .$$

(3) From ν and $\bar{\nu}$ production of charm, the CDHS group[5] had deduced

$$|V_{cd}| = 0.24 \pm 0.03\ .$$

(4) By comparing the experimental value[6] for $\Gamma(D \to \overline{K}e^+\nu_e)$ with the expression that follows from the standard weak interaction amplitude, one derives:

$$|f_+^D(0)|^2|V_{cs}|^2 = 0.51 \pm 0.07\ .$$

where f_+^D is the form factor for $D_{\ell 3}$ decay which is the analogue of f_+ for $K_{\ell 3}$ decay. With the conservative assumption that $|f_+(0)| < 1$,

$$|V_{cs}| > 0.66\ .$$

(5) The ratio $|V_{ub}/V_{cb}|$ is obtained from the semileptonic decay of B mesons by fitting to the lepton energy spectrum as a sum of contributions involving $b \to u$ and $b \to c$. As more data had accumulated, the inadequacy of previous parametrizations of the lepton spectrum became clear.[6] Using only the lepton momentum region beyond the end-point for $b \to c\ell\overline{\nu}_\ell$ resulted in[6]

$$\Gamma(b \to u\ell\overline{\nu}_\ell)/\Gamma(b \to c\ell\overline{\nu}_\ell) < 0.08\ ,$$

which translates to

$$|V_{ub}/V_{cb}| < 0.19\ .$$

(6) The magnitude of V_{cb} itself can be determined if the measured semileptonic bottom hadron partial width is assumed to be that of a b quark decaying through the usual $V - A$ interaction (which from (5) is $BR(b \to c\ell\overline{\nu}_\ell)$ to within 8%):

$$0.037 < |V_{cb}| < 0.053\ .$$

One can not prove there are three generations from these data, but only show consistency with that as a hypothesis. The crucial test comes from the constraint which unitarity of the 3 × 3 matrix imposes on the first row:

$$(0.9729 \pm 0.0012)^2 + (0.221 \pm 0.002)^2 + (< 0.01)^2 = 0.9954 \pm 0.0025, \qquad (2)$$

with a couple of standard deviations being nothing to make a fuss about.

Since the Review of Particle Properties went to press, there have been some small shifts in the central values of some of the matrix elements due to reanalysis and/or new data, such as incorporating newer charm semileptonic branching ratios in extracting[7] $|V_{cs}|$. More importantly, a change[8] in the order $Z\alpha^2$ Coulomb corrections brought different experiments into better agreement and raised the value of $|V_{ud}|$:

$$|V_{ud}| = 0.9747 \pm 0.0010,$$

to be compared with a very recent result[9]

$$|V_{ud}| = 0.9755 \pm 0.0017,$$

which also improves on previous analyses of this quantity, primarily in terms of the electron screening correction.[10] The unitarity sum for the first row is now 0.9989 ± 0.0021 or 1.0004 ± 0.0035, depending on which new result one uses. One couldn't ask for better agreement with three generations. Turning this around, and using unitarity to restrict the coupling between the u quark and a new charge -1/3 quark results in

$$|V_{ub'}| \leq 0.06. \tag{3}$$

This is not very restrictive and, looking at its primary origin in the error bar on $|V_{ud}|$, it seems unlikely that there will be a very significant improvement upon it in the future.

CP Violation

CP violation has still only been observed in the neutral K system. There it is conveniently parametrized in terms of ϵ, which characterizes CP violation in the Kaon mass matrix, and ϵ', which is non-zero only due to CP violation in the neutral Kaon decay amplitude.

For ϵ one takes the short distance contribution (corresponding to the box diagram with W's and quarks). For $m_q^2 \ll M_W^2$ this leads to the expression:[11]

$$\begin{aligned}\epsilon \approx \frac{e^{i\pi/4}}{\sqrt{2}}\ \frac{BG_F^2 f_K^2 m_K}{6\pi^2 \Delta M_K} \\ \times\, s_1^2 s_2 s_3 s_\delta[-\eta_1 m_c^2 + \eta_2 s_2(s_2 + s_3 c_\delta)m_t^2 + \eta_3 m_c^2 \ell n(m_t^2/m_c^2)],\end{aligned} \tag{4}$$

where the s_i are the sines of the KM angles θ_i, $i = 1,2,3$ (these are known to be small so that the approximation $c_i = \cos\theta_i = 1$ has been used in Eq. (14)). A non-zero value of the angle δ is indicative of CP violation in the KM parametrization.[1] The factors η_1, η_2, and η_3 are due to strong interaction (QCD) corrections and have the values 0.7, 0.6, and 0.4, respectively, with usual quark and W boson masses.[12] The infamous parameter B is the ratio of the actual value of the matrix element between K^0 and $\overline{K}^0$ states of the operator composed of the product of two V-A neutral, strangeness changing currents divided by the value of the same matrix element obtained by inserting the vacuum between the two currents.

