PROPERTIES OF HEAVY QUARKS AND LEPTONS

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Abstract

Selected properties of the heavy quarks c and b and of the third generation leptons τ and ν_τ are reviewed and updated.

1 Introduction

The Standard Model (SM) breaks the world into the constituents of matter, which are fermions, and the carriers of the forces, which are gauge bosons. The fermions divide into three generations, based loosely on increasing mass, with each generation having two quarks and two leptons.

The electromagnetic interaction is mediated by the photon (γ) and acts on a constituent's electric charge, never changing the identity of the fermion. The weak interaction is mediated by three bosons (Z^0, W^+, W^-) and has a neutral current component, which again preserves the species, and a charged current. This charged current makes the natural representation of the leptons and quarks as weak isodoublets, with the charged W's working within each doublet; this current is taken to be left-handed and the symmetry is usually denoted as $SU(2)_L$. Finally there is the strong interaction which works on the color "charge" of the quarks and has no effect on the leptons.

The lepton doublets each consist of a charged lepton and its corresponding neutrino: $(\nu_e, e)_L, (\nu_\mu, \mu)_L, (\nu_\tau, \tau)_L$ with the subscript "L" noting the left-handed nature of the weak interaction. The quark doublets are then given as $(u, d')_L, (c, s')_L, (t, b')_L$ where the "prime" on the d, s and b quarks reminds us that the weak eigenstates of these isodoublets do not correspond directly to the mass eigenstates of these quarks; i.e., the lower member each isodoublet is a superposition of the true d, s and b quarks.

This contribution to the proceedings and the talk on which it is based by no means exhaust the properties of the heavy quarks and leptons. This is a very rich area of the field and several hours and many pages would be needed to do a thorough job. I have chosen to concentrate on some of the important properties of the b quark and the τ lepton, with some information as well on c and ν_τ. The t quark is the subject of a separate talk[1] at this conference and other speakers will also be addressing issues involving neutrini.

In putting this presentation together I am indebted to the many people who have graciously given me their data and copies of their results; I thank them all. I have also benefited by having three references as a starting point from which to launch my investigations:

- PDG: Particle Data Group compilations [2]

- LP93: Proceedings of the 1993 Lepton-Photon Conference [3]
- TAU93: Review article by Weinstein and Stroynowski on τ physics [4]

2 The τ and its Neutrino

2.1 Mass of the Tau - m_τ

For some fourteen years the measured mass value of was dominated[2] by the 1978 DELCO value [5] of $m_\tau = 1784.1 MeV$ with an uncertainty of about 0.2%. However there has been a recent flurry of activity in this area. The BES group at the Bejing e^+e^- machine BEPC has taken data at the $\tau\tau$ threshold. Their initial result,[6] based on only seven events, shifted the mass lower by 7 MeV and reduced the uncertainty a factor of eight! It is important to note that their data collection strategy placed great emphasis on data points for which **no** τ pairs were observed! Since then the ARGUS [7] and CLEO [8] collaborations have corroborated the result with data in the Υ energy range ($E_{cm} \sim 10.6$ GeV) and the BES group has added more decay modes to their study [9] bringing their event count to 29. The world average value, as compiled by Tomasz Skwarnicki [10], is:

$$m_\tau = (1777.0 \pm 0.3) MeV,$$

which represents a fractional uncertainty of 0.017%.

2.2 Lifetime of the Tau - τ_τ

There have been many new results since 1992, although most of them are still "preliminary", having been presented at conferences but not yet polished enough for publication. Driving these new measurements is the advent of high-resolution silicon vertex detectors at the LEP experiments DELPHI, OPAL, and ALEPH[11] and the high statistics available at CESR for CLEO.[12] Two basic techniques are used, and the results are often the average of these:

- Vertexing: Using the τ decays to three charged tracks, a vertex is found that is distinct from the beam position; in some cases both decays are to three charged particles, eliminating the need to know the beam position.
- Impact Parameter: Each track is projected back to the beam spot and the lifetime is inferred from the distribution of these impact parameters; sometimes the difference in the impact parameters of the daughters of both τ's is used instead.

Despite the use of the same techniques the two laboratories have rather different problems to resolve: at LEP, operating at $E_{cm} \sim 91 GeV$ the Lorentz boost is roughly 26, making for decay lengths on the order of a millimeter but very small opening angles; at CESR the boost is only about 3, making for short path lengths but larger decay angles.

