What We Learnt from Weak Decays of Heavy Quarks^{*}

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ABSTRACT

An analysis of recent data on weak decays is performed. Regularities are pointed out and interpreted. A qualitative picture of the dominant effects in weak decays from K- to B-decays is emerging but needs further support from theory and experiment.

1. INTRODUCTION

Historically, the study of weak decays gave rise to many fundamental discoveries. Examples are the discovery of the neutrinos, of chiral symmetry, of CP-violation, and of the W- and Z-particles. Weak decays played also an important role in revealing important properties of the strong interaction. The structure of nuclei, their spins and parities, and the chiral properties of strong interactions were deduced from weak decays which also provided much information for the description of hadrons in terms of quarks.

However, as long as one was restricted to the physics of u, d, and s quarks and their leptonic partners there remained many questions. In this regime only few fundamentally different channels are open and the energy release is very limited. Due to these facts up to today there is no coherent understanding of non-leptonic decays and the intricate interplay of weak and strong interaction occurring there.

New chances for a better understanding of weak and strong interaction came with the discovery of charmed and bottom quarks. Simultaneously, new fundamental questions arose as to the universality of weak

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interactions, the values of the new quark mixing angles, and the origin of the families and their mass matrices.

In D- and B-decays many channels are open which allow a detailed study of some of these questions, and in particular of the still largely unknown effects of QCD. In fact, it can safely be expected that in the not too distant future the decays of c- and b-flavoured states will provide the most valuable information on long-range QCD. The reasons are

- o the initial state consists of a single isolated particle;
- o the operators for the decay have simple Lorentz and flavour quantum numbers;
- o one can study a large variety of transitions to different flavour and spin states.

One can probe the hadron structure in many different ways, in particular the tails of wave functions, colour factors, loop contributions (Penguins), the annihilation and creation of quarks as well as final state interactions in well-defined states. Such studies are indeed necessary if one wants to extract precise values for the quark mixing angles and the CP-violating phase: angles and phase refer to quarks and not to hadrons.

Thanks to great efforts of several experimental groups a first analysis of a few of the issues mentioned here could recently be performed. Most of the data¹⁻³⁾ refer to D-decays, but there exist already a number of very important results from B-decays.

In this article I will report on what we learnt from the theoretical analysis of these data with emphasis on non-leptonic decays. I cannot go into all details and have to leave out important results. The reader is referred to review papers and conference reports¹⁻⁷⁾ and the vast literature quoted there. Recent theoretical methods and achievements are well described in a review article by Wirbel⁷⁾. All the analysis is done in the framework of the standard model. Within the experimental and theoretical uncertainties there are as yet no indications for deviations from this model.

It will be seen that a number of unexpected and very interesting regularities can be extracted from the data. They cannot yet be unambiguously derived theoretically and also need further experimental confirmation but are very suggestive. In the interpretation of these effects I will present a rather personal view. The picture I can give is a very qualitative one and not on very firm grounds. But since it provides for many links between D- and B-decays and sheds new light on strange particle decays I do not hesitate to present it.

In section 2 semileptonic decays are treated, not in great detail, however, since these decays are extensively discussed in the literature. Decisive information about the hadron structure is contained in the formfactors for which so far only simple model calculations are available. These formfactors are also needed in the treatment of non-leptonic decays which are discussed in section 3. A specific model^{8,9)} which allows for many testable predictions is described in some detail. For QCD-sum rule calculations⁵⁾ and the $1/N$ expansion¹⁰⁾ the reader is referred to the literature. Where a comparison can be made, there is generally good agreement among the results from these different methods. A very informative and critical comparison is presently prepared by R. Rückl. In section 4 which deals with inclusive decays the significance of the quark-quark interaction leading to virtual diquark formation is pointed out. The diquark coupling to a scalar diquark current is approached in a variety of ways. All estimates given for the various inclusive decays are crude and thus in any single case not very trustworthy. But the consistency of the results and the pattern seen is quite remarkable. It gives some confidence that a qualitative understanding of the dominant effects in non-leptonic decays has been achieved. But very little is known today about more detailed effects from non-perturbative long-range QCD which manifest itself in weak decays. Their study as well as the study of CP-violation, particle mixing, and rare decays, which we could not comment upon in this article, will be crucial for a deeper understanding and a challenging task for many years to come.

2. SEMILEPTONIC DECAYS

2.1 Inclusive Semileptonic Decays

The theoretical spectra from free quark decay corrected for QCD effects and Fermi motion have been given by Altarelli et al.¹¹⁾. The comparison with D- and B-decay data shows the shapes expected from the V-A Fermi interaction, in particular the characteristic difference between D⁰-decays and $\bar{B}^0$ -decays. Assuming strict V-A interaction, i.e. the standard model, the semi-leptonic branching ratios and spectra can be used to extract elements of the Kobayashi-Maskawa quark mixing matrix. The result is¹²⁾

$$|V_{sc}| \approx 1.0 \quad |V_{cb}| \approx 0.05$$

with an estimate error of about 16 %. A detailed discussion of the ratio $|V_{ub}/V_{cb}|$ requires some knowledge about the contribution of exclusive channels for the upper end of the lepton spectrum.