One can see that there can be a potential problem in getting the right-hand-side of Eq. (14) to reproduce the experimental value of $|\epsilon| = 2.27 \times 10^{-3}$ if the combination of the KM angles, m_t, and B are not large enough. To get some idea of where the experimental situation places us, take $B = 1/3$, a b quark lifetime of 1 picosecond, and $b \to u/b \to c < .04$. Then for $m_t \lesssim 60\ GeV$ we would have trouble satisfying Eq. (4).

This is not far from the situation that existed a couple of years ago. Since then there has been a retreat from confrontation. On the experimental side, as noted in the previous section, the upper limit on $b \to u/b \to c$ has become less stringent. This allows s_3 to be larger, relieving some of the pressure on the right hand side of Eq. (4).

On the theoretical side, the argument[13] that $B \approx 1/3$, was found to have potential 100% corrections from the next order (in chiral SU(3) breaking) and is therefore unreliable.[14] A flurry of papers[15] on the subject followed with values of B ranging from 0.3 to 1.5 or so. Finally, there is the value of m_t, which theoretical prejudice somehow kept near its ever increasing lower bound or at some nominal "discovered" value. Higher values of m_t lead to less of a problem in explaining the value of ϵ; they may now even be demanded by the size of $B-\bar{B}$ mixing (see the next section).

The situation for ϵ' has also become more open. By inserting experimentally measured quantities, the contribution to ϵ' from the "penguin" operator contribution to $K \to \pi\pi$ can be written[16]

$$\epsilon'/\epsilon = 6.0\ s_2 s_3 s_\delta \left(\frac{Im\widetilde{C}_6}{-0.1}\right) \left(\frac{<\pi\pi|Q_6|K^0>}{1.0\ GeV^3}\right) \tag{5}$$

where Q_6 is the "penguin" operator in the short distance expansion of the strangeness-changing weak Hamiltonian[17] and $Im\widetilde{C}_6$ is the imaginary part of the corresponding Wilson coefficient with the Kobayashi-Maskawa factor taken out.

The value of -0.1 for this last quantity is relatively stable from calculation to calculation, as the imaginary part depends on momentum scales from m_c to m_t where the short distance expansion is well justified. The value of the matrix element of Q_6 is much less certain. If it is large enough to explain the magnitude of $A(K \to \pi\pi)$, then, combined with the value of $s_2 s_3 s_\delta$ needed to fit ϵ (see above), it yields the prediction $\epsilon'/\epsilon \approx +10^{-2}$. This was the basic observation in Ref. 17: if the "penguin" operator is to be an explanation of the $\Delta I = 1/2$ rule and the magnitude of $A(K \to \pi\pi)$, then ϵ'/ϵ should be at the 1% level.

We note first that larger values of m_t or of B indirectly make the prediction for ϵ' decrease, for they allow a smaller KM factor from fitting ϵ. Early calculations of the matrix element of Q_6 gave numbers of order 1 GeV^3, to which we have normalized in Eq. (5). Later calculations incorporating current algebra constraints in a correct manner gave much smaller numbers,[18] but they do not allow one to understand the magnitude of the overall $K \to \pi\pi$ amplitude. Recent results from lattice gauge theory[19] (still in its infancy in regard to this kind of calculation) and from a 1/N expansion approach to weak matrix elements[20] give hope of understanding the magnitude of the K decay amplitude while indicating somewhat smaller values of ϵ'/ϵ. There have also been calculations of the electromagnetic "penguin" contributions which have already undergone a rather tortuous history from significantly suppressing the magnitude of ϵ/ϵ',[21] to finding two sign errors that led to a cancellation and a small suppression,[22] to uncovering another error and a net small to large enhancement.[23]

By comparison, the most recent experiments obtain:[24–26]

$$\begin{aligned} \epsilon'/\epsilon &= (-0.46 \pm 0.53 \pm 0.24) \times 10^{-2} \quad \text{(Ref. 24)} \\ \epsilon'/\epsilon &= (+0.17 \pm 0.82) \times 10^{-2} \quad \text{(Ref. 25)} \\ \epsilon'/\epsilon &= (+0.35 \pm 0.30 \pm 0.20) \times 10^{-2} \quad \text{(Ref. 26)} \end{aligned} \tag{6}$$

In light of this, very divergent possibilities are still open. It is still possible that "penguin" contributions are "large", that CP violation originates in the KM phase and we will still end up with a value of $|\epsilon'/\epsilon|$ of order 1%. The opposite alternative, that "penguin" contributions are small, is open as well. In either of these cases it is possible that there is a fourth generation, thereby allowing the severing of the connection between "large penguin" contributions and "large" (of order 1%) ϵ'/ϵ values.[27] Finally, it is possible that CP violation does not stem from the KM phase and has its origin in physics at a much higher mass scale.[28]