The new world average, again courtesy of Skwarnicki [10], is

$$\tau_\tau = (293.3 \pm 2.3) fs.$$

This represents an accuracy of 0.8%. It is interesting to note that this new world average is roughly 4% lower the the 1992 PDG value of (305 ± 6) fs. The various experiments feel a factor of two further reduction in the uncertainties is possible in the near future.

2.3 Mu-Tau Universality - G_τ/G_μ

If the τ is really a "sequential" lepton, *i.e.*, a heavy version of e or μ, then its coupling strength to the charged current weak interactions should be the same as these lighter leptons. The decay of $L^- \to e\nu_e\overline{\nu}_L$ is well described in the theory and can be compared for $L = \mu, \tau$. Breaking up the Fermi coupling constant G_F^2 into $G_L G_e$ the partial width for the decay is:

$$\Gamma(L^- \to e\nu_e\overline{\nu}_L) = m_L^5 \cdot G_L G_e/192\pi^3 \tag{1}$$

with the fifth power of the mass being the familiar Sargent factor[13] associated with the phase space of such decays. This partial width is also related to the lifetime by

$$\Gamma(L^- \to e\nu_e\overline{\nu}_L) = \Gamma_{tot}^L \cdot B_e^L = B_e^L/\tau_L, \tag{2}$$

with B_e the branching fraction to $e\nu\overline{\nu}$. The comparison of the coupling strengths then becomes:

$$G_\tau/G_\mu = (\tau_\mu/\tau_\tau) \cdot (m_\mu/m_\tau)^5 \cdot (B_e^\tau/B_e^\mu). \tag{3}$$

Recent improvements have been made to the electronic branching fraction of the τ to complement the new measurements of m_τ and τ_τ noted previously. Skwarnicki [10] gives the new world average as

$$B_e^\tau = (17.91 \pm 0.14)\%$$

with the greatest weight coming from a recent CLEO measurement [14]. Putting these together shows $\tau - \mu$ universality nicely,

$$G_\tau/G_\mu = 0.997 \pm 0.011.$$

Note that the uncertainty in this ratio is still dominated by the three τ measurements.

2.4 Tau Weak Neutral Couplings - v_τ, a_τ

Since the neutral carrier of the weak force is the Z^0, it is natural that these couplings of the τ are measured by the four LEP experiments - L3, OPAL, DELPHI, and ALEPH. The two couplings (v is for "vector" and a for "axial-vector") most often enter observables in the combination [4]

$$A_f = \frac{2a_f v_f}{a_f^2 + v_f^2}, \tag{4}$$

for any fermion; for $L = e, \mu, \tau$, the variables v_L and a_L are related, to the Weinberg parameter in SM as

$$4 sin^2\theta_W = 1 - v_L/a_L. \tag{5}$$

At LEP one looks at $Z^0 \to \tau^+\tau^-$ defining θ_f as the angle between the incoming fermion (e^-) and the outgoing fermion (τ^-). The helicity of the τ^-, denoted h_τ, is inferred from the momentum of its daughter(s), in that the left-handedness of ν_τ, which is **assumed**, dictates the direction of the daughter(s) in the τ rest frame. The τ polarization, P_τ, is defined theoretically and experimentally by

$$P_\tau(cos\theta_f) = -\frac{A_\tau(1 + cos^2\theta_f) + 2A_e cos\theta_f}{(1 + cos^2\theta_f) + 2A_e A_\tau cos\theta_f} = \frac{\sigma(h_\tau > 0) - \sigma(h_\tau < 0)}{\sigma(h_\tau > 0) + \sigma(h_\tau < 0)}. \tag{6}$$

Evidence from other processes [2] gives $sin^2\theta_W \sim 0.23$, predicting $A_L \sim 0.12$. Thus $P_\tau(-1) \sim A_e - A_\tau$ and $P_\tau(+1) \sim -(A_e + A_\tau)$ so that the results for A_e and A_τ are rather independent, with $< P_\tau >= -A_\tau$.

The recent LEP results[11] are

$$A_\tau = 0.150 \pm 0.010; \quad (v_\tau/a_\tau) = 0.075 \pm 0.005$$

$$A_e = 0.120 \pm 0.012; \quad (v_e/a_e) = 0.060 \pm 0.006,$$

so that $\tau - e$ universality seems "OK" at the 2σ level. Assuming such universality these measurements give $sin^2\theta_W = 0.233 \pm 0.001$, perfectly consistent with values from other sources.

