WEAK DECAYS OF HEAVY QUARKS

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I. Introduction

More than a year ago new experimental data became available which indicated that the theoretical predictions people have made with respect to the weak decays of charmed particles were not correct. Subsequently many people have worked on the problems of weak decays of heavy quarks. A logical possibility to understand the puzzles of the nonleptonic weak decays in particular is to introduce new types of weak interactions, e.g. new currents etc. (similar attempts have been made in the past in order to understand the nonleptonic decays of the strange particles, but failed). I believe that such steps are not necessary, and that there are good chances that all weak decays can eventually be described within the framework of the standard SU(2) x U(1) model (not, however, excluding the possibility that this model turns out to be a good approximation to a one involving a larger gauge group, e.g. the left-right symmetric gauge group $SU(2)_L \times SU(2)_R \times U(1)$). This point of view implies that all weak decay effects, presently not or not fully understood, must be attributed to specific details of the strong interactions. It may well be that many of these effects are very complicated, like details of the hadronic spectrum, and very little can be said by the theorists. I hope this is not the case, and the weak decays of charmed or b- flavored particles will teach us interesting new things about the strong interactions. The chances for this are quite good, in particular if it turns out that the so-called annihilation or W-exchange mechanism to be discussed later is correct.

Whatever the outcome is, one expects that a satisfactory understanding of the weak decays of charmed particles will also shed some new light on the problems theorists are dealing with in understanding the weak decays of strange particles. In fact, there seems to be some relationship between the weak decays of strange and charmed particles. In both cases the charged mesons ($K^\pm$, $D^\pm$) live longer than the neutral ones (K^0, D^0), the baryons (hyperons, Λ_c) live shorter than the charged mesons (K^+, D^+), etc. One has argued that the strengths of the decay amplitudes for the nonleptonic weak decays of strange particles can be accommodated by including the so-called penguin diagrams[1]. However the latter do not contribute to the main decays of the charmed particles. Therefore the new situation which has arisen with respect to the weak decay of charm puts into question the relevance of the penguin diagrams. At present the situation is confused, and probably a clarification of the issue will take a few years. In my talk I shall concentrate on the discussion of the decays of the c- and b- flavors.

II. Simple ideas about charm decay

We shall assume the standard form of the charm changing weak current:

$$j_\mu(|\Delta C| = 1) = \cos\theta_C \; \bar{c}\gamma_{\mu L}s - \sin\theta_C \; \bar{c}\gamma_{\mu L}d \tag{2.1}$$

(θ_C: Cabibbo angle, $\gamma_{\mu L} = \gamma_\mu(\frac{1+\gamma_5}{2})$).

A generalization to include t and b leads to a more complicated mixing pattern involving three angles. However such a generalization is easily made and would introduce only unnecessary complications in our analysis. Therefore we shall work with the current (2.1). The application of the current (2.1) to the semileptonic decays of charmed particles leads in the limit $\theta_c = 0$ to the well-known result based on isospin invariance:

$$\Gamma(D^+ \to l^+ + \nu_l + X) = \Gamma(D^o \to l^+ + \nu_l + X), \quad (l = e,\mu). \tag{2.2}$$

Furthermore one expects that the semileptonic decay rate of the Λ_c^+ is similar to the one for the D^+:

$$\Gamma(D^+ \to l^+ + \nu_l + X) \cong \Gamma(\Lambda_c^+ \to l^+ + \nu_l + X) \tag{2.3}$$

From eq. (2.2) it follows that any difference in the lifetime of the D^+ and the D^o must be due to a difference in the nonleptonic decay rates.

The bare nonleptonic weak Hamiltonion is:

$$H(|\Delta C| = 1) = 2\sqrt{2}\, G\, (\bar{u}d')\, (\bar{s}'c) + h.c. \tag{2.4}$$

($d' = d\cos\theta_c + s\sin\theta_c$, $s' = -d\sin\theta_c + s\cos\theta_c$; $(\bar{s}'c)$ stands for $\bar{s}'\gamma_{\mu L}c$).

