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On Charm and Beauty Decays - A Theorist's Perspective*

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ABSTRACT

The present understanding of charm and bottom decays is reviewed. Special emphasis is placed on discussing the theoretical uncertainties in view of the particularly rich harvest of new data from the last year. A semi-quantitative description of D decays has emerged enabling us to address rather detailled and relatively subtle questions there, like on once and twice Cabibbo suppressed decays. Beauty physics having left its infancy is now in its adolescence; its future development towards maturity is analyzed.

I. Motivation

Giving a review talk is like playing simultaneous chess; not much attention is paid to the games you win – almost everybody focuses on the ones you lose, on your failures. The similarity between the two situations extends also to the question on which strategy to adopt: Do you attribute the same weight to every opponent/problem and divide your time equally among them? Or do you exercise some personal judgement by dividing the field into "easy, tough and entertaining"? Then you proceed to run over the first kind and draw honorably with the second kind; that way you boost your confidence and gain in respectability. Finally you

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can indulge yourself with the third category; by that time it is probably too late to worry unduly about winning or losing. It is the second strategy I am going to adopt, yet it is not in my self-interest to specify which of the problems I regard as "easy, tough or entertaining". May I add that I will not cover mixing, CP violation or truly rare decays.

There exists a triple motivation for dedicated work in this field.

1. Charm and beauty decays present us with a rather unique opportunity to learn important lessons about QCD on the interface between the perturbative and non-perturbative regimes. Open flavor states $Q\bar{q}$ with $Q[q]$ denoting a heavy (light) flavor can help to bridge the gap between the light hadrons, $q\bar{q}$, where our understanding is rather unsatisfactory, and quarkonia states, $Q\bar{Q}$, where potential models work increasingly well. Heavy flavor baryons Qq_1q_2 offer interesting studies as well; in essence this is similar to structural studies with molecules into which radioactive atoms have been implanted.

2. We want to extract the KM parameters like $V(ub), V(cb)$, etc. They obviously represent fundamental parameters which have to be known and, hopefully, understood. (On a practical level it is always helpful to know what one is trying to understand). The KM parameters describe quark couplings whereas it is the couplings of hadrons only that can be observed directly. The impact of QCD on heavy flavor decays has thus to be understood to some degree at least.

3. We all strive to find "New Physics." This noble endeavor is however hampered by the sometimes annoying presence of Old Physics. The search for

the former is thus determined by the understanding of the latter.

The outline of the talk will be as follows:

In Section II, I will analyze charm decays, both the present understanding and its future refinements; in Section III, I discuss beauty decays with particular emphasis on $|V(cb)|$ and $|V(ub)|$ before concluding with some remarks on the future in Section IV. In general, I will not present a comprehensive review with all numbers and experimental findings; those can be found in other talks at this conference.[1] Instead I will focus on the most topical features and pass theoretical judgement on them.

II. The Decays of Charm

A. Lessons on Strong Interactions in D^o/D^+ Decays.

1. Semi-Leptonic D^o/D^+ Decays.

These decays are not expected to pose as big a theoretical challenge as non-leptonic decays since they involve only one type of hadronic matrix element: $<(S=0,1)|j_\mu|D>$. A host of models have been put forward to calculate those. A typical one was developed by Bauer, Stech and Wirbel (=BSW);[2] others will be mentioned later:

$$\Gamma_{\rm BSW}(D \to \ell\nu K^*, K) \sim (15-20)\cdot 10^{10}\mathrm{sec}^{-1} \tag{1}$$

which compares favorably with the data

$$\Gamma_{\rm exp}(D \to \ell\nu K\pi, K) \sim (17.8 \pm 2.6)\cdot 10^{10}\mathrm{sec}^{-1}\ . \tag{2}$$

Yet a more detailed look reveals a potential problem of considerable relevance: MARK III has reported[3]

$$\frac{\Gamma(D \to \ell\nu K^*)}{\Gamma(D \to \ell\nu K\pi)} = (0.55 - 0.57) \pm 0.13 \ . \tag{3}$$

It should be noted that the quoted error is statistical only and that Eq. (3) does not represent a unique interpretation. The problem is not that only half the $K\pi$ in semileptonic D decays come from a K^* resonance – why not? The problematic aspect of Eq. (3) concerns the relative weight of K and K^*: for BWS predict

$$\frac{\Gamma(D \to \ell\nu K^*)}{\Gamma(D \to \ell\nu K, K^*)} \sim 0.53 \cong \frac{\Gamma(D \to \ell\nu K^*)}{\Gamma(D \to \ell\nu K)} \sim 1.1 \tag{4}$$