2.5 Tau as a Window on New Physics

The SM has no symmetry associated with lepton number or lepton flavor conservation; *i.e.,* there is nothing to demand $\Delta L = \Delta L_e = \Delta L_\mu = \Delta L_\tau = 0$. In fact several extensions of SM[15] predict such violations. Given the large mass of the τ one would perhaps expect such "new" physics to show up in τ decays, such as decays without neutrini.

CLEO has recently looked [16] for neutrinoless τ decays into a wide variety of modes involving either three leptons (*e.g.,* $\tau^- \to e^-e^+e^-$) or one lepton and two hadrons (*e.g.,* $\tau^- \to e^+\pi^-\pi^-$). Hence they all involve non-conservation of lepton flavor and some also involve $\Delta L = 2$. Events were selected to be "τ-like" with a 1-v-3 topology and the invariant three body mass was calculated. In most channels there were zero events in the signal region, leading to 90% C.L. limits of less than $4 \cdot 10^{-6}$ for the τ branching fraction into the purely leptonic modes: $e^-e^+e^-$, $\mu^-e^+e^-$, $e^-\mu^+e^-$, $e^-\mu^+\mu^-$, $\mu^-e^+\mu^-$, and $\mu^-\mu^+\mu^-$. Similarly, they report limits between $4 - 20 \cdot 10^{-6}$ for the following modes involving hadrons: $e^-\pi^+\pi^-$, $\pi^-e^+\pi^-$, $e^-K^+\pi^-$, $e^-\pi^+K^-$, $\pi^-e^+K^-$, $\mu^-\pi^+\pi^-$,

$\pi^-\mu^+\pi^-$, $\mu^-K^+\pi^-$, $\mu^-\pi^+K^-$, and $\pi^-\mu^+K^-$. These limits are roughly 4 to 10 times more restrictive than the previous limits set by ARGUS [17] and CLEO [18].

Another possible hint of "new" physics would be the inability to classify all τ decays. One way this would manifest itself is if the sum of all the exclusive one-prong decays did not equal the inclusive one-prong "topological" branching fraction, often denoted B_1; this is the so-called "one-prong deficit". Another approach is to see that the sum of all exclusive τ decays adds to unity. Evaluating (and worrying about!) these deficits has a long history [19], and we have two new attempts.

The first is from LEP [11], at which the L3 and OPAL experiments report

$$L3: \quad \Sigma_{ex}B(\tau^- \to h^- X) = (84.2 \pm 1.2)\%; \quad B_1 = (85.6 \pm 0.7)\%,$$

$$OPAL: \quad \Sigma_{ex}B(\tau^- \to h^- X) = (83.3 \pm 1.5)\%; \quad B_1 = (84.5 \pm 0.4)\%,$$

showing no obvious one-prong deficit. ALEPH looks at the more global picture reporting

$$\Sigma_{ex}B(\tau \to X) = (99.9 \pm 0.8 \pm 0.7 \pm 0.7)\%,$$

with the last quoted uncertainty due to the $\tau\tau$ normalization; this is clearly consistent with unity.

Skwarnicki [10] instead uses the newest world averages to obtain

$$\Sigma_{ex}B(\tau^- \to h^- X) = (83.7 \pm 0.6)\%; \quad B_1 = (85.3 \pm 0.2)\%,$$

$$\Sigma_{ex}B(\tau \to X) = (97.5 \pm 0.8)\%.$$

These show lingering signs of deficits in both areas. However, adding new results to existing averages that show a deficit will only slowly remove such a deficit. We have certainly not heard the last word on this topic!

2.6 Existence of the Tau Neutrino - ν_τ

No experiment has **ever** observed an interaction initiated by a tau neutrino. To firmly state that ν_τ exists would mean seeing the inverse beta decay process $\nu_\tau N \to \tau^- N'$ with N, N' being nucleon systems. There are, however, three pieces of evidence that make ν_τ's existence almost certain.

First, in the decays $\tau \to \mu$ and $\tau \to e$ the momentum spectrum of the daughter lepton is that of a three body decay.[20] If both of the missing, low-mass, neutral particles were ν_e or ν_μ then one would expect that τ's would be produced in charged current interactions involving ν_e or ν_μ; they are not.