However the current-current product is subject to strong interaction corrections, which can be calculated in QCD perturbation theory. The four-body quark operator is well-defined only if we specify at which energy (at which typical distance scale) the operator is analyzed. If we choose this scale to be of the order of M_W, the QCD radiative corrections to the nonleptonic decay rate is very small (of the order of $\alpha_s(M_W)/\pi \sim$ few percent). However the hadronic matrix element of an operator defined at the energy scale of M_W is rather complicated (involving the effects of many gluons and quark-antiquark pairs). It would be more appropriate to work with an operator defined at $E \sim m_c \sim 1.5$ GeV. In order to do so, large corrections arise, including terms of order $\alpha_s^c \cdot l_n(M_W/m_c)$ [2].
One finds

$$H(|\Delta C| = 1) = 2\sqrt{2}\, G \left[\frac{f_+ + f_-}{2} (\bar{u}d')(\bar{s}'c) + \frac{f_+ - f_-}{2} (\bar{s}'d')(\bar{u}c) \right] + h.c. \tag{2.5}$$

In the leading log-approximation one has[2]:

$$f_- = \left[1 + \frac{b}{4}\alpha_s(m_c^2)\, \ln\left(\frac{M_W^2}{m_c^2}\right)\right]^{\frac{4}{b}} \tag{2.6}$$

$$f_+ = (f_-)^{-1/2}, \quad b = 11 - \frac{2}{3}\, n(\text{flavors}).$$

$$(f_+ = f_- = 1 \text{ for } \alpha_s = 0).$$

In the free quark model the rate for the decay of a massive c-quark into three massless quarks $(s'\bar{d}'u)$ is given by:

$$\Gamma^o_{nl}(c \to s'\bar{d}'u) = G^2 m_c^5 / 2^6 \pi^3. \tag{2.7}$$

Including the leading QCD corrections, one finds:

$$\Gamma_{nl} = \frac{1}{3}(2f_+^2 + f_-^2)\ \Gamma_{nl}^{o} \tag{2.8}$$

The semileptonic branching ratio for the c-quark decay is:

$$B = \frac{1}{2+f_-^2 + 2f_+^2}.$$

Typical values are: $f_+ \approx 0.7$, $f_- \approx 2.1$. This leads to $\Gamma_{nl}/\Gamma_{nl}^{o} \approx 1.8$ and $B \approx 13\%$. Recently the next-to-leading corrections have been calculated[3] (see also ref. (4)). One finds that the nonleptonic c-quark decay rate is given by the leading log result multiplied by a parameter $J = (1 + \text{const.} \cdot \alpha/\pi)$:

$$\Gamma(c \to s'\bar{d}'u) = \Gamma^{ll} \cdot J. \tag{2.9}$$

Numerically one obtains $J \approx 1.22$ for $\Lambda_{\overline{MS}} = 250$ MeV[3]. Thus the next to leading corrections enforce the leading log result; the nonleptonic rate is enhanced.

Furthermore the semileptonic decay rate receives a correction of order α_s/π[5] described by a parameter I:

$$\Gamma_{sl} = \Gamma_{sl}^{o}\ [1 + \frac{2\alpha_s}{3\pi}\ (\frac{25}{4} - \pi^2)] = \Gamma_{sl}^{o} \cdot I \tag{2.10}$$

(Γ_{sl}^{o}: semileptonic decay rate for a free quark). One obtains for the semileptonic branching ratio:

$$B = \frac{I}{2I + (2f_+^2 + f_-^2) \cdot J}. \tag{2.11}$$

Using $I \approx 0.65$ and $J \approx 1.28$, B is about 10 %. Despite the uncertainties in α_s, I, J, f_+ and f_- one cannot have B larger than about 12 %.

Thus far we have discussed the c-quark decay. However we are finally interested in the decay of charmed particles. The simplest approach would be to assume that the weak decay of a charmed particle proceeds via the weak decay of a charmed quark inside the charmed particle. Thus the dynamics of the decay would be governed by the decaying c-quark. All other quarks present in the particle ($\bar{u}$ in D^o, $\bar{d}$ in D^+, (ud) in Λ_c) behave as "spectators", i.e. do not participate actively. It follows immediately that the lifetimes or the semileptonic branching ratios of all charmed particles are approximately equal:

$$\begin{aligned} &\tau(D^+) \cong \tau(D^o) \cong \tau(F^+) \cong \tau(\Lambda_c{}^+) \\ &B(D^+) \cong B(D^o) \cong B(F^+) \cong B(\Lambda_c{}^+). \end{aligned} \tag{2.12}$$