Most other models, in particular the one by Grinstein, Isgur and Wise (=GIW)[4] , attribute even more prominence to K^* final states. Experimentally

$$\left.\frac{\Gamma(D \to \ell\nu K\pi)}{\Gamma(D \to \ell\nu K, K\pi)}\right| \sim 0.44 \begin{array}{l} +0.08 \\ -0.09 \end{array} . \tag{5}$$

Using Eq. (3), one then concludes

$$\left.\frac{\Gamma(D \to \ell\nu K^*)}{\Gamma(D \to \ell\nu K)}\right|_{\mathrm{exp}} \sim 0.44 \pm 0.13 \ . \tag{6}$$

If Eq. (6) were confirmed by more data, we could not claim to have necessarily a theoretical disaster at hand – after all there is an old prediction[5] consistent with it. Yet it would constitute at least an acute embarassment in practice since all the detailed models of more recent vintage point in the direction of Eq. (4). If Eq. (6) were to hold up in spite of the rather general expectation $\Gamma(D \to \ell\nu K^*) \sim \Gamma(D \to \ell\nu K)$, one had to view the success of these models in accounting for the considerably more complex non-leptonic decays as a mere coincidence. Furthermore one should then trust them even less in B decays – despite some early evidence to the contrary as I will discuss later on.

Considering these – for a theorist – unpleasant consequences, I feel strongly inclined to belief that Eq. (6) does not represent the last word – that instead it will go up by a factor of two or so.

2. Non-leptonic D^o/D^+ Decays.

   (a) The "Art of Theoretical Engineering"

   In an effort to be practical and to concentrate on the doable, Stech and coworkers have developed a phenomenological framework to deal with non-leptonic decay modes. All transition amplitudes $T(D \to f)$ are expressed as a linear combination of two more elementary amplitudes with fixed coefficients:

$$T(D \to f) = a_1 T_1(D \to f) + a_2 T_2(D \to f) \tag{7}$$

$$a_1 = \frac{1}{2}(c_+ + c_-) + \frac{\xi}{2}(c_+ - c_-) \tag{8}$$

$$a_2 = \frac{1}{2}(c_+ - c_-) + \frac{\xi}{2}(c_+ + c_-)\ . \tag{9}$$

   The renormalization coefficients $c_\pm$ are produced by QCD radiative corrections; $c_\pm = 1$ holds in the absence of QCD. The parameter ξ denotes the relative size of matrix elements in color space; e.g.

$$\xi = \frac{\langle 0|\bar{u}_i d_j|\pi^+\rangle}{\langle 0|\bar{u}_i d_i|\pi^+\rangle} \tag{10}$$

$i, j = 1, 2, ...N_c$. Naively, just counting numbers, one might expect $\xi \simeq \frac{1}{N_c} = \frac{1}{3}$.

Something has to be clearly kept in mind here: It is (trivially) true that changing the values of $c_\pm$ can offset almost any change in ξ (apart from $(a_1 + a_2)^2(a_1 - a_2) \cong (1-\xi^2)(1+\xi)$). Yet this observation amounts to little more than numerology, since the origins of these parameters are very different: $c_\pm$ are due to **hard** gluon effects, ξ on the other hand to **soft** gluons.

Eq. (7) shows there are three categories of decays:

- Class I transitions: $D^o \to M_1^+ M_2^-$; only the a_1 term contributes;
- Class II transitions: $D^o \to M_1^o M_2^o$; only the a_2 term contributes;
- Class III transitions: $D^+ \to M_1^0 M_2^+$; both a_1 and a_2 terms contribute and can thus even interfere.

If you complain that these names while being typical of scholarly tradition lack a Shakespearean ring to them, you are quite right. If you observe further that somebody living and working in Heidelberg should come up with more colorful, if not romantic names, you are right again. However, such gripes should not obscure the fact that these distinctions are very important. Unfortunately, quite often they are misrepresented or at least not appreciated in the literature.

Thus there are two a priori free parameters a_1, a_2 to be determined from the data – plus a not insignificant amount of "poetic license" entering via the formfactors adopted and final state interactions(=FSI) that are included.