Next we have the line shape of the Z^0 at LEP, in which the four experiments compare the observed width with the sum of the partial widths to exclusive observed modes. The "leftover" width must be due to light, neutral, weakly interacting particles, *i.e.*, neutrini. Using the SM prediction for the contribution of each neutrino species to this width the published result[21] is

$$N_\nu = 3.00 \pm 0.05,$$

with a recent conference update[22] placing the number at 2.985 ± 0.024. Either of these is fine; N_ν is not two and it is not four.

Finally, one can look in detail at the Z^0 partial widths to the three lepton species: $\Gamma_{ee}, \Gamma_{\mu\mu}$, and $\Gamma_{\tau\tau}$. The SM prediction for the left- and right-handed couplings of a fermion pair to the Z^0 involve the fermion's electric charge, its weak isospin, and the Weinberg angle[13]; viz;

$$g_L = I_3 - Q \cdot sin^2\theta_W; \quad g_R = -Q \cdot sin^2\theta_W. \tag{7}$$

These combinations result from the fact that the Z^0 and γ are really rotations by θ_W of the more primordial neutral carriers of the weak and electromagnetic forces. The recent LEP results[22] are

$$\Gamma_{ee} = (84.0 \pm 0.2)MeV; \quad \Gamma_{\mu\mu} = (84.0 \pm 0.3)MeV; \quad \Gamma_{\tau\tau} = (84.1 \pm 0.4)MeV.$$

clearly showing these partial widths to be equal. This implies that $I_3(\tau)$ is $-1/2$, just like that of the lighter leptons and that there must be a corresponding neutrino in the isodoublet.

Experiments are being run to try to actually observe charged current interactions involving ν_τ. Two of these, NOMAD and CHORUS at CERN, are looking for ν_τ in neutrino oscillations from ν_μ [23]; these are actually in progress. At FNAL there are two other experiments, E803 and P872, the latter of which is situated behind a beam dump, looking for ν_τ from the decay $D_s \to \tau\nu_\tau$ and the subsequent τ decay. These experiments could start as early as 1995.

2.7 Mass of the Tau Neutrino - m_{ν_τ}

Since neutrino masses are the subject of another talk at this conference [23] I will not dwell on the subject here. The two most recent limits on the mass of ν_τ come from ARGUS [24] and CLEO, [25] both of whom look at the end-point of the invariant mass spectrum of the five pions in the decay $\tau \to 5\pi\nu_\tau$.

The ARGUS group used the all-charged mode, finding 20 events near the endpoint from which they conclude $m_{\nu_\tau} < 31MeV$ at 95% C.L. The recent CLEO result uses both the all-charged mode and the final state involving three charged and two neutral pions. They have 113 events near the endpoint, allowing them to assert that $m_{\nu_\tau} < 32.6MeV$, again at 95% C.L.

Two interesting points to note. Placing the limits in terms of relative mass, these represent $m_\nu/m_L < 2 \cdot 10^{-2}$, whereas for the electron and muon this ratio is known to be less than $2 \cdot 10^{-5}$ and $3 \cdot 10^{-3}$, respectively. Second, there are astrophysical implications[26] of heavy neutrini on the synthesis of the light elements He, Li, and deuterium. Assuming ν_τ has a lifetime in excess of 300 sec, the abundances of these nuclei would **exclude** the region $0.4 < m_{\nu_\tau} < 30MeV$. Therefore the next round of endpoint results, which should place limits on the order of 25 MeV, stand to gain a factor of 50 from this astrophysical observation!

2.8 Lorentz Structure of $W - \tau - \nu_\tau$

Even if the τ and ν_τ are in a weak isodoublet there is no guarantee that it is left-handed, or $V - A$ in nature. There is a set of 10 parameters[27] that completely specify this Lorentz structure of the charged current vertex. Many of these are difficult to measure, but I will detail recent efforts on three of these:

- ρ : the "Michel parameter" which describes the lepton energy spectrum in $\tau \to L\nu\overline{\nu}$;
- η : the "low energy parameter" which manifests itself in the energy spectrum of the muon in $\tau \to \mu\nu\overline{\nu}$;
- h_ν : the helicity of the neutrino.