It is difficult to make definite statements about the possible uncertainties in these relations, since they depend on how the final quarks arrange to form hadrons (i.e. on soft hadronic dynamics). However they should not be larger than 20 %. The relations (2.12) are in disagreement with the experimental data, which give $\tau(D^+) / \tau(D^o) \approx 3...4$ and $B(D^+) \approx 20$ %, $B(D^o) \approx 4$ % (for a detailed discussion of the data see the various articles on weak decays in these proceedings). There are various conclusions one may draw from the experimental data.

a) The spectator picture cannot be correct; the other constituent quarks must play a rôle.

b) Either the nonleptonic decay rate of the D^o is enhanced compared to the naive estimate, and the D^+-rate is normal or the nonleptonic rate of the D^+ is suppressed, and the D^o-rate is normal (or both). Either way one must explain why the semileptonic branching ratio of the D^+ is larger than expected, and $B(D^o)$ is smaller than expected. Subsequently we shall discuss two models which realize these possibilities.

Finally we should like to mention the so-called color selection rules. One may be tempted to use the color quantum number in a static sense (like isotopic spin), in particular by considering few body final states[6]. It is easy to see that in the decay $D^o \to \bar{K}^o\pi^o$ the $(s\bar{d})$ system in the final state is quite often in a color octet configuration, i.e. cannot form a $\bar{K}^o$, while in the decay $D^o \to K^-\pi^+$ the $(s\bar{u})$-system is always a color singlet. For this reason one expects the decay $D^o \to \bar{K}^o\pi^o$ to be relatively suppressed:

$$\frac{\Gamma(D^o \to \bar{K}^o\pi^o)}{\Gamma(D^o \to K^-\pi^+)} = \frac{1}{2} \cdot \frac{(2f_+ - f_-)^2}{(2f_+ + f_-)^2} \approx \frac{1}{50} \tag{2.13}$$

Experimentally one finds[7]

$$\frac{\Gamma(\bar{K}^o\pi^o)}{\Gamma(K^-\pi^+)} = 0.73 \pm 0.35, \tag{2.14}$$

a number, which is consistent e.g. with 1/2, but not with 1/50. From this one can either learn that the D^o decay is not described by the c-quark decay, or that the naive color counting is wrong. The latter may well be the case since the color counting can be modified by including soft gluons. In fact, before the new data came, it has been predicted that due to a continuous emission and absorption of soft gluons the ratio (2.14) should be 1/2, and not 1/50[8]. However the issue is still unsettled, due to the possible importance of the annihilation diagrams to be discussed later (see also ref. (9))

III. Interference effects

A possible way to suppress the D^+ nonleptonic decay rate is to assume that a negative interference takes place between the $\bar{d}$ quark emitted in the c-quark decay, and the $\bar{d}$ quark present in the D^+ wave function[10,11]. Such an interference will take place, however the sign and the magnitude of the effect depends on the details of the D wave function (overlap, color structure of state, etc.). In the free quark model ($f_+ = f_- = 1$) the interference turns out to be constructive (it is proportional to $(2f_+^2 - f_-^2)$), however due to the QCD corrections which give $f_- \approx 2.1$, $f_+ \approx 0.7$ the interference is destructive. The magnitude of this effect is rather uncertain; it seems difficult to attribute the difference of the D^+ and D^o lifetimes solely to the interference effect. In order to do so, one has to admit a rather strong violation of the relation $f_+^2 = f_-^{-1}$.

If one accepts the interference picture, the D^+ nonleptonic rate is reduced, but the D^o and F^+ have "normal" nonleptonic decays. In particular the Cabibbo favored F^+ decays lead to a $(s\,\bar{s}\,u\,\bar{d})$- system, i.e. the final state in the F^+ decay should contain a $K\bar{K}$-system or an η-meson. Due to the suppression of the nonleptonic D^+ decay rate one expects the semileptonic branching ratio for the D^+ to be larger than expected naively within the spectator model. Qualitatively this is in agreement with the observation. On the other hand the D^o decay is not affected by the interference effect. Thus $B^l(D^o)$ should be equal to the value expected within the spectator model ($\sim$ 10 %); the experiment gives $B^l(D^o) \lesssim 4$ %. Thus the interference model fails to explain the smallness of $B^l(D^o)$.