This "poetic license" certainly introduces some fuzziness into the theoretical description. Yet even so it is highly non-trivial – and I regard it as significant – that with

$$a_1 \simeq 1.2 \pm 0.1\,, \qquad a_2 \simeq -0.5 \pm 0.1 \tag{11}$$

a very decent fit is obtained to some twenty-odd D^0/D^+ decay channels![6] A priori there is no reason to expect that one set of values for a_1, a_2 should be adequate to describe so many so diverse decays

$$D \to PP, \quad PV$$

where $P[V]$ denotes pseudoscalar [vector] states; for the kinematical and dynamical environments, i.e. phase shifts, vary very significantly. Yet we learn from the success of the fit that there is a simple pattern underlying charm decays. The specialties of individual channels can be factored off into the rather simple formfactors and FSI employed thus allowing a universal value for a_1, a_2. Even so soft gluon effects play an important role. For Eq. (11) leads to

$$\frac{1}{3} \neq \xi \simeq 0 \tag{12}$$

when adopting the usual values for $c_\pm$, i.e., $c_+ \sim 0.7, c_- \sim 1.9$.

Further pleasant surprises emerge from this analysis:

- Adding up $\Gamma_{\rm th}(D \to PP, PV, VV)$ where the $D \to PP, PV$ modes have been more or less confirmed experimentally and comparing it with $\Gamma_{\rm exp}(D)$ one finds

$$\Gamma(D \to PP,\ PV,\ VV) \sim 0.7 \times \Gamma_{\rm non-lept.}(D) \tag{13}$$

- $$\frac{\Gamma(D^0 \to \ell\nu K/K^*,\ PP,\ PV,\ VV)}{\Gamma(D^+ \to \ell\nu K/K^*,\ PP,\ PV,\ VV)} \sim 2-3 \tag{14}$$

- $$BR(D^0 \to \ell\nu\, X) \sim 8\% \tag{15}$$

The two-body modes thus dominate non-leptonic D decays and the global features of D decays are well reproduced. And all of this is achieved without any contribution from weak annihilation!

A more detailed look reveals some phenomenological deficiencies:

- The predicted values for $BR(D^o \to \bar{K}^o\phi, \bar{K}^o\omega, \bar{K}^o\eta)$ are all low compared to the data. I do not perceive this as a major problem. They all represent class II transitions, i.e., are smallish $\sim O(1\%)$; thus even relatively small rescattering from the large class I transitions will have a big impact on them while affecting the overall picture very little.

- $$\frac{\Gamma(D^0 \to K^+K^-)}{\Gamma(D^0 \to \pi^+\pi^-)} \sim \begin{cases} 3-4 & \text{experim.} \\ 1.4 & \text{theoret.} \end{cases} \tag{16}$$

  I will come back to this point later on.

(b) The "Mackintosh Approach": $\frac{1}{N}$

It is fair to say that the previous approach contained a few ad-hoc assumptions like factorization, etc. There is another approach impressive in its multicoloured graphics which is based on an expansion in $\frac{1}{N}$, N being the number of colors. It has some precursors[7] , yet the most comprehensive application to charm decays has been given by Buras, Gerard and Ruckl[8] . The transition amplitude is written down as follows:

$$T(D \to f) = \sqrt{N}\left(b_0 + \frac{b_1}{N} + \mathcal{O}\left(\frac{1}{N^2}\right)\right) . \tag{17}$$

For actual calculations one retains only the leading term – b_o – and drops all non-leading contributions b_1/N, etc. This represents the basic assumption. From it follows:

- $\xi \cong 0$ effectively since it is of higher order in $\frac{1}{N}$: $\xi = \frac{1}{N}$;
- factorization holds;
- W exchange and FSI have to be ignored.

The description of the data obtained in this approach is not bad, though definitely poorer than in the Stech et al. approach. This can be traced back largely to the fact that FSI effects are ignored. On the other hand this approach is certainly more compact and obviously self-consistent since it is based on just one basic assumption, namely ignoring terms that are non-leading in $\frac{1}{N}$. This one assumption however is purely ad-hoc.

(c) The "High T_c Superconductor" Approach.

There is one approach that will (hopefully) solve all our problems and settle all issues once and for all – the use of lattice Monte Carlo calculations. However, like with high T_c superconductors, its benefits will not be reaped in the very near future; quite a few years will pass before it will yield definitive results on charm decays.

(d) "Best Available Technology": QCD Sum Rules.