The spectrum of the lepton energy, E_L, in the rest frame of the parent τ is given by, to within constant factors,

$$\frac{d\Gamma}{dE_L} = E_L^2 \cdot [a(E_L) + \rho \cdot b(E_L) + \eta \cdot \frac{m_L}{m_\tau} \cdot c(E_L)] \tag{8}$$

In the above expression polarization and radiative effects have been ignored. The values of ρ and η for a $V - A$ coupling are 3/4 and 0, respectively.[4] Note that the term involving η has a factor of the ratio of daughter to parent masses, making η a more difficult parameter to measure. The best published values for ρ are from ARGUS [28] who, assuming $\eta = 0$, looked at both the e and μ energy spectra obtaining:

$$\rho_e = 0.747 \pm 0.045 \pm 0.028; \quad \rho_\mu = 0.734 \pm 0.055 \pm 0.027,$$

clearly in agreement with the $V - A$ hypothesis. Recently ARGUS has a new result [29] in which they use the other τ to predict the boost of the τ being investigated, enhancing their analyzing power. This leads to $\rho_e = 0.735 \pm 0.036 \pm 0.020$. More importantly this new analysis allows them to look at their muon spectrum and determine a best fit value for η, marking the first time this parameter has been measured in τ decay;

$$\eta = 0.03 \pm 0.15 \pm 0.12 \pm 0.12,$$

with the last error dictated by the uncertainty in the value of ρ.

The helicity of the neutrino should be $h_\nu = -1$ for a left-handed system. This parameter is related to the charged current couplings by

$$\gamma_{av} = -h_\nu = \frac{2g_a g_v}{g_a^2 + g_v^2}. \tag{9}$$

The ARGUS collaboration has two analyses that bear on this issue. The first, already published, [30] looks at asymmetries in the three prong decay $\tau \to \pi\pi\pi\nu$ to obtain, **including the sign**,

$$\gamma_{av} = 1.25 \pm 0.23 + 0.15/ - 0.08.$$

Recently they have used energy-energy correlations[31] in the decay products of the two τ's to obtain

$$|\gamma_{av}| = 0.98 \pm 0.04 \pm 0.03.$$

Both of these are also nice confirmations of the left-handedness of the charged current in the τ isodoublet.

3 The Heavy Quarks c and b

3.1 Meaning of Mass in the Quark Sector

All the observed hadrons are triplets of quarks (the baryons) or quark-antiquark pairs (the mesons). In the parlance of color $SU(3)$, all the observed objects are color singlets, or "colorless". Since quarks possess color, they are not seen by themselves. One might ask then whether mass is a meaningful property to ascribe to a quark. Since the basic theory starts at the quark level, mass in indeed an important input. In fact, there are (at least) two kinds of masses that are used in discussing the quarks.

The first is the "current" mass, which is the variable used in the Lagrangian (as in $\overline{\psi} m \psi$). Those working in lattice QCD often call this the "bare" mass. The current mass for the u and d quarks is essentially zero, making isospin a useful concept for them.

The other type of mass is the "constituent" mass. This is the mass imposed by confinement, the mass which the quarks "seem" to have. Sometimes this is called the "dressed" mass. This is the value used in estimating magnetic moments of the hadrons, guessing masses of the hyperons, *etc.*. In lattice QCD the closest concept is the "pole" mass, which is the correct mass to use in potential models and other applications which have no additional mass renormalizations.

One measure of how heavy a quark is would be to look at the ratio of its current mass to its constituent mass. If this is close to unity, the quark is sufficiently massive that the QCD dressing is unimportant. Taking the values from Sanda[32] this ratio is 0.0, 0.0, 0.5, 0.7, and 0.9 for u, d, s, c and b respectively.

Another way to look at this is to ask that the QCD scale factor (Λ_{QCD}) be small with respect to the mass. In fact many expansions in the theory involve the ratio Λ/m. Taking $\Lambda_{QCD} \sim 250 MeV$ and using the constituent masses gives

$$\frac{\Lambda_{QCD}}{m_q} = 2(u), \quad 2(d), \quad 1(s), \quad 0.15(c), \quad 0.05(b), \quad 0.001(t). \tag{10}$$

By these measures, then, the u, d, s quarks are "light", b and t are "heavy", and c is somewhere in between.

3.2 Mass of the b Quark - m_b

QCD on the lattice is a vibrant field and seems exceptionally well-suited for heavy systems such as the Υ, which is a $b\overline{b}$ state. As an example, there is a recent result[33] that calculates the pole mass of the b quark. Such a lattice calculation places the b and $\overline{b}$ on the nodes of the lattice and the gluons on the links. These lattices are four-dimensional so that time dependent phenomena and motion of the Υ system can be simulated. This new result uses a non-relativistic QCD Lagrangian and has only one input, namely the bare mass, m_0. In essence, the calculation determines the amount of QCD dressing for the b.