IV. W-exchange mechanism and flavor annihilation

A possible way to understand the fast decay of the D^o relative to the D^+ decay is to incorporate the other "light" constituent quark[12)13)] in the decay dynamics. In priniciple the D^o can decay via the annihilation (W-exchange) of the ($\bar{u}c$)pair into $\bar{d}s$. No such process exists for the D^+ decay in the Cabibbo favored decay mode. However the "weak annihilation" is strongly suppressed (see, ref.13) since it vanishes in the limit $m_s = m_d = 0$.

A number of authors have proposed to interpret the fast D^o decay as a QCD radiative effect[14,15,16)]. Before the weak annihilation of the ($\bar{u}c$)-pair in the D^o sets in, a gluon (or several gluons) can be emitted. The ($\bar{u}c$) pair can be in a $J = 1$ state, and no helicity suppression results. After the weak transition $(\bar{u}c) \rightarrow (\bar{d}s)$ the gluon (or the gluons) combine with the quark to form the final hadronic state.

In QCD perturbation theory[14)15)] one finds that the inclusive decay rate for the W-exchange process is of the same order as the inclusive quark decay $c \rightarrow s\,\bar{d}\,u$. However the gluon emitted during the decay is fairly soft (and may be regarded as a hadronic constituent like the quarks[15,17)])and an exact calculation is not possible. However it is quite plausible that the W-exchange mechanism is responsible for the fast D^o decay. (In this respect it is satisfactory to note that the ratio of life times $\tau(D^+)/\ \tau(D^o)$ has come down from an order of magnitude as reported earlier to about three, a number one might expect within the QCD approach.) If this should be the case, the situation becomes rather simple, and many consequences follow.

a) The final hadronic system in the D^o decay has the quantum numbers of ($\bar{d}s$), i.e. it has $S = +1$, $I = 1/2$. It follows that $\Gamma(D^o \rightarrow \bar{K}^o\pi^o)\ /\ \Gamma(D^o \rightarrow K^-\pi^+) = 1/2$, in agreement with observation. However we must emphasize that this fact alone constitutes no proof that the W-exchange mechanism is correct. Furthermore one may expect that the ratio mentioned above deviates slightly from 1/2, due to the contribution of the c-quark decay mechanism.

Furthermore one expects the ratio $\Gamma(D^o \rightarrow \rho^o\bar{K}^o)\ /\ \Gamma(D^o \rightarrow \rho^+K^-)$ to be 1/2 (again neglecting effect due to the c-quark decay, and likewise $\Gamma(D^o \rightarrow K^{+o}\pi^o)\ /\ \Gamma(D^o \rightarrow \bar{K}^{+-}\pi^+) = 1/2$. Here the situation is unclear. While the second ratio has been measured to be consistent with 1/2, the first ratio is consistent with zero (the decay $D^o \rightarrow \rho^o\bar{K}^o$ has not been seen)[7)]. Perhaps here lies trouble ahead for the W-exchange mechanism. However I regard the issue as not yet settled; perhaps the experiments setting a limit on the mode $D^o \rightarrow \rho^o\bar{K}^o$ are wrong.

b) Taking into account the color quantum number and assuming that the annihilation of a $\bar{q}q$-pair in a charm meson can only proceed by emitting one gluon (two or several gluons are supposed to be suppressed), the F^+ cannot decay via annihilation since the ($\bar{s}c$)-pair must be in a color singlet in order to annihilate. It can annihilate if we include the QCD radiative corrections, described by the factors f^+ and f^-, in which case the F^+ can decay via the second term in eq. (2.5); its decay amplitude is proportional to $f_+ - f_-$.

However we find it dangerous to use lowest order perturbation theory in the gluonic annihilation process, since evidently one is in a region where strong coupling effects play a significant rôle. For this reason we would not be surprised if it turns out that the F^+ has about the same life-time as the D^o. In general we would expect that one has

$$\tau(D^+) > \tau(F^+) \gtrsim \tau(D^o).$$

We emphasize that the W-exchange mechanism leads to a nonstrange final state, e.g. $F^+ \rightarrow$ pions.