This approach involves three ingredients

- One employs an operator product expansion of $\mathcal{L}(\Delta C = 1)$:

$$\mathcal{L}(\Delta C = 1) = \sum c_i O_i \ . \tag{18}$$

  With the help of perturbative QCD one identifies the local operators O_i and computes their Wilson coefficients c_i.

- Non-perturbative effects are introduced by allowing for non-vanishing vacuum expectation values

$$\langle 0|O_i|0\rangle \neq 0 \ . \tag{19}$$

- The concept of "duality" is implemented by matching up quark-gluon amplitudes determined in the Euclidean region with hadron amplitudes in the Minkowskian region.

Block and Shifman[9] have developed and applied such an analysis to

$$D \to PP,\, PV \tag{20}$$

decays, where one has six fit parameters altogether, namely three for $D^0, D^+, D_S \to PP$ and three for $D^0, D^+, D_S \to PV$, yet many more decay modes.

Since the theoretical analysis involves four-point functions rather than two- or three-point functions, it represents a very ambitious and challenging program. Therefore one has to grant it some time for maturing. Even so a first analysis yields very promising results by producing a rather decent fit to the "old" MARK III branching ratios; in particular $BR(D^0 \to \bar{K}^0\phi) \sim 1\% \sim BR(D^0 \to \bar{K}^0\omega)$ is obtained. Since six parameters have to be fitted one has to redo the analysis with the "new" MARK III branching ratios, yet I do not anticipate a major problem to emerge. Therefore, I would like to summarize why I consider this approach so promising. A priori one does not make assumptions like factorization or ignoring weak annihilation or non-leading terms in $\frac{1}{N}$. Non-factorizable contributions are actually included and treated in an at least semi-quantitative fashion. The dominance of factorizable contributions emerges then self-consistently from the duality match-up, yet other terms like W-exchange are still present on the $\sim 20\%$ level.

3. Purely Leptonic Decays.

From the branching ratios $D^+ \to \ell^+\nu, D_s^+ \to \ell^+\nu$ one determines very important hadronic parameters, namely the decay constants f_D and f_F. In a non-relativistic potential model they are related to the hadronic wavefunction at the origin

$$f \simeq \frac{\sqrt{12}|\phi(0)|}{\sqrt{M}} \tag{21}$$

where M denotes the meson mass. On very general grounds, one expects

$$f_D < f_F \ .$$

Specific models yield[10] (with the normalization $f_\pi \sim m_\pi$)

$$f_D \sim 150 - 200\, MeV\ , \qquad f_F \sim 180 - 220\, MeV\ . \tag{22}$$

MARK III has obtained[11]

$$f_D < 290\, MeV \qquad (90\%\ C.L.) \tag{23}$$

from their upper bound on $D^+ \to \mu^+\nu$. Of course, it is highly desirable to improve the sensitivity on f_D, hopefully reaching the level indicated in Eq. (22); of course, it is equally desirable to obtain a comparable number on f_F. Yet even Eq. (23) represents a very intriguing bound, in particular if one adopts the prescription of non-relativistic dynamics, Eq. (21). For in that case

$$f_B \simeq \sqrt{\frac{m_D}{m_B}}\, f_D \lesssim 170\, MeV \tag{24}$$

a number of great relevance in dealing with $B^0 - \bar{B}^0$ mixing.

B. Cross Checks in D_s Decays.

A pleasantly simple dynamical pattern has emerged from D^0, D^+ decays:

- Two-body final states dominate non-leptonic D^0, D^+ decays.
- The large $D^+ - D^0$ lifetime ratio is dominantly though maybe not exclusively produced by a **destructive** interference in D^+ decays.

Accepting these findings is however tantamount to giving up much flexibility in treating D_s decays - the model parameters have been basically fixed. D_s decays thus offer us quite honest tests of the statement that we have indeed developed a rather satisfactory understanding of D decays.