$B^0 - \overline{B}^0$ Mixing

As in the neutral K system, the neutral B system is capable of exhibiting mixing between an initial $B_d^0(\bar{b}d)$, for example, and its charge conjugate state, $\bar{B}_d^0(\bar{d}b)$. A typical signature (but not the only one) arises from the ensuing semileptonic decay involving a negatively charged lepton instead of the positively charged one which would come from a B_d^0. If we examine the 2×2 mass matrix of the $B^0 - \bar{B}^0$ system, we expect that Γ_{12}/M_{12} will be of order m_b^2/m_t^2, and that it is the mass difference between the two neutral B eigenstates, $|\Delta M| = \frac{1}{2}|M_{12}|$, which is the primary source of the mixing. This should be short distance dominated, with the box diagram involving t quarks. It is straightforward to rewrite the K result for B_d:[29]

$$|\Delta M| = \eta_{QCD} \frac{G_F^2 f_B^2 B_B m_B}{6\pi^2} | - e^{i\delta} \cdot s_1 s_2|^2 m_t^2, \tag{7}$$

where the QCD correction factor,[30] $\eta_{QCD} = 0.85$, and the factors of $-e^{i\delta} \approx V_{tb}$ and $s_1 s_2 \approx V_{td}^*$ are KM angle factors that arise at the $t - b$ and $t - d$ vertices, respectively. We have again used the form of the answer valid when $m_t^2/m_W^2 << 1$, although it is simple enough to copy the longer, exact expression.[11] Moreover, for the $B_s^0(\bar{b}s)$ meson, we need simply make the replacement, $V_{td}^* \rightarrow V_{ts}^* \approx s_2 + s_3 e^{-i\delta}$, to get the appropriate expression for ΔM_{B_s}.

The relationship to experiment is made through the quantity

$$r = \frac{(\Delta M)^2 + (\Delta\Gamma/2)^2}{2\Gamma^2 + (\Delta M)^2 - (\Delta\Gamma/2)^2} \approx \frac{(\Delta M/\Gamma)^2}{2 + (\Delta M/\Gamma)^2}. \tag{8}$$

For the case where the initial B is tagged as to being a B^0 rather than $\bar{B}^0$, $r = \ell^-/\ell^+$, the number of "wrong" to "right" sign leptons in its semileptonic decay. For uncorrelated $B^0 + \bar{B}^0$ pairs it follows that $2r/(1 + r^2) = \ell^\pm \ell^\pm / \ell^+ \ell^-$, but for correlated pairs produced at the $\Upsilon(4S)$, $r = \ell^\pm \ell^\pm / \ell^+ \ell^-$.

Experimentally, Mark II has an upper limit[31] on the mixing for uncorrelated B's at PEP, as does the CLEO experiment[32] for correlated B's at the $\Upsilon(4S)$ that corresponds to $r_d < 0.24$. UA1 on the other hand, claims[33] a several standard deviation signal in same-sign dimuons, but has attributed it to B_s. At this meeting, the ARGUS collaboration[34] is claiming for the first time the observation of a non-zero value of $r_d \approx 0.20$ using three different methods from data taken at the $\Upsilon(4S)$. Moreover, they claim a 90% C. L. lower bound of $\Delta M/\Gamma > 0.44$. This is similar to a K_S^0, *i.e.*, $\Delta M_K/\Gamma_{K_S} \approx 0.5$, but for a particle about 10 time heavier and 100 times shorter lived!

How does this match with theory? For B_d, the quantity of merit for the mixing is

$$\left(\frac{\Delta M}{\Gamma}\right)^2_{B_d} \approx 0.06\left(\frac{f_{B_d}}{f_K}\right)^4 B^2_{B_d}\left(\frac{s_2}{0.1}\right)^4\left(\frac{m_t}{35\text{ GeV}}\right)^4, \tag{9}$$

where we have reproduced an old result,[35] written with the parameters normalized to "standard" values of a few years ago (0.1 was then, and is still roughly now, the maximum allowed value of s_2). If we stretch the matrix element to the large end of a "reasonable" range ($f_B = f_K$ and $B_B = 1$) and do the same for the KM factor ($s_2 = 0.1$), then $r_d = 0.2$ is reproduced for $m_t \approx 60$ GeV. If we reduce the matrix element and KM factor ($B_B = 0.7$ and $s_2 = 0.07$), then m_t is pushed above $\approx$ 100 GeV.[36]

Note that for the B_s system, the relevant KM factor is $|V_{ts}|$, which in the (very good) approximation of small KM angles, θ_i, is equal to $|V_{cb}|$. The latter is fixed by the B lifetime, so there is no room to maneuver with respect to the KM angles in the expression for $\Delta M/\Gamma$, which becomes

$$\left(\frac{\Delta M}{\Gamma}\right)^2_{B_s} \approx 1.0\left(\frac{f_{B_s}}{f_K}\right)^4 B^2_{B_s}\left(\frac{m_t}{35\text{ GeV}}\right)^4, \tag{10}$$

It is impossible to avoid large mixing of B_s for any reasonable set of parameters which are in accord with moderate mixing for B_d.