2.2 Exclusive Semileptonic Decays

Exclusive decays provide detailed information on the internal structure of the hadrons involved. The transition rates are determined by hadron matrix elements of the weak currents such as

$$\langle K^* | (\bar{s}c)_{V-A} | D \rangle \quad \text{and} \quad \langle D^* | (\bar{c}b)_{V-A} | B \rangle.$$

The Lorentz structure of such matrix elements is usually known from spin and parity measurements. The dynamics is contained in the form-factors. For these formfactors various models¹³⁾ have been used. In the model of ref. 14) we applied relativistic wave functions in the infinite momentum limit. They are especially suited for the evaluation of form-factors at $q^2 = 0$, a point essential for the high energy part of the spectra where exclusive states are important. The extension to $q^2 \neq 0$ was performed using dominance of the nearest meson poles, a method which in most cases should be sufficient for presently required accuracies. The wave functions are plotted in Fig. 1 where one sees that at infinite momentum a meson containing a heavy quark is quite different in structure from a light meson. Correspondingly, the wave function overlap

Fig. 1 Longitudinal momentum distribution of the ^{*)} non-spectator quark in π , K, D and B mesons. Taken from M. Wirbel, ref. 13).

between initial and final hadrons at $q^2 = 0$ is rather sensitive to the structure of the hadrons involved and thus a very interesting quantity. Our wave functions describe the π -K-formfactor very well. There is also good agreement - within experimental errors - with the D $\rightarrow$ K ν spectrum measured by E691 at FNAL¹⁶⁾ and Mark III¹⁾ and with the Argus measurement³⁾ of B $\rightarrow$ D^{*} e⁻ $\bar{\nu}$. The experimental D $\rightarrow$ K^{*}/D $\rightarrow$ K ratio turned out to be somewhat smaller than expected¹⁶⁾. It should be checked again. But certainly, the transversal formfactors entering D $\rightarrow$ K^{*} depend more sensitively on the internal quark dynamics than the longitudinal formfactors and the ones describing $0^- \rightarrow 0^-$ transitions.

Non-relativistic quark model wave functions have also been used¹⁷⁻¹⁹⁾. They are best at the maximal value of q^2 , i.e. $q^2 = (m_i - m_f)^2$ where initial and final mesons are at rest. Extrapolations from this

^{*)} These wave functions are applicable for $q^2 \ll 1 \text{ GeV}^2$ only. They differ, therefore, from the ones discussed by Chernyak and Zhitnitsky, ref. 15).

point to smaller values of q^2 have been performed by assuming exponential behaviour or by using again pole dominance. The new calculations¹⁹⁾ which take all formfactors into account are in agreement with our earlier results except for the $B \rightarrow \pi$, $B \rightarrow \rho$ transitions where all model predictions are uncertain by at least a factor 2. Nevertheless the various models can be used to extract a limit on $|V_{ub}/V_{cb}|$ from a comparison with the upper end of the lepton spectrum and the limit for the exclusive transition $\bar{B} \rightarrow \rho^0 e^- \bar{\nu}_e$. The result is^{2,3,12)}

$$|V_{ub}/V_{cb}| \lesssim 0.2$$

3. NONLEPTONIC DECAYS

In non-leptonic decays a full interplay between weak and strong interactions takes place. The fact that in strange particle decays the rates of $|\Delta \vec{I}| = 1/2$ transitions dominate over $|\Delta \vec{I}| = 3/2$ transitions by two orders of magnitude demonstrates that QCD effects can be of paramount importance. Since nonperturbative effects of long-range QCD are involved, there is at present no strict treatment possible. One is in a situation doctors are used to: to find even a qualitative explanation for the "symptoms" one needs experience from large data samples and intuition as well. Fortunately, thanks to the great efforts of several experimental groups, many experimental results are now available which can be analysed.

3.1 The Effective Hamiltonian

It has been known for a long time that at least the short distance effects of QCD, namely hard gluon exchanges and loop contributions involving heavy quarks, can reliably be calculated²⁰⁾. The resulting effective Hamiltonian relevant for D-decays reads

$$H_{\text{eff}} = \frac{G}{\sqrt{2}} \left\{ c_1(\mu)(\bar{u}d')_{V-A}(\bar{s}'c)_{V-A} + c_2(\mu)(\bar{s}'d')_{V-A}(\bar{u}c)_{V-A} + \text{Penguins} \right\} + \text{h.c.} \quad (1)$$

In this expression G denotes the Fermi constant and d' , s' are the Ca-

is rotated down and strange quark field operators, respectively^{*)}. $c_1(\mu)$ and $c_2(\mu)$ are scale-dependent QCD coefficients. The matrix elements of the quark fields have to be evaluated at the same scale to give a scale-independent result. For a scale $\mu \geq 1$ GeV the coefficients of the Penguin operators²¹⁾ are small. Thus, the V-A structure of the uncorrected original interaction remains practically intact. Very important, however, $c_1(\mu)$ is different from one and a neutral current product not present in the original Hamiltonian is induced with coefficient $c_2(\mu)$. At the scale of the charmed quark one has^{20,4)}

$$c_1(m_c) \approx 1.24 \quad c_2(m_c) \approx -0.47 \quad (2)$$

At the scale of the bottom quark the calculation gives

$$c_1(m_b) \approx 1.11 \quad c_2(m_b) \approx -0.25 \quad (3)$$

3.2 Factorization

How to deal now with the hadron matrix elements of the effective Hamiltonian? The simplest approach is to express the quark currents by the hadronic fields these currents can generate, treating stable particles π , K , ... and resonances ρ , K^* ... in the same way:

$$(\bar{u}d)_{V-A}^\mu = f_\pi \partial^\mu \pi + f_\rho m_\rho \rho^\mu + f_{A_1} m_{A_1} A_1^\mu + \dots \quad (4)$$

Here, f_π , f_ρ , ... denotes the decay constants of π , ρ , By writing the effective Hamiltonian in terms of hadron fields, we have to replace the QCD coefficients c_1 , c_2 in (1) by new coefficients a_1 and a_2 multiplying the charged current product and neutral current product, respectively. The reason is that by a rearrangement of the quark fields in eq. (1) the term multiplying c_1 (c_2) can contribute to the neutral (charged) current product. This is seen from the Fierz transformation

$$(\bar{u}d')_1 (\bar{s}'c)_1 = \frac{1}{3} (\bar{s}'d')_1 (\bar{u}c)_1 + (\bar{s}'d')_8 (\bar{u}c)_8 \quad (5)$$

The indices 1 and 8 indicate color singlet and color octet currents, respectively. Unfortunately, after performing the Fierz transformation

^{*)} The modification due to quark mixing with the third family can safely be neglected in (1).

one does not know how to handle the matrix elements of the colour octet current product. The naive relations between a_i and c_i

$$a_1 = c_1 + \xi c_2 \quad a_2 = c_2 + \xi c_1 \quad (6)$$

$\xi = 1/N_c$, N_c : number of quark colors is certainly questionable²²⁾. It is better to take a_1 and a_2 (or at least ξ) as free parameters.