The value of m_0 is **not** arbitrary. It is tuned to give the correct dispersion relationship ($\omega = \omega(k)$) for a slowly moving Υ. This determines the best bare mass to be $m_0 = (4.11 \pm 0.06) GeV$. Now the Υ spectrum is examined, verifying that the lattice simulation gives the experimentally observed values of the two other S-wave states (Υ(2S) and Υ(3S)) and the observed splitting of the lowest-lying P-wave triplet ($\chi_{b0}, \chi_{b1}, \chi_{b2}$). The pole mass is then calculated from the known Υ mass and the effective binding energy yielding:

$$m_b(Lattice) = (4.94 \pm 0.15) GeV.$$

This then is the mass the authors suggest be used in heavy-quark expansions and mass-dependent calculations of rates and widths.

3.3 Lifetimes of the Heavy Quarks - τ_Q

Do the c, b and t quarks have meaningful, measurable lifetimes? Since the t quark decays to a b and a **real** W, it's lifetime does not involve G_F^2 from the W propagator. The estimated value is $\tau_t \sim 10^{-19} s$, which is too short to be directly measured. It also means that $t\bar{t}$ states are unlikely unless there are T mesons lighter than half of $m_{t\bar{t}}$ so that these states could decay strongly.

For the c quark its lifetime could be inferred from the lifetimes of the charmed mesons. However it is observed [2] that $\tau(D^+) = 2.7 \cdot \tau(D^0)$. This means that the light quark is affecting the c quark, implying that the c is too light to have a meaningful lifetime.

The b quark, however, is in the right mass range to have a useful characterization of its lifetime, $\Lambda_{QCD} << m_b << m_W$. The four LEP experiments have new, updated results[34] on the average lifetime of all produced hadrons containing b quarks and, using reconstruction, on the individual lifetimes of B^0, B^+ and B_s:

$$\tau_b = (1.53 \pm 0.02) ps;$$

$$\tau(B^0) = (1.51 \pm 0.12) ps; \quad \tau(B^+) = (1.66 \pm 0.14) ps; \quad \tau(B_s) = (1.60 \pm 0.19) ps.$$

The CDF collaboration at FNAL also has results on both the inclusive lifetime[35] and, reconstructing B decays to states involving J/ψ, the individual bottom meson lifetimes:[36]

$$\tau_b = (1.46 \pm 0.06 \pm 0.06) ps;$$

$$\tau(B^0) = (1.57 \pm 0.20) ps; \quad \tau(B^+) = (1.61 \pm 0.17) ps; \quad \tau(B_s) = (1.42 \pm 0.27) ps.$$

Given that the ratio of lifetimes for the D^+ and D^0 is so different from unity, one can explore this ratio further for the B^+ and B^0; this ratio is usually written τ_+/τ_0 in the literature. For LEP[34] and CDF[36] this ratio is:

$$(\frac{\tau_+}{\tau_0})_{LEP} = 1.07 \pm 0.13; \quad (\frac{\tau_+}{\tau_0})_{CDF} = 1.02 \pm 0.15.$$

CLEO and ARGUS[37], operating near $B\overline{B}$ threshold, cannot observe decay lengths for B^+ or B^0. However, they can obtain τ_+/τ_0 by measuring the ratio of the leptonic branching fractions of the two B species:

$$\frac{B(B^+ \to XL\nu)}{B(B^0 \to XL\nu)} = \frac{\Gamma^+_{L\nu}}{\Gamma^0_{L\nu}} \cdot \frac{\tau_+}{\tau_0} = \frac{\tau_+}{\tau_0}. \tag{11}$$

The two partial widths cancel because the semi-leptonic decays can only proceed through so-called "spectator" processes in which the decay of the b quark is totally independent of the light quark in the hadron. The recent CLEO result[38] is:

$$(\frac{\tau_+}{\tau_0})_{CLEO} = 0.93 \pm 0.18 \pm 0.12.$$

Therefore, for the b hadrons the lifetimes of the various species are very similar and one rightfully assigns the b quark a lifetime of roughly $1.50ps$.