An interesting possibility to test the W-exchange mechanism in the F^+-decay is to look for the decay mode $F^+ \rightarrow p\bar{n}$[18)]. If the F^+ decays simply by c-quark decay, one has either two ($\cos\theta_c$-mode) or one ($\sin\theta_c$-mode) s or $\bar{s}$-quark in the final quark configuration. As a result the decay does not lead to a $p\bar{n}$-final state. A $p\bar{n}$-state can only be obtained if the $(\bar{s}c)$- pair in the F^+ annihilates. In the absence of gluons the decay is strongly suppressed due to PCAC[18]. If the F^+ decays predominantly via the $(\bar{s}c)$-annihilation in the presence of gluons, one expects $B(F^+ \to p\bar{n}) \sim 1$ %; a simple mechanism for this decay is provided by the process $F^+ \to (\bar{s}c) \to (\bar{s}c)gg \to (\bar{d}u)gg \to (\bar{d}u)(\bar{u}u)(\bar{d}d) \to (uud)(\bar{d}\bar{d}\bar{u}) \to p\bar{n}$. The decay $F^+ \to p\bar{n}$ would be the first weak decay observed in nature in which a heavy meson decays into a baryon-antibaryon pair.

Another test for the flavor annihilation in the F-decay is the semileptonic F-decay. If the nonleptonic F-decay proceeds largely via the transition $(\bar{s}c) \to (\bar{u}d)$ + gluons, one expects that the semileptonic decay proceeds correspondingly via $(\bar{s}c) \to (\nu_l l^+)$ + gluons ($l = e,\mu$). This implies that the semileptonic branching ratio of the F meson is expected to be larger than for the D^o (the W-exchange mechanism supposed to be responsible for the D^o-decay cannot lead to a semileptonic final state). One expects $\Gamma(F \to (\nu_l l^+) + \text{gluons}) / \Gamma(F \to (\bar{d}u) + \text{gluons}) \approx 3$, i.e. the semileptonic branching ratio should be $\sim 10 \ldots 15$ % depending on the relative importance of the $(\bar{s}c) \to (\bar{d}u)$ transition. The semileptonic F-decay constitutes a "flavor annihilation device". The valence quarks of the F-meson annihilate into leptons. The left-over debris consists of gluons, i.e. in the semileptonic F-decay one expects the appearance of glue-states and of η or η' mesons ($F \to \nu_l l^+ + \eta,\eta'$, "glue balls").

c) An important test of the annihilation hypothesis is to consider the Cabibbo suppressed D^+ decays. The point is that the Cabibbo suppressed nonleptonic decays of the D^+ can proceed via an annihilation like the Cabibbo favored F^+ decay. If the latter is indeed enhanced compared to the Cabibbo favored D^+ decay, we expect that the Cabibbo suppressed D^+ decay is enhanced in the same way, i.e. it proceeds mainly via the annihilation $D^+ \to (u\,\bar{d} + \text{glue})$. The final state has $S = 0$ and $I = 1$, i.e. it cannot contain a single K meson and cannot consist of $\pi^+\pi^o$. Probably the final state consists mainly of three or more π-mesons. The annihilation decay mode of the D^+ contributes more to the total decay rate than expected on naive grounds, i.e. significantly more than $\sin^2\theta \sim 5$ %. Estimates, given in ref. (7), range between 20 ... 40 %. Indeed an unexpectedly large portion of the nonleptonic D^+ decays seems to lead to a final state without K mesons[7].

A further interesting test of the weak decay mechanism discussed above is to consider the Λ_c^+ decay. Like in the case of the hyperon decays the nonleptonic decays of the Λ_c^+ involving the weak interaction of two constituent quarks may be of particular importance. Those decays are such that the (cd) diquark system in the Λ_c^+ turns itself via the weak interaction (W-exchange) into a (us) system, i.e. the Λ_c^+ decay proceeds via the process $c\,d\,u \to s\,u\,u$. The hadronic final system is then given by the hadronization of the $(s\,u\,u)$ system giving rise to final states like $\Lambda\pi^+$, $\Lambda\rho^+$, $\Sigma^+\pi^o$, $\bar{K}^o p$, $K^+ n$, etc.