A strong assumption is now to replace successively the hadron fields by free fields, e.g. outgoing fields: $\pi \rightarrow \pi^{\text{out}}$ etc. As a consequence the matrix elements factorize. For example, the amplitude for the process $D^0 \rightarrow X^+ \pi^-$ is now simply

$$\frac{G}{\sqrt{2}} a_1 \cos \theta_c \text{ if } \pi p_\mu^\pi < X^+ | (\bar{s}' c)_{V-A}^\mu | D^0 \rangle$$

In the factorization approximation²³⁾ the effects of long-range QCD are contained in the decay constants and - as in the case of semileptonic decays - in the matrix elements of a single current. We note, however, that unlike in semileptonic decays the longitudinal part of the current cannot be neglected here. In the detailed analysis of ref. (9) the relativistic wave functions described in section 2 have been used for the estimate of the relevant current matrix elements.

For several years factorization was in disrepute for a number of reasons:

- i) It fails in the estimate of the $|\Delta \vec{I}| = 1/2$ amplitudes in hyperon decays by large factors.
- ii) It predicts for pseudoscalar meson decays small "annihilation" amplitudes, i.e. amplitudes for processes in which the effective interaction annihilates the two-valence quarks and recreates a new quark-antiquark pair which then hadronizes. They are small because of asymptotic (large q^2) conservation of the current of light quarks. It was believed, however, that the semileptonic branching ratios of D^+ and D^0 and the short lifetime of the D^0 shows that annihilation processes are very important.
- iii) By taking in (6) the conventional value for ξ , namely $\xi = 1/3$, certain ratios like $\Gamma(D^0 \rightarrow \bar{K}^0 \pi^0) / \Gamma(D^0 \rightarrow K^- \pi^+)$ came out to be less

than 1/10 of the experimental numbers²⁴⁾.

- iv) By replacing fields by free fields one neglects final state interactions which are known to be non-negligible in S- and P-wave scatterings of the generated mesons.

Thus, the case for a meaningful use of the factorization approximation appeared to be hopeless, and it took some courage to take it up again. However, the objections i) to iii) mentioned above are fading away as I will show. Final state interactions remain a problem. One has to treat them on a case by case basis and perform corrections whenever possible^{25,26)}.

3.3 Exclusive Two-Body Decays

The amplitudes for two-body and quasi two-body decays can easily be calculated in the factorization approximation. Together with the decay constants and the "semileptonic" current matrix elements the real coefficients a_1 , a_2 determine the rates. (Annihilation and the additional contributions from the Penguin interaction are small in factorization approximation). With respect to a_1 and a_2 it was realised in ref. 8) that there is little reason to stick to the value $\xi = 1/3$ in the relation (6).

The decays $D^0 \rightarrow X^+ Y^-$ are determined by a_1^2 , the decays $D^0 \rightarrow X^0 Y^0$ by a_2^2 and the decays $D^+ \rightarrow X^+ Y^0$ by the interference of a_1 and a_2 , approximately in the form $(a_1 + a_2)^2$. However, due to final state interaction of the outgoing mesons the experimental amplitudes are complex while factorization provides us with real amplitudes only. Thus, it is of advantage to compare the magnitudes of amplitudes of definite isospin in the decay channel with the corresponding ones extracted from experiment.

As the result from the analysis^{9,27,28)}, one finds that by setting

$$\begin{aligned} a_1 &\approx 1.2 \approx c_1(m_c) \\ a_2 &\approx -0.5 \approx c_2(m_c) \end{aligned} \tag{7}$$

good agreement for the numerous measured ratios is obtained, see Fig. 2. This success was quite surprising in view of the simplicity of the model

and the objections raised before.

Fig. 2a, b: D- and D_s-branching ratios

The experimental values are given with their statistical errors only. The black squares denote the theoretical values from factorized amplitudes, using $a_1 = 1.2$ and $a_2 = -0.5$. The branching ratios marked by a cross include an additional contribution from channel mixing as described in ref. 9).

a: Cabibbo-allowed decays

b: Cabibbo-suppressed decays

The theoretical predictions agree remarkably well with the QCD sum rule results of Blok and Shifman⁵⁾ which is an approach similar in spirit but very different in the calculation method.

The empirical rule $a_i \approx c_i$ ($\xi = 0$) found here is very interesting. It implies that the quark-antiquark pair generated by a color singlet current remains together in forming a final meson. Does the same property also hold at the scale of the B-meson? So far, only few exclusive two-body channels could be measured in B-decays. Nevertheless, the measured branching ratios³⁾ of the decays $\bar{B}^0 \rightarrow D^{*+} \pi^-$ and $\bar{B}^0 \rightarrow \bar{K}^0 J/\psi$ by ARGUS and CLEO strongly suggest that this rule is also valid in B-decays and exclude the value $\xi = 1/3$ ^{28,29)}. *) As to strange particle decays, the rule reduces by a factor 3/4 the usual factorization result for $|\Delta I| = 3/2$ amplitudes and by the same number the so-called B-factors which control the $\Delta S = 2$ and $\Delta b = 2$ matrix elements. It also increases $|\Delta I| = 1/2$ amplitudes but certainly not strong enough as will be discussed in section 4.3.