Quite a few very interesting experimental results have been obtained in the last year on D_s decays. As far as the overall rates are concerned, the news have been mixed. The good news has been that $\tau(D_s)$ has been found to agree with $\tau(D^0)$ within quite decent errors:

$$\frac{\tau(D_s)}{\tau(D^0)} \simeq 1.0 \pm 0.15 \ . \tag{25}$$

The bad news are that still no **absolute** branching ratios are known. The importance of D_s decay modes can then be expressed only relative to the "standard" mode $D_s^+ \to \phi\pi^+$. Definite numbers have been given for three other modes:

$$\frac{BR(D_s^+ \to \bar{K}^{*0} K^+)}{BR(D_s^+ \to \phi\pi^+)} = \begin{cases} 0.75 \pm 0.12 \pm 0.06 & \text{E691} \\ 0.85 \pm 0.23 & \text{MARK II} \\ 1.44 \pm 0.37 & \text{ARGUS} \\ 0.6 - 0.86 & \text{theoret.} \end{cases} \tag{26}$$

$$\frac{BR(D_s^+ \to (K^+K^-\pi^+)_{\rm nonres})}{BR(D_s^+ \to \phi\pi^+)} = 0.23 \pm 0.07 \pm 0.07 \qquad E691 \tag{27}$$

$$\frac{BR(D_s^+ \to (\pi^+\pi^-\pi^+)_{\rm nonres})}{BR(D_s^+ \to \phi\pi^+)} = 0.29 \pm 0.07 \pm 0.05 \qquad E691 \tag{28}$$

and an upper limit

$$\frac{BR(D_s^+ \to \rho^0\pi^+)}{BR(D_s^+ \to \phi\pi^+)} < 0.09 \; . \qquad E691 \tag{29}$$

Up to this conference no decay mode f had been found with

$$\frac{BR(D_s^+ \to f)}{BR(D_s^+ \to \phi\pi^+)} > 1 \; .$$

Since one estimates theoretically

$$BR(D_s^+ \to \phi\pi^+) \sim 4\%$$

one is then lead to the question: "Where and what are the non-leptonic D_s^+ decay modes?" While it is true that theoretically one tends to expect two-body modes to be less dominant for D_s than for D^o decays this occurs only on the $\sim$ 10% level, i.e., it is not highly significant. It was a very pleasing experience at this symposium to hear from both the MARK II and III groups about preliminary findings that

$$\frac{BR(D_s^+ \to \eta\pi^+)}{BR(D_s^+ \to \phi\pi^+)} \sim 2 \tag{30}$$

with a possibly even larger signal for $D_s^+ \to \eta'\pi^+$.

While the spectre of "missing D_s^+ decays" is thus receding, many intriguing observations can be made:

- The relative weight of the class II transition $D_s \to \bar{K}^* K^+$ and the class I transition $D_s \to \phi\pi^+$ is as predicted, Eq. (26).
- The size of the non-resonant $D_s \to KK\pi$ mode is only about 20% of the resonant modes, Eq. (27) – again as expected.
- The D_s does decay into final states without open or hidden strangeness, Eq. (28). Annihilation processes thus do occur, though with a reduced rate, namely with only 20-30% of the strength of spectator processes.
- The tight upper bound on $D_s \to \rho^0\pi^+$ provides some prima facie evidence that $D_s \to \pi\pi\pi$ is generated by weak annihilation and not just by FSI. For in the latter case one would expect $BR(D_s^+ \to \rho^0\pi^+) \gtrsim BR(D_s^+ \to \pi^+\pi^-\pi^+)$ unless some accidental cancellations take place. To look at it in a slightly different way, there could be a π–like, i.e., pseudoscalar resonance π with $m_\pi \sim m(D_s)$ that enhances apparent annihilation transitions

$$D_s^+ \to \pi' \to n\pi \tag{31}$$

where G parity requires $n =$ odd. It would be only natural to expect $D_s^+ \to \rho^0\pi^+$ to occur that way as well.

- There is one loophole in this argument that can be closed by further observation: The Beijing group has suggested that[12]

$$BR(D_s^+ \to \phi\pi^+) \sim BR(D_s^+ \to \omega\pi^+) \gg BR(D_s^+ \to \rho^0\pi^+) \tag{32}$$

might hold. Blok and Shifman find large isospin cancellations in $D_s \to \rho\pi$:

$$\frac{BR(D_s^+ \to \rho^0\pi^+)}{BR(D_s^+ \to \omega\pi^+)} \lesssim 0.25 \tag{33}$$

with $D_s \to \omega\pi^+$ still being suppressed relative to $D_s \to \phi\pi$. Any data on $D_s \to \omega\pi$ are thus highly desirable, though hard to come by. It should be noted that the reaction of Eq. (31) could not contribute here.