In the nonrelativistic quark model the decay rate for the decay $\Lambda_c^+ \to s\,u\,u$ (the quarks are treated as free Dirac particles) can be calculated[19]. Because of the color antisymmetry of the baryon wave function the operator proportional to f_+ does not contribute, and therefore the decay rate is multiplied by $(f^-)^2$:

$$\Gamma(\Lambda_c^+ \to s\,u\,u) \cong \frac{G^2}{2\pi}\, f_-^2 |\psi(0)|^2 \cdot m_c^2 \tag{4.38}$$

(we have set $\theta_c = 0$, and have neglected the effects due to the light quark masses), where $\psi(0)$ denotes the Λ_c^+ wave function at the origin.

The major source of uncertainty in the relation above is $|\psi(0)|^2$. Using e.g. the value $|\psi(0)|^2 = 7.4 \cdot 10^{-3}$ GeV^3, as derived in ref. (18) by taking into account the hyperfine splitting of the baryons interpreted within QCD, one finds

$$\Gamma(\Lambda_c^+) \approx 2 \cdot 10^{-12}\ \text{GeV} \approx 0.3 \cdot 10^{13}\ s^{-1}. \tag{4.39}$$

Furthermore on expects the ratio $\tau(D^+) / \tau(\Lambda_c^+)$ to be of the order of 2...3. In general one can say that the weak interaction of two constituent quarks inside the Λ_c^+ leads to a decay rate which is larger (factor 2... 3, perhaps even more) than the one derived on the assumption that the Λ_c^+ decays weakly via the c quark decay. In any case one expects that the Λ_c^+ decays at least as fast as the D^o, perhaps even slightly faster.

The W-exchange mechanism requires the presence of a cd-pair in the baryon. This implies that the strange partner of the Λ_c, the (c u s)-baryon, cannot decay (in the $\cos\theta_c$-mode) via W-exchange. Correspondingly we expect τ(c u s) >> τ(c u d), and B^l (c u s) >> B^l (c u d).

It is interesting to note that the W-exchange mechanism in the Λ_c-decay leads to a final state formed out of (s u u), which can without problems be e.g. $K^-\Delta^{++}$. On the other hand in the c-decay mechanism the final hadronic state is formed out of ($\bar{u}$ s d d u). Since this quark configuration does not contain three u-quarks, the channel $\Lambda_c^+ \to K^- \Delta^{++}$ is suppressed. The latter channel has been seen in the ISR-experiments[7]; this must be interpreted as an indication that the Λ_c-decay proceeds via W-exchange.

V. Weak decays of b-quarks

One of the interesting experimental results, reported at this meeting, implyies that the weak current responsible for the b-decay is not of the type ($\bar{b}$s) or ($\bar{b}$d) (flavor changing neutral current). Therefore the b-decay must proceed via the charged currents ($\bar{b}$u), ($\bar{b}$c). It seems that the ($\bar{b}$c)-current dominates the b-decay. As a consequence it is expected that the b-decay current arises from weak interaction mixing, and one is dealing with at least three weak doublets (involving the heavy t-quark):

$$\begin{pmatrix} u \\ d' \end{pmatrix} \quad \begin{pmatrix} c \\ s' \end{pmatrix} \quad \begin{pmatrix} t \\ b' \end{pmatrix}.$$

The relative strength of the ($\bar{b}$c)-current compared to the strength of the ($\bar{b}$u)-current is determined by the six-quark mixing parameters. It is unlikely that all these parameters conspire such that $|b \to c|^2 \approx |b \to u|^2$. Very likely the strength of the $b \to u$-current is small compared to the strength of the $b \to c$-current (typical estimates give $|b \to u|^2 / |b \to c|^2 \approx$ few %). Presumable the b-decay proceeds dominantly via the chain $b \to c \to s$. In this talk I shall concentrate on the $b \to c$-current.