There exists as yet no clear understanding for the success of this rule. Its discovery stimulated interesting theoretical investigations, a detailed analysis of the $1/N_c$ expansion¹⁰⁾ and the comparison with the results of QCD sum rules⁵⁾. Obviously, the rule suggests that next to leading order terms in the $1/N_c$ expansion have to cancel to some extent. This is indeed what is observed in the QCD sum rule calculation of several decay channels⁵⁾. However, the fact that the rule seems to work quite generally points to a fundamental property which is presumably connected with the local property of QCD. Local gauge invariance requires a string to be formed as soon as the quarks are no more at the same point. In the direct generation of an energetic meson the formation of a string between quarks from the original colour singlet currents seems to be dynamically favoured compared to other string combinations.

In any case the study of exclusive decays has already taught us important facts:

- o Using only the two parameters a_1 and a_2 factorization gives good results for energetic two-body decays of D- and B-mesons and even for the $|\Delta I| = 3/2$ amplitudes in K-decays.

*) However, the value $\xi = 1/3$ in (6) could still be kept if one would take scales μ much smaller than the particle masses. E.g., $\mu \approx 0.7$ GeV ($c_1 \approx 1.6$, $c_2 \approx -1$) for D-decays and $\mu \approx 1.0$ GeV ($c_1 \approx 1.3$, $c_2 \approx -0.7$) for B-decays would lead to acceptable values for a_1 and a_2 .

- o We found an empirical rule which seems to hold universally:

$$\begin{aligned} a_i &\approx c_i(m_c) && \text{for D-decays} \\ a_i &\approx c_i(m_b) && \text{for B-decays} \end{aligned} \quad i = 1, 2 \quad (8)$$

- o Two-body D^+ -decays are strongly suppressed because of the destructive interference between a_1 and a_2 amplitudes.

Of course, several checks are required before one can be sure about the validity and the limitations of the above statements. Furthermore, a detailed look into the fit reveals a number of deficiencies. In particular, the amplitudes for the channels $D^0 \rightarrow \omega \bar{K}^0$, $\eta \bar{K}^0$, $\bar{K}^0 \phi$ came out too small while the calculation of the Cabibbo-forbidden decay $D^0 \rightarrow \pi^+ \pi^-$ gave a too large amplitude. D-decays occur in a resonance region such that channel mixing by final state interaction will occur. In particular, small channels may be fed by stronger ones via rescattering^{30,9)}. This fact makes it also difficult to obtain from D-decays a precise answer to what extent annihilation processes³¹⁾ occur. For instance, the annihilation process $D^0 \rightarrow \bar{K}^0 \phi$ can be the result of a weak decay to $K^- \rho^+$ and other states followed by a strong interaction scattering process leading to $\bar{K}^0 \phi$. This is indeed most likely to be the case since an analysis assuming rescattering to the $\bar{K} \phi$ channel improves the results for the channels connected with it^{9,32)}. More important, this assumption leaves the predicted branching ratio for the annihilation process $D_S^+ \rightarrow \pi^+ \rho^0$ small even though this channel has a much larger phase space factor and its amplitude is proportional to a_1 instead of a_2 . Indeed, a recent measurement from FNAL¹⁶⁾ gave an upper limit on the branching ratio for $D_S^+ \rightarrow \pi^+ \rho^0$ which is less 0.08 times the branching ratio for $D_S^+ \rightarrow \pi^+ \phi$. Thus, the conclusion is:

- o At least for energetic two-body decays annihilation processes are of little importance, as expected in factorization approximation.

A further check on this statement, for instance a good limit on $D_S^+ \rightarrow \omega \pi^+$ would be very helpful. The non-resonant annihilation process $D_S^+ \rightarrow 3\pi$ has been seen at the level of a 1 % branching ratio¹⁶⁾. This decay and indications³³⁾ for relatively large branching ratios for $D_S^+ \rightarrow \eta \pi^+$, $\eta' \pi^+$ are a challenge for further investigations. Virtual diquark formation which will be discussed in section 4.1 may play a role here.

3.4 The D^+-D^0 Lifetime Ratio

The lifetime ratio τ_{D^+}/τ_{D^0} has been measured by many groups^{1,16)}. The world average is 2.4 ± 0.2 . This result came as a great surprise, since one expected the c-quark to decay almost independently of the spectator quark giving equal lifetimes to D^+ and D^0 . This independent quark decay picture describes the inclusive semileptonic decays very well but fails now obviously for inclusive non-leptonic decays. To explain the observation several suggestions have been put forward.

- a) The decay width of the D^0 is strongly increased by contributions from quark annihilation diagrams which cannot be drawn for D^+ decays³⁴⁾.
- b) The Pauli exclusion principle for the two $\bar{d}$ quarks in D^+ decays reduces the decay width of the D^+ ³⁵⁾.
- c) Destructive interference of amplitudes similar as in two-body decays reduces the decay width of the D^+ ³⁶⁾.

It was soon realized that the effect of the Pauli principle can hardly be large enough and only the possibilities a) and c) remained⁴⁾. An important clue is obtained by summing up all theoretically calculated two-body decay widths. It turned out that these decays provide for almost 70 % of the total non-leptonic widths for D^0 - and for D^+ -decays^{37,27)}. The destructive interference in almost all two-body decays of D^+ keep the corresponding D^+ width small. Although nothing can be said about the remaining 30 % of the non-leptonic width, we concluded that a sizeable part of the observed lifetime difference is due to this destructive interference in D^+ -decays.