Quite a new element enters if indeed

$$BR(D_s^+ \to \eta'\pi^+) \sim BR(D_s^+ \to \eta\pi^+) \sim 2BR(D_s^+ \to \phi\pi^+) \tag{34}$$

were found since factorization yields typically

$$BR(D_s^+ \to \eta'\pi^+) \sim BR(D_s^+ \to \eta\pi^+) \sim BR(D_s^+ \to \phi\pi^+) \ . \tag{35}$$

The presence of a nearby **scalar** resonance would offer a natural explanation for an enhancement in $D_s \to \eta\pi, \eta'\pi$ since

$$0^+ \to PP \qquad 0^+ \not\to PV \ . \tag{36}$$

Also it should be noted that

$$0^+ \not\to 3\pi \tag{37}$$

Such a scalar resonance would therefore not contribute to $D_s \to 3\pi$.

As a final remark or appeal for data, we would like to know the semileptonic branching ratio. In particular, does

$$BR(D_s \to \ell\nu X) \simeq BR(D^0 \to \ell\nu X)$$

hold or

$$BR(D^0 \to \ell\nu X) < BR(D_s \to \ell\nu X) < BR(D^+ \to \ell\nu X) \ .$$

Also the composition of the hadronic state X is of considerable interest:

$$X = \eta,\ \eta',\ \phi,\ \omega,\ \pi\text{'s} \ .$$

C. Refinements

1. Once Cabibbo Suppressed Decays

The oldest puzzle in charm is represented by the following two transition rates

$$\Gamma(D^0 \to K^+K^-) = \begin{cases} 1.2 \pm 0.3 \\ 1.9 \end{cases} \times 10^{10} sec^{-1} \quad \begin{matrix} \text{exp.} \\ \text{theor.} \end{matrix} \qquad (38)$$

$$\Gamma(D^0 \to \pi^+\pi^-) = \begin{cases} 0.33 \pm 0.12 \\ 1.4 \end{cases} \times 10^{10} sec^{-1} \quad \begin{matrix} \text{exp.} \\ \text{theor.} \end{matrix} \qquad (39)$$

Three mechanisms can be invoked to explain $\Gamma(D^0 \to K^+K^-) > \Gamma(D^0 \to \pi^+\pi^-)$.

· $SU(3)_{FL}$ breaking in Eqs. (38, 39) has been implemented basically via $(f_K/f_\pi)^2 > 1$. Maybe one has overlooked another important source of $SU(3)_{FL}$ breaking. This can be checked quite clearly in D^+ decays:

$$\frac{\Gamma(D^+ \to \pi^0\pi^+)}{\Gamma(D^+ \to \bar{K}^0\pi^+)} = \frac{1}{2} tg^2\theta_c \times F \times PS \tag{40}$$

where PS denotes the relative phasespace factors and $F \neq 1$ measures $SU(3)_{FL}$ breaking.

· Maybe FSI or weak annihilation has not been included properly. Measuring

$$D^0 \to K^0\bar{K}^0,\ \pi^0\pi^0$$

while not an easy task would help greatly in disentangling these effects. One warning is in order here: contrary to some claims, weak annihilation can — despite the GIM mechanism — produce $D^0 \to K^0\bar{K}^0$ due to $SU(3)_{FL}$ breaking!

· Once the first two loopholes are closed one can turn one's attention to the most intriguing explanation for Eqs. (38, 39) – Penguin operators! For they contribute to both $D^0 \to K^+K^-$ and $D^0 \to \pi^+\pi^-$ with a positive sign while the usual charged currents contribute with a positive [negative] sign to $D^0 \to K^-K^+$ [$D^0 \to \pi^+\pi^-$]. Therefore even a suppressed (coherent) Penguin amplitude can have a significant impact.

2. Doubly Cabibbo Suppressed Decays.

There are (at least) two reasons why one wants to find and understand $\Delta S = -\Delta C$ transitions like

$$D^+ \to K^+\pi^+\pi^- \ . \tag{41}$$

- The neutral counterparts of Eq. (41) – $D^0 \to K^+\pi^-$, $K^+\pi^-\pi^0$ – form an important background to present searches for $D^0 - \bar{D}^0$ mixing.[13]
- Such transitions can exhibit a high sensitivity to New Physics in the form of charged Higgs fields. For Old Physics transitions get suppressed by $tg^4\theta_c \sim 2.3 \times 10^{-3}$ when going from $\Delta S = \Delta C$ to $\Delta S = -\Delta C$ processes; charged Higgs contributions on the other hand can get enhanced by $\sim (m_s/m_d)^2$. The signal to noise ratio thus improves by $(m_s/m_d)^2/tg^4\theta_c \sim 4 \times 10^4$!