We shall address the following problems.

a) QCD radiative corrections

The coefficients f_+ and f_- which enter in the nonleptonic b-decay Hamiltonion are expected to deviate less strongly from 1 as in the charm case since $m_b >> m_c$. Typical values are: $f_+ \approx 0.85$, $f_- \approx 1.5$.

b) Provided the b-flavored hadrons decay via b-decay, there exist two major nonleptonic decays: $b \to c(\bar{u}d)$ and $b \to c(\bar{c}s)$ (we neglegt $\sin\theta_c$). The first mode leads to a final state containing a charmed particle (C = + 1), the second mode leads either to a pair of charmed particles + X or to a charmonium state + X. The mode involving a $\bar{c}$c-pair will be suppressed in comparison to the $b \to c\,\bar{u}\,d$-mode, due to phase space. Estimates based on simple quark model calculations and using m_b = 4.5 GeV, m_c = 1.5 GeV, give [20]

$$\frac{\Gamma(b \to c\,\bar{u}\,d)}{\Gamma(b \to c\,\bar{c}\,s} \approx \frac{3}{1} \tag{5.1}$$

(We emphasize that this is a very crude estimate. In the decay $b \to c\,\bar{c}\,s$ one is fairly close to the kinematical threshold, and final state effects can be very important).

c) An important problem concerns the relative importance of the W-exchange or annihilation mechanism. The B^o state can decay via W-exchange: $(\bar{d}\,b) \to (\bar{u}\,c) \to D,\,F,\,\Lambda_c + X$, just like the B_s^o: $(\bar{s}\,b) \to (\bar{c}\,c) \to D\,\bar{D},\,\Lambda_c\bar{\Lambda}_c,\,F\,\bar{F}$, charmonium + X. No such process exists in case of the B^--decay. In the case of D^o-decay one has:

$$\frac{\Gamma(\text{W-exchange})}{\Gamma(\text{c-decay})} \approx \text{const.} \left(\frac{F_D}{m_c}\right)^2 \tag{5.2}$$

(F_D: meson decay constant). According to the experiments the ratio (5.2) is of the order of 2... 4. In the B^o- decay one finds correspondingly

$$\frac{\Gamma(\text{W-exchange})}{\Gamma(b\text{-}c(\bar{u}\,d))} \approx \text{const.} \left(\frac{F_B}{m_b}\right)^2 \tag{5.3}$$

The constant in (5.2) and (5.3) is a measure of the $(\bar{q}\,q\,g)$- part of the meson wave function[15]. The latter is not expected to depend on the heavy quark mass. Hence the constants in eq. (5.2) and (5.3) are the same. One concludes using simple estimates of F_B that the ratio (5.3) is of the order of 1. The b-decay rate and the W-exchange rate in the B^o-decay are expected to be approximately equal[15,20]. It follows that the B^o and B^- life times should be of the same order of magnitude, but the B^o decays slightly faster than the B^-. A typical estimate gives[20]:

$$\frac{\tau(B^-)}{\tau(B^o)} \approx 1.6 \tag{5.4}$$

In the B_s^o decay the W-exchange mode $(\bar{s}\,b) \to (\bar{c}\,c)$ should constitute a sizable fraction of the total decay mode (about 25 %).

As in the Λ_c-decay the W-exchange is expected to be important in the Λ_b-decay. The W-exchange mode $(b\,u\,d) \to (c\,d\,d)$ will be as important as the b-decay mode $(b\,u\,d) \to c(\bar{u}\,d)\,u\,d$. Presumably the following inequality for the lifetimes of b-flavored particles holds:

$$\tau(\Lambda_b) \lesssim \tau(B^o) \approx \tau(B_s^o) \lesssim \tau(B^-). \tag{5.5}$$

d) One of the important tasks for the experimentalists is to find the B particles. The decay mode $b \to c(\bar{u}\,d)$ as well as the various annihilation modes will give a fairly large number of particles in the final state (comparable to the average number of particles produced in e^+e^--annihilation at ~ 5 GeV). For this reason I believe that the best way to observe the b-flavored particles is to investigate the decay modes involving a J/ψ meson. Such decays are due to the $b \to c\,\bar{c}\,s$-mode. The phase space for these decays is such that quite often the $\bar{c}\,c$-system has an invariant mass which is less than $2\,M_D$, and one expects in this case that a $\bar{c}\,c$-meson $(J/\psi,\,\psi',\,\chi,\,\eta_c)$ is produced[21]. The chance that a J/ψ is produced is estimated to be fairly large[21,22]

$$B(B^- \to J/\psi + X) \approx 3\ \%. \tag{5.6}$$

This prediction rests on the assumption that the color selection rules discussed previously in the D-decay are not valid, i.e. color is rearranged with probability one.