3.4 Neutral Current Couplings of the b Quark

As indicated for the τ, the couplings of a fermion to the Z^0 depend on both the fermion electric charge and the third component of its weak isospin. Taking into account the charge of the b quark being $-1/3$, the SM predicts the partial width of the Z^0 to $b\bar{b}$ to be $\Gamma_{b\bar{b}} = (376 \pm 3)MeV$ if $I_3 = -1/2$ but $\Gamma_{b\bar{b}} \sim 24MeV$ for $I_3 = 0$. The four LEP experiments use the fact that b-flavored hadrons are quite massive, decaying to leptons with large p_T, to get enriched samples of $Z^0 \to b\bar{b}$ events. They find

$$\Gamma_{b\bar{b}} = (383 \pm 5)MeV,$$

clearly indicating that the b is the lower member of a weak isodoublet, implying, to no surprise, that there should be a t quark. The width of the Z^0 to all hadrons is [40] $\Gamma_{had} = (1740.3 \pm 5.9)MeV$ and many times the ratio is quoted, *i.e.*, $\Gamma_{b\bar{b}}/\Gamma_{had} = 0.220 \pm 0.003$.

As in the case of the τ, one can also look at asymmetry measurements in the case of b or c production at the Z^0. Here one cannot measure the quark polarization but instead looks at the forward-backward asymmetry, A_{FB}, defined as

$$A^q_{FB} = \frac{(\sigma_F - \sigma_B)}{(\sigma_F + \sigma_B)} \sim \frac{3}{4} \cdot A_q \cdot A_e. \tag{12}$$

Here σ_F and σ_B correspond to the production of the b or c (*i.e.*, the final state **fermion**) forward and backward, respectively, with respect to the incident electron beam.

For the b, the LEP experiments use both their high-p_T leptons and the correlation of jet charge to parent quark to get enriched samples, leading to measurements of A^b_{FB} and $sin^2\theta_W$ of[41]

$$A^b_{FB} = 0.095 \pm 0.004 \pm 0.002; \quad sin^2\theta_W = 0.2327 \pm 0.0008.$$

Similarly they use other kinematic constraints on the high-p_T leptons and D^* tags to obtain enriched samples of $c\bar{c}$ final states, obtaining,[41]

$$A^c_{FB} = 0.067 \pm 0.008 \pm 0.007; \quad sin^2\theta_W = 0.2320 \pm 0.0026.$$

The difference in the values of A_{FB} should not be surprising since[13] $v_f = I_3 - 2Q_f sin^2\theta_W$ and $a_f = I_3$, leading to different values for A_b and A_c. Both of these results for the Weinberg parameter are in good agreement with the overall combined LEP-SLD value[41] of $sin^2\theta_W = 0.2316 \pm 0.0004$.

3.5 Weak Charged Currents - $V_{ub}, V_{cb}, b \to s\gamma$

As mentioned in the introduction, the weak eigenstates of the quarks are not the same as the mass eigenstates. This is evident, for example, in that both the $\pi^+ = (u\bar{d})$ and $K^+ = (u\bar{s})$ can decay weakly to the same leptonic final state of $e^+\nu_e$. Clearly the weak interaction must connect the u quark to some linear combination of d and s quarks.

With two generations the mixing is simply described in terms of a single parameter, the Cabibbo angle θ_c, with[13]

$$d' = d \cdot cos\theta_c - s \cdot sin\theta_c = V_{ud}d + V_{us}s \tag{13}$$

$$s' = s \cdot cos\theta_c + d \cdot sin\theta_c = V_{cs}s + V_{cd}d. \tag{14}$$

The V_{ij} are then the weak couplings between quark i and j. Adding the third generation of (t, b') means that the mixing matrix, called the Cabibbo-Kobayashi-Maskawa matrix, must become 3X3, with now four independent parameters.[32] I will concentrate on the developments involving the couplings of the b, namely V_{ub}, V_{cb}, and V_{tb}.

First, there is the measure of these from semileptonic B decay. As mentioned earlier, such decays leave the light quark as a spectator so that the branching fraction can be derived as:

$$B(b \to qL\nu) = \frac{G_F}{192\pi^3} \cdot \tau_b \cdot m_b^5 \cdot (\gamma_{cb}|V_cb|^2 + \gamma_{ub}|V_{ub}|^2). \tag{15}$$

The factors γ_{ub}, γ_{cb} involve phase space and other considerations that are model dependent.[42] One then fits the observed semileptonic decay energy spectrum assuming the various decay models and accounting for other sources of leptons such as $B \to DX \to YL\nu$. The preliminary CLEO result[42] is:

$$|V_{cb}| = 0.042 \pm 0.001 \pm 0.004 \pm 0.004,$$

with the last uncertainty due to variations in τ_b and m_b. Their fitted value for V_{ub} is given as $|V_{ub}/V_{cb}| \sim 0.10$, consistent with other results that I'll later detail. Since the b must couple to u, c, and t with unit probability, it is clear that $|V_{tb}|^2 = 1 - |V_{ub}|^2 - |V_{cb}|^2$ is essentially unity.