One may object that in the summation of two-body decays use has been made of the not yet tested predictions for decays to two-vector particles. These transitions are not very energetic and are likely to be strongly affected by long-range QCD interactions. Only a fraction may really come out as two-vector particles. However, because of the unitarity of the strong interaction S-matrix our conclusion about the importance of destructive interference in D^+ -decays will still be valid if only final state interactions affect the calculated individual decay rates.

4. ESTIMATES FOR INCLUSIVE DECAYS

4.1 D-Decays

We just have seen that in D-decays a pure spectator picture cannot be trusted even after perturbative QCD corrections are applied. The formation of mesons from quark-antiquark pairs and the amplitude interference has to be taken into account even in the inclusive calculation of the total width. In the charm decay process $c \rightarrow s \bar{u} d$ the strong attraction between u and $\bar{d}$ quark can partly be taken into account by evaluating³⁸⁾ $c \rightarrow s \pi^+$, $c \rightarrow s \rho^+$, which gives - using factorization -

$$\Gamma_{c \rightarrow s \pi^+, s \rho^+} \approx 70 a_1^2 10^{10} \text{ sec}^{-1} \quad (9)$$

Similarly, the strong attraction between s and $\bar{d}$ leads to the formation of $\bar{K}^0$ and $\bar{K}^{0*}$

$$\begin{aligned} c \rightarrow u \bar{K}^0 \quad c \rightarrow u \bar{K}^{0*} \\ \Gamma_{c \rightarrow u \bar{K}^0, u \bar{K}^{0*}} \approx 70 a_2^2 10^{10} \text{ sec}^{-1} \end{aligned} \quad (10)$$

(I took $m_c = 1.6$, $m_s = 0.5$, $m_u = 0.35$ GeV, $\theta_c = 0$ and SU3 symmetry for the decay constants.)

Adding the two contributions (9) and (10) incoherently as it is appropriate for D^0 -decays one essentially recovers numerically the result of the summed-up two-body decays given in section 3.4. This is to be expected since in D-decays excited states of π , ρ , K , K^* cannot contribute efficiently due to phase space contributions.

In the inclusive calculation of the decay $c \rightarrow s \bar{u} d$ the force between the s and the d quark must also be taken into account. From one-gluon exchange one expects the short-range force between two quarks in a color antitriplet state to be attractive and 1/2 of the strength of the force between quark and antiquark. The long-range part of the quark-quark force should also be comparable to the corresponding quark-antiquark force as seen from the size of baryons. Thus, these forces are strong enough to give binding effects. At least in discussing baryons we can speak of diquark states³⁹⁾. Diquarks have the same status as constituent quarks with constituent masses: They are extended objects which

dissolve at high q^2 into smaller partons. Of course, diquarks cannot appear as final particles. The formation of a diquark in c-quark decay

$$c \rightarrow (su) \bar{d} \quad (11)$$

will at most be an intermediate state followed by quark rearrangement or annihilation and creation processes due to the long-range part of QCD. In B-decays, however, where more energy is available, diquarks will be the building blocks of the baryons found in the final states.

For an estimate of the significance of diquark formation the weak Hamiltonian (1) can be rewritten in the form³⁸⁾

$$H = - \frac{G}{\sqrt{2}} c_- \epsilon_{kij} (\bar{s}'_i (1 + \gamma_5) u_j^c) \epsilon_{klm} (\bar{d}'_l (1 - \gamma_5) c_m) \quad (12)$$

+ product of color sextet currents, Penguins + h.c.

In this expression u^c , d^c denote charge conjugate fields and $c_- = c_1 - c_2$. Apart from the Penguin contribution the weak Hamiltonian written in terms of diquark operators contains only scalar and pseudoscalar currents. The product of color triplet currents is shown explicitly. A color sextet current cannot produce a bound diquark system. It is neglected in the following discussion.

I define the normalized (us)-diquark field operator of positive parity $\phi_{us}^k(x)$ by the local quark field product

$$\epsilon_{kij} (\bar{s}_i \gamma_5 u_j^c) = h (\phi_{us}^k)^+ \quad (13)$$

The strength of the constant h determines the impact the formation of diquarks will have in decay processes. h can be estimated in a variety of ways:

1) The analogy with the K-meson matrix element of the pseudoscalar density

$$\langle 0 | (\bar{s}_i \gamma_5 u_i) | K \rangle = f_K v \quad v = \frac{m_K^2}{m_u + m_s} \approx 1.4 \text{ GeV}$$

gives

$$h = (2/3)^{1/2} f_{us} v \quad (14)$$

where f_{us} denotes the "diquark decay constant" and the factor $(2/3)^{1/2}$

accounts for the different color structure. If the wave function of the diquark at the origin would be the same as the one of the K meson one has

$$f_{us} \approx f_K \quad h_{us} \approx 0.18 \text{ (GeV)}^2 \quad (15)$$

2) QCD sum rule calculations⁴⁰⁾ agree on the value for the proton decay constant Z

$$\langle 0 | u^k \epsilon_{kij} (\bar{d}_i^c \gamma_5 u_j) | P \rangle = Z u_{\vec{p}} \quad (16)$$

$$Z \approx 0.01 \text{ (GeV)}^3$$

By projecting the scalar (ud) diquark from the proton wave function with average transversal quark momentum of 300 MeV one finds⁴¹⁾

$$h_{ud} \approx 0.16 \text{ (GeV)}^2.$$

3) A QCD sum rule calculation⁴¹⁾ of the coupling $f_{ud} \cdot v$ from the diquark two-point function shows the same behaviour as $f_{\pi} v$ obtained from the π meson pseudoscalar two-point function with the result

$$f_{ud} \cdot v \approx f_{\pi} v \quad \text{i.e.} \quad h_{ud} \approx 0.15 \text{ (GeV)}^2$$