These new data do not then necessitate new physics beyond the standard model with three generations, although the matrix element, KM factor and m_t are being squeezed upward, and some or all of them must have larger values than was assumed over the last few years. This is the most important short term consequence. Over the longer term, the most important implication of reasonably large B_d mixing may well be as engineering information for studies of CP violation in B decay at a B factory or the SSC. The new results have given a boost to the chances of doing this important but difficult physics in the future.

Tau Decay

As now known, the properties of the tau lepton and the tau neutrino are generally in excellent accord with those expected in the standard model for the third generation charged and neutral leptons, respectively. The decays $\tau \to \nu_\tau e \bar{\nu}_e$, $\tau \to \nu_\tau \mu \bar{\nu}_\mu$, $\tau \to \nu_\tau \pi$, $\tau \to \nu_\tau 2\pi$, $\tau \to \nu_\tau 3\pi$, and $\tau \to \nu_\tau 4\pi$, occur[37] at the expected rates and account for almost 90% of tau decays.

However, there is a nagging problem in accounting for all tau decays.[38] It shows up in doing the bookkeeping for the sum of the exclusive modes that result in one charged prong and comparing the result with the corresponding inclusive topological branching ratio[37] of $86.3 \pm 0.3\%$. Taking all the modes listed above plus Cabibbo-suppressed modes into account, there remains about 7% of tau decays that are not assignable to known exclusive channels.

The least disturbing explanation for this discrepancy, that the measurements of the major one-prong exclusive channels needed to be scaled up, became less likely as new and more accurate measurements became available.[39] By the time of the Kyoto Conference in 1985, the World-average branching ratios had significantly reduced errors and the discrepancy remained.[40]

However, data published in the past year seemed to point toward a resolution of the problem in a still relatively conventional manner through decays of the tau involving eta mesons. The MarkII[41] and TPC[42] collaborations each used slightly different tagging techniques and, constraining the sum of all the branching fractions to be unity, found that tau decays into a neutrino, charged pion, and two or more neutral hadrons were well in excess of the theoretical expectations[50] for the sum of just $\tau^- \to \nu_\tau \pi^- 2\pi^0$ and $\tau^- \to \nu_\tau \pi^- 3\pi^0$. As other modes involving only pions and kaons had been shown to make very small contributions to the one-prong plus multi-neutrals topology,[50] by process of elimination decays involving the eta meson in the "multi-neutrals" became prime suspects.[43]

The finger was put more directly on the eta by the Crystal Ball[44] and the HRS[45] collaborations, who both claimed evidence for an eta signal in tau decays.

HRS reported a branching fraction for $\tau^- \rightarrow \nu_\tau \pi^- \eta +$anything of $5.0 \pm 1.0 \pm 1.2\%$. Thus, by the Berkeley Conference the discrepancy seemed to be moving toward a resolution in terms of tau decays to an eta meson.[37][46]

Even though no one expected such large branching ratios involving the eta, everything seemed to be quieting down to a quite conventional result. Now, the situation has come alive again with the HRS collaboration claiming that the decays involving the eta occur at the 5% branching ratio level in exactly the mode, $\tau^- \rightarrow \nu_\tau \pi^- \eta$, that is not expected in the standard model.[47] The $\eta\pi$ system, which is G odd, has natural spin-parity and in the standard model it must come from the vector current, which is G even; we have by definition a process that involves a second class current. Within the standard model this should happen at a level of roughly α^2 in the rate when compared to processes arising through the usual first class currents and such a decay would be completely negligible.[48] Other experiments should soon be able to confirm or refute this result.[49]

If we stay within the confines of the standard model, we can still ask the question of whether tau decays involving the eta can account for the remaining one-prong modes. The most obvious candidate which is allowed in the standard model is $\tau \rightarrow \nu_\tau \eta 2\pi$. This proceeds through the vector current and can be related by CVC to a weighted integral over $\sigma_{e^+e^- \rightarrow \eta\pi^+\pi^-}$. The data that has recently become available on the latter process allow one to place the bound[50] $BR(\tau^- \rightarrow \nu_\tau \eta \pi^- \pi^0) < 0.24\%$. Examination of all the other tau modes involving eta's shows[50] that a generous upper limit on the sum of their branching ratios is 2%. Within the standard model, the "missing" exclusive modes have to come from somewhere else unless production of eta's is a major part of the e^+e^- total cross section at low energy and has been completely missed. The puzzle has only become deeper as the possibilites have been further narrowed.

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