Another technique[42] involves Heavy Quark Effective Theory (HQET), looking at the process "B" $\to$ "D"$L\nu$. HQET is exact in the limit of $m_q \to \infty$ or, in other words, $\Lambda_{QCD}/m_q \to 0$. The theory predicts a universal form factor $\hat{\xi}(y)$ with y related to the q^2 of the event by

$$y = \frac{m_B^2 + m_D^2 - q^2}{2m_B m_D}, \tag{16}$$

which is, in the rest frame of the decaying B just E_D/m_D. Note that the masses involved are those of the **mesons** not the quarks! The limiting value of y is unity, for which the D is at rest in the B frame. HQET goes on to predict that for this limiting y, $\hat{\xi}(1) = 1 + O(\Lambda/m)$, and that for the decay of a psuedoscalar to a vector (*e.g.*, $B \to D^* L\nu$) the first order corrections are identically zero so that $\hat{\xi}(1) = 1 + O(\Lambda/m)^2$ for this case. The yield with respect to y is given by

$$\frac{d\Gamma}{dy} = f(y) \cdot m_{D^*}^3 \cdot (m_B - m_{D^*})^2 \cdot |V_{cb}|^2 \hat{\xi}^2(y) \tag{17}$$

CLEO has used this technique to obtain V_{cb}.[43] They need to convolve the above equation with the effects of detector resolution and the small motion of the B mesons from running at $\Upsilon(4S)$ energies, and then extrapolate to $y = 1$. Their result is

$$\hat{\xi}(1) \cdot |V_{cb}| = 0.0355 \pm 0.0019 \pm 0.0020.$$

Most theoretical prejudice is that the $O(\Lambda/m)^2$ corrections are very small, giving $\hat{\xi}(1) = 1.00 \pm 0.03$, making the CLEO result a direct, accurate measure of V_{cb}.

For a better measure of V_{ub} ARGUS[44] and CLEO more closely examine the endpoint of the lepton energy spectra in semileptonic decays. A recent CLEO publication[45] has greatly improved statistics, but is still hampered by model dependence in the prediction of the shape of the $b \to u$ component of the spectrum, giving

$$|V_{ub}/V_{cb}| = 0.78 \pm 0.08 \pm 0.22,$$

with the second error depicting the range of the models.

My last topic will be the observation by CLEO of $b \to s\gamma$ in the decay $B \to K^*\gamma$.[46] This cannot proceed at "tree level" since the electromagnetic neutral current cannot change quark species from b to s. Instead, this is a second order weak process with $b \to Wq^*$, (q^* being a "virtual" t, c, or u), q^* emitting a photon, and finally $Wq^* \to s$. Such a diagram in whimsically called an electromagnetic penguin. CLEO's result is

$$B(B \to K^*\gamma) = (4.5 \pm 1.5 \pm 0.9) \cdot 10^{-5}.$$

CLEO also looks inclusively at its γ spectrum to place a limit on the quark level process

$$B(b \to s\gamma) < 5.4 \cdot 10^{-4} \qquad @95\% C.L.$$

Both of these numbers should be improved for the summer 1994 conferences.

One might wonder why the observation of these penguin decays is so exciting. The first step is to realize that if electromagnetic penguins exist, then so do hadronic penguins in which the virtual quark emits a gluon instead of a photon.

One of the CKM parameters is a phase, δ. This phase is related to direct CP violation, one of the remaining mysteries of particle physics. To extract a phase from data, one needs to measure more than one amplitude, since $|Ae^{i\delta}|^2 = A^2$, hiding the phase. It is only through interference terms that the phase becomes measurable, viz. $|Ae^{i\delta} + B|^2 = A^2 + B^2 + 2ABcos\delta)$. Thus we need to have two different paths for a particular initial state ($e.g.$, B^+) to go to a particular final state ($e.g.$, $K^+\pi^0$) to observe such a CP violating phase. Penguins afford that possibility.

4 Conclusion

The studies of the heavy quarks b, c and the third generation leptons τ, ν_τ are extremely rich and active areas. So far there are no surprises ... the Standard Model is alive and well!

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