4) About the same numerical result, namely⁴¹⁾

$$0.13 \leq h \leq 0.20 \text{ (GeV)}^2 \quad (17)$$

is obtained using the baryon matrix element of the $|\Delta S|=1$ weak Hamiltonian, factorizing with respect to the diquark components in the baryon wave function and comparing the result with the hyperon decay analysis. Turning the argument around one can also state that $(h_{ud} h_{us})^{1/2} \approx 0.16$ gives the correct magnitude of the $|\Delta I| = 1/2$ decay amplitudes of strange baryons. We see that all the different determinations of h give

$$h \approx 0.15 \text{ (GeV)}^2 \quad (18)$$

or slightly higher values. This large diquark coupling constant has important consequences, as we will see.

For the process $c \rightarrow (su) \bar{d}$ one finds, taking $m_{su} \approx 0.85 \text{ GeV}$,

$$\Gamma_{c \rightarrow (su) \bar{d}} \approx 14 \text{ c}^2 \cdot 10^{10} \text{ sec}^{-1} \quad (19)$$

An estimate for the total D^0 width can now be given by adding incoherently the contributions (9), (10), and (19). There is only small danger of double counting because virtual diquark formation will mainly lead to multimeson states. Including an estimate of the semileptonic width

$\Gamma_{sl} \approx 2 \times 18 \times 10^{10} \text{ sec}^{-1}$ one has

$$\begin{aligned} \Gamma_{D^0} &\approx (2 \times 18 + 70 \cdot (a_1^2 + a_2^2) + 14c_-^2) 10^{10} \text{ sec}^{-1} \\ &\approx 192 \times 10^{10} \text{ sec}^{-1} \end{aligned} \quad (20)$$

The experimental width is $(233 \pm 7) \times 10^{10} \text{ sec}^{-1}$. For the estimate of the D^+ total decay width I assume maximal interference in the quasi two-body modes and add incoherently the contribution from virtual diquark formation. The latter contribution has to be reduced by a factor $\approx 3/4$ because of the Pauli principle for the $(\bar{d}\bar{d})$ diquark state which appears in this case.

$$\begin{aligned} \Gamma_{D^+} &\approx (2 \times 18 + 70 (a_1 + a_2)^2 + 3/4 14c_-^2) 10^{10} \text{ sec}^{-1} \\ &\approx 99 \times 10^{10} \text{ sec}^{-1} \end{aligned} \quad (21)$$

The experimental D^+ width is $(95 \pm 4) 10^{10} \text{ sec}^{-1}$.

It seems that a qualitative understanding for the large D^0 width has been achieved and that the attraction between quarks in color triplet states plays an important role. In this estimate no direct weak annihilation processes have been taken into account. There is still some room for it but its contribution should not exceed $\approx 20\%$. The estimated width for D^+ is very sensitive to the amount of amplitude interference. It may be fortuitous that the rough estimate eq. (21) gives a result so close to the experimental value. If taken at face value we learn that amplitude interference strongly reduces the width which is then raised up again by the effect of virtual diquark formation in which a_1 and a_2 interfere constructively ($c_- \approx a_1 - a_2$). This picture is more informative than the very naive one where one neglects the strong destructive interference in quasi two-body decays and simply argues that the D^+ transition rate should be 5 times the $e^- \nu$ semileptonic rate.

For the total decay width of the $F^+ = D_S^+$ one obtains practically the same result as for the D^0 . Virtual diquark production

$$F^+ \rightarrow (su) (\bar{s}\bar{d}) \quad (22)$$

is again expected to occur at a sizeable rate. There could be an interesting difference compared to D^0 decay for the final states: Since both di-quarks contain strange quarks and may be relatively slow, simple quark rearrangement can more frequently occur. This effect could be responsible for the observed decay rates for $F^+ \rightarrow \eta\pi^+$, $\eta'\pi^+$ which are larger than expected from factorization with mesons states³³⁾.

4.2 Inclusive B decays

In B-decays several different inclusive processes can be studied. In the decay processes

$$b \rightarrow c \bar{u} d' \quad b \rightarrow c \bar{c} s' \quad (23)$$

and the tiny, but interesting ones

$$b \rightarrow u \bar{u} d' \quad b \rightarrow u \bar{c} s' \quad (24)$$

quark pairs can form mesons in a variety of ways.

The branching ratio for the inclusive process

$$\bar{B}^0 \rightarrow J/\psi + X \quad (25)$$

where J/ψ is directly produced (not coming from ψ' decay) has been measured by Argus³⁾ to be 0.81 ± 0.2 %. With $|V_{cb}| \approx 0.05$ and a b-quark mass of 5.0 GeV one obtains theoretically for $b \rightarrow J/\psi + s$

$$\Gamma_{b \rightarrow s J/\psi} \approx 12 a_2^2 10^{10} \text{ sec}^{-1} \quad (26)$$

This gives (with $|a_2| \approx |c_2(m_b)| \approx 0.25$) a branching ratio of 0.9 %, which compares favorably with the Argus result.

The calculated inclusive rates

$$b \rightarrow F^- + c \quad b \rightarrow F^{*-}(1^-) + c \quad b \rightarrow F^{*+}(1^+) + c$$

sum up to^{*)}

$$\Gamma_{b \rightarrow c(F, F_-^*, F_+^*)} \approx 8.7 a_1^2 (f_F/f_K)^2 10^{10} \text{ sec}^{-1} \quad (27)$$

(assuming $f_{F^*}/f_\rho \approx f_F/f_K$)

^{*)} replace 8.7 by 5.5 if $F^{*+}(1^+)$ does not decay to F

Thus, the inclusive branching ratio for F^- production is expected to be $BR(\bar{B}^0 \rightarrow F^- + X^+) \approx 13(f_F/f_K)^2 \%$. Cleo and Argus obtained for the inclusive D_s^- production a branching ratio of $13 \pm 2.5 \pm 4 \%$. Since QCD sum rules give $f_F/f_K \approx 1$, the theoretical and experimental numbers agree within errors.