The $B \to J/\psi + X$ decays are especially interesting since arguments can be given that the invariant mass of the recoiling system X is fairly small (~ 1 GeV). Therefore X is expected to be dominated by the $K\pi$ - channel, and one is dealing with a three - body final state: $B \to J/\psi\, K\pi$.

We note that a J/ψ cannot be produced in the B^o-decay, if the decay proceeds via the W-exchange mechanism. Thus the J/ψ decay mode is slighty suppressed in the B^o - decay.

In the B_s^o decay the W-exchange mechanism leads to $\bar{c}\, c\, g$. This system will mostly produce a pair of charmed particles (plus pions etc.). However the chance is not small that the invariant mass of the $\bar{c}\, c$ system is smaller than $2M_D$, in which case a charmonium state is produced. Thus one should look for decays like $B_s^o \to J/\psi +$ η, η', "glue ball".

In the Λ_b decay the b-quark decay mode can leads also to a J/ψ. Thus one should look for decays like $\Lambda_b \to (J/\psi)\, pK$ or $\Lambda_b \to (J/\psi)\Lambda\pi$. One expects $B(\Lambda_b \to J/\psi + X) \approx 2\ \%$.

The decays of the type $B \to J/\psi\ X$ are, of course, well suited to be observed in hadronic production experiments (e.g. at the CERN collider).

Other interesting few - body decay channels of the B-mesons are of the type $B \to$ baryon + antibaryon[23], e.g. $B \to \Lambda_c\bar{N}$. One may expect $B(B \to \Lambda_c\bar{N}) \approx 1\ \%$, e.g. these decay modes could eventually be observed in the e^+e^--annihilation experiments.

VI. Final comments

The field of weak decays of heavy particles has become very interesting, especially since the experimental findings turned out to be in disagreement with the theoretical predictions. By now it has become clear that no new weak currents or new types of the weak interactions are needed in order to understand the pattern observed in the experiments, the conventional weak currents are sufficient. However the interplay between the strong and weak interactions is more complicated than previously thought. I believe that the annihilation or W-exchange mechanism is basically correct. If this turns out to be true, one will learn interesting details about the bound state structure of heavy hadrons, especially about the gluonic components. In general one can say that the study of weak decays of heavy hadrons is an interesting method to investigate the dynamics of QCD. Presumably during the next few years a large fraction of particle physics will be concerned with the investigation of heavy quark decays.

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Discussion

R. E. Marshak, Virginia Polyt. Inst., Blacksburg: Is it correct to say that the gluon corrections for the hadronic decays of strange particles will be more difficult to be calculated than for charmed decays because of smaller quarkmasses involved?

H. Fritzsch: I had no time to discuss these problems. Here the situation is more complicated. In strange particle decays exist new problems concerning in particular the so-called penguin processes. Crudely speaking, one can say that the soft gluon effects (including wave function effects) affect the strange particle decays in a way which is very difficult to control. The main reason in the small energy release in the decay and the fact that the final states are given by a few channels. Probably the gluonic radiative corrections (QCD-perturbative effects), wave function effects (including soft gluons) and the penguin processes add up such as to reproduce the observed nonleptonic enhancement. But I think the issue is not closed. Perhaps a careful study of the weak decays of charmed particles will give us an important clue in order to understand the strange particle decays in a more satisfactory way.

S. D. Drell, SLAC: How large a ratio of $\tau(D^+)/\tau(D^o)$ could you accept with this approach of corrections to the standard model. For example what would you say if the ratio was to be closer to 10?

H. Fritzsch: As I said, the calculations give that the annihilation is about as large as the decay, perhaps larger by a factor of 2 or 3. A factor of 10 is impossible to get, and I was very pleased to hear last year that the lifetimes ratio came down from 10 to 3 or 4. I would be even more happy if it were 2.