Of great interest are B-decays to baryon-antibaryon pairs. According to Cleo and Argus the total baryonic mode has a branching ratio of $7.1 \pm 2 \%$. It is mainly due to Λ_c production. For a theoretical estimate the rate of diquark formation appears essential^{42,38}). The constant h_{cd} responsible for the generation of the $(cd)_0^+$ diquark state scales up to about $h_{cd} \approx 0.45 \text{ (GeV)}^2$ (using $f_D \approx f_K$). With this number the rate for $b \rightarrow (cd)_0^+ + \bar{u}$ is $\approx 3 \times 10^{10} \text{ sec}^{-1}$. Since a fast diquark in a bound state will appear very likely as a baryon in the final state, we find, therefore, that the direct production of baryons via the lowest 0^+ diquark state can account for $\approx 50 \%$ of the total decay rate to baryons.

The transition to charm and strangeless baryons can be estimated in the same way. With $h_{ud} = 0.16 \text{ (GeV)}^2$ one finds

$$\Gamma_{b \rightarrow (ud)_0^+ \bar{u}} \approx 0.5 \cdot |V_{ub}/V_{cb}|^2 10^{10} \text{ sec}^{-1} \quad (28)$$

The branching ratio for B-decays to non-charmed baryons, in which the proton is directly produced via a diquark in its lowest state (spin parity 0^+ , $I = 0$), is, therefore

$$BR(\bar{B} \rightarrow P_{(\text{direct})} + X) \approx 0.3 |V_{ub}/V_{cb}|^2 \% \quad (29)$$

For the decay $B^- \rightarrow P \bar{P} \pi^-$ seen at the Argus detector eq. (29) should be applicable. The measured branching ratio $5.2 \pm 1.4 \pm 1.9 \%$ requires $|V_{ub}/V_{cb}| \geq 0.2$ even if we allow for a factor 2 increase in (29) due to additional QCD effects or an additional proton formation process. It appears that $|V_{ub}/V_{cb}|$ must be rather close to the upper limit as obtained from semileptonic processes^{29,43}).

An important prediction of the diquark picture for charmless baryonic decays is the $|\Delta I| = 1/2$ isospin selection rule which should hold since the current generated spin-zero color triplet (ud) diquark

has necessarily isospin zero. In addition, in two-body decay processes $\bar{B} \rightarrow N^* \bar{\Delta}$ can occur but not $\bar{B} \rightarrow \Delta \bar{\Delta}$ (except through the effect of final state interactions)²⁹⁾.

A very reliable result for $|V_{ub}/V_{cb}|$ could be obtained from a measurement of the inclusive rate $B^- \rightarrow D_s^- X^0$ with X^0 not containing charmed and strange particles. The calculation using the corresponding inclusive b-quark decay processes gives

$$BR(B^- \rightarrow D_s^- X_{\ell, s}^0)/BR(B^- \rightarrow D_s^- X) \approx 1.5 |V_{ub}/V_{cb}|^2 \quad (30)$$

with little theoretical error.

Finally, I will give here an estimate for the lifetime ratio $\tau(B^-)/\tau(\bar{B}^0)$. Decay rates to leptons, to F's and to J/ψ's and χ's should be the same for $\bar{B}^0$ and B^- . Assuming maximal interference (with $a_1 = 1.1$ and $a_2 = -0.25$) for the remaining B^- amplitudes and adding an annihilation contribution of 15 % to the $\bar{B}^0$ width, one obtains the result

$$\tau(B^-)/\tau(\bar{B}^0) < 1.5 \quad (31)$$

It is an upper limit since for multibody decays the interference need not be maximal.

4.3 Strange Particle Decays

It is tempting to reconsider strange particle decays in the light of what we have learnt from D and B decays. One of the basic problems in nonleptonic decays concerns the empirical $|\Delta I| = 1/2$ rule⁴⁴⁾ which for more than 3 decades has remained a mystery. From the weak Hamiltonian one expects an about equal contribution from the pieces which transform as $I = 1/2$ and $I = 3/2$, while in K-decays to two π-mesons the experimental amplitude ratio is 22! The $|\Delta I| = 3/2$ amplitude is smaller than obtained theoretically and the $|\Delta I| = 1/2$ amplitude much larger. As it is well known, the situation improves when hard gluon and heavy quark exchange effects are taken into account. Using as an effective Hamiltonian the $|\Delta S| = 1$ analog of eq. (1) with QCD coefficients at the scale of 1 GeV $c_1 \approx 1.5$ and $c_2 \approx -0.9$, the discrepancy is reduced. In fact, the $|\Delta I| = 3/2$ amplitude in K-decays is satisfactorily described in fac-

torization approximation if one uses in addition $a_1 \approx c_1$ and $a_2 \approx c_2$ according to our experience from D decays. However, the $|\Delta\vec{I}| = 1/2$ amplitude calculated in the factorization approximation and with the rule $a_i \approx c_i$ is still off by a factor 4. It was believed for some time that the Penguin interaction²¹⁾ is sufficiently strong to solve the puzzle. Detailed studies showed, however, that its contribution is by far not enough. Also a QCD sum rule approach for the $|\Delta\vec{I}| = 1/2$ amplitude led to a discouraging result⁴⁵⁾. On the other hand, an expansion in $1/N_c$ seems to lead in the right direction⁴⁶⁾. To first order in $1/N_c$ the amplitude increases. However, since the zero'th order is off by a factor 4 and a cut-off has to be used, it is still controversial to what extent the $K \rightarrow 2\pi$ $|\Delta\vec{I}| = 1/2$ amplitude is explained in this way. Lattice gauge theory calculations⁴⁷⁾ of the weak matrix element are still in a starting phase. They are promising, but do not yet give convincing results. What is missing in all these approaches is a good understanding of the underlying physics and the relation between K-decay and other processes.

In D and B decays we learnt that the attraction between quarks should be taken into account in a similar way as the attraction between quarks and antiquarks which leads to bound states. Furthermore, we saw that the diquark matrix element of the scalar diquark current is about as large as the meson matrix element of the pseudoscalar current which - for a slow meson - is much larger than the corresponding matrix element involving the axial vector current. For kinematical reasons the generation of hadrons by vector or axial vector currents (e.g. in the decay $c \rightarrow \pi^+ s$) goes with the 3rd power of the mass of the decaying quark ($\sim G^2 f_\pi^2 m^3$). The creation of states by scalar currents, on the other hand, goes linearly with this mass ($G^2 f_\pi^2 v^2 m$). Thus the relative importance of virtual diquark formation compared to direct meson generation is largest for strange particle decays. If virtual diquark formation is important in D and B decays, it must be the dominant process in strange particle decays!^{38,29)} In fact, factorization with respect to the diquark component in the baryon wave function using $h \approx 0.16$ (GeV)² gives the correct magnitude for the baryon matrix element of the weak Hamiltonian⁴¹⁾.

In the decay $K_S^0 \rightarrow 2\pi$ the contribution of diquarks is not so easily

established. The diquarks are virtual and their strong transition to meson states hard to calculate. However, at least the amplitude $K_S^0 \rightarrow (ud)(\bar{u}\bar{d})$ can be estimated by factorization with respect to diquarks. The result is

$$A(K_S^0 \rightarrow (ud)(\bar{u}\bar{d})) \approx \frac{G}{\sqrt{2}} s_\theta c_\theta c_- h^2 \frac{\sqrt{2}}{f_\pi} \sqrt{3} \approx 2 \times 10^{-6} \text{ GeV} \quad (32)$$

This number is a factor ~ 18 larger than the one obtained in a factorization calculation for the direct decay into mesons. It is also much larger than the experimental amplitude corresponding to the total K-decay rate and thus leaves room for suppression effects in the transition from diquarks to mesons.

Thus, the diquark mechanism gives a very qualitative but suggestive picture of the physics behind the $|\Delta I| = 1/2$ rule³⁸⁾. As far as I know there exists no counterexample. Whenever in strange particle decays diquarks can play a role, the effects are big: The $|\Delta I| = 1/2$ amplitudes in hyperon and K meson decays as well as the total width of Λ_c . Whenever scalar diquarks can play no role as in $|\Delta I| = 3/2$ transitions, in Ω^- decays and for the matrix element of the operator Q_6 , which determines the CP-violating K-2 π decay amplitude ϵ' , only small values are found. These latter matrix elements can be estimated by factorization with respect to asymptotic states. Since the corresponding amplitudes are small, corrections from Penguin diagrams, from electromagnetic Penguins, and from on- and off-shell final state interactions can be important, however.

Straightforward factorization applied to the matrix element of the Penguin operator Q_6 , neglecting the corrections mentioned, and taking ϵ from experiment gives⁴⁸⁾

$$\text{Re}(\epsilon'/\epsilon) \approx 8 |V_{cb}| |V_{ub}| \sin \delta' \quad (33)$$

Here δ' is the CP-violating phase in the Maiani representation. By comparing this equation with the recently announced value for ϵ'/ϵ ⁴⁹⁾

$$\text{Re}(\epsilon'/\epsilon) = (3.3 \pm 1.1) 10^{-3}$$

gives another information on $|V_{ub}|$:

$$|V_{ub}/V_{cb}| \sin \delta' \approx 0.16 \quad (34)$$

Unfortunately, aside from the experimental error, the theoretical error from eq. (33) can be almost a factor 2.

5. SUMMARY

The experimental data on D and B decays provide for new insights into the interplay of interactions in weak processes. Weak decays are far from understood but some dominant effects can now be seen and interpreted. Exclusive semi leptonic decays follow pretty well the pattern expected from simple-valence quark models in which the heavy quark carries most of the particle momentum. The decay rates of energetic two-body non-leptonic decays agree with the predictions obtained from the factorization assumption. Remarkably, the observed coefficients a_1 , a_2 which govern the strength of charged and neutral current products are in magnitude and sign equal to the QCD coefficients at the mass scale of the decaying quark. In the two-body decays of the D^+ meson to particles and resonances sizeable amplitude interference occurs. It is responsible for the main part of the D^0 - D^+ lifetime difference! Direct weak annihilation processes do not seem to give a dominant contribution but cannot clearly be separated from the effect of annihilation and creation processes by the long-range QCD interaction which takes place before the particles separate. Appreciable channel mixing can occur this way in transitions with small energy release. In inclusive decays the non-perturbative binding effects due to quark-antiquark and quark-quark forces are more important than one might have expected. Since scalar states are strongly coupled to the corresponding scalar currents virtual diquark formation gives a sizeable contribution to the decay widths and cannot be neglected. Diquark production is the first step in the decay of B-mesons into a baryon-antibaryon pair. Diquark effects are of even greater importance in strange particle decays. The corresponding estimates shed new light on the empirical $|\Delta I| = 1/2$ rule and uncover thereby relations between many processes.

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