3. Λ_c, etc., Decays.

It appears to be established now that

$$\frac{\tau(\Lambda_c)}{\tau(D^0)} \lesssim \frac{1}{2} \tag{42}$$

holds strongly suggesting that weak annihilation drives one full half of all Λ_c decays! While it is expected on rather general grounds that weak annihilation is more significant in Λ_c than in D^0 decays, I am somewhat surprised by its apparent prominence.

D. $V(cs), V(cd)$

The best numbers on these KM parameters at present

$$|V(cs)| = 0.95 \pm 0.15 \qquad |V(cd)| = 0.207 \pm 0.024 \tag{43}$$

are obtained from the di-muon signal in deep inelastic neutrino scattering. I am optimistic that in the foreseeable future more precise values can be extracted from $D \to \ell\nu K, K^*, \pi, \rho$.

III. The Decays of Beauty

Dedicated studies of beauty decays promise an extremely rich harvest: The a priori unknown parameters $V(cb), V(ub)$ can be extracted, $B^0 - \bar{B}^0$ mixing can be studied, rare decays and finally CP violation can be searched for.

This is all true in principle; in practice however a lot of very hard work of not necessarily the most lucid kind is required since it is the hadrons that decay, not the quarks. This is the issue I want to address.

A. $V(cb)$ in Semi-leptonic Decays.

Already anticipating that $|V(cb)|^2 >> |V(ub)|^2$ we can write down

$$\Gamma(B \to X) = f(V(cb)) \ .$$

The crucial question is what kind of function is involved here. No general answer to this question exists. Therefore we take recourse to a time-honored stop-gap measure. We employ different models of reasonable, though not always overwhelming integrity and hope that their differences in the output represent a good measure of the inherent uncertainties.

1. Quark Level Description.

The Spectator Ansatz leads to

$$\Gamma(B \to \ell\nu X) \simeq \Gamma(b \to \ell\nu c) = \frac{G_F^2 m_b^5}{192\pi^3} \, |V(cb)|^2 \, K\left(\frac{m_c^2}{m_b^2}\right) \tag{44}$$

$$K(x) = 1 - 8x + 8x^3 - x^4 - 12x^2 \log x \ . \tag{45}$$

From the data on τ_B one then deduces

$$|V(cb)|_{Sp} \simeq 0.045 \pm 0.008 \tag{46}$$

where the uncertainty reflects mainly our inability to make a unique choice for the quark masses m_b and m_c. It describes only the uncertainty *within* a single simple model, but not the theoretical uncertainty in general. Among other things one has assumed here implicitly $\tau(B^{\pm}) = \tau(B^0)$ – an equality that has been checked experimentally only within a factor of two.

2. Hadron Level Description.

Quite a few different model descriptions have been suggested in the literature. I will concentrate here only on two of these since they seem rather complementary to me. These are the descriptions provided by Grinstein, Isgur and Wise (=GIW)[14] and by Bauer, Stech and Wirbel (=BWS).[2]

There one finds

$$\Gamma(B \to \ell\nu\, D/D^*) \simeq \left\{ \begin{matrix} 0.58 \\ 0.30 \end{matrix} \right\} \times |V(cb)|^2 10^{14} \ sec^{-1} \quad \begin{matrix} \text{GIW} \\ \text{BSW} \end{matrix} \ . \tag{47}$$

In these models one expects, cum grano salis, these two final states to almost saturate the total semi-leptonic width

$$\Gamma(B \to \ell\nu\, D/D^*) \lesssim \Gamma(B \to \ell\nu X_c)\ .$$

Hence one extracts from the data

$$|V(cb) \simeq \begin{cases} 0.04\ \ \pm 0.01 & \text{GIW} \\ 0.053 \pm 0.01 & \text{BSW} \end{cases} \tag{48}$$

The exclusive modes can of course be calculated as well in such schemes:

$$\Gamma(B \to \ell\nu D^*) \simeq \begin{Bmatrix} 0.41 \\ 0.22 \end{Bmatrix} |V(cb))^2 \sec^{-1} \quad \begin{matrix} \text{GIW} \\ \text{BSW} \end{matrix} \tag{49}$$

From the recent ARGUS measurement[14]

$$BR(B^0 \to D^{*-}\ell^+\nu_\ell) = (7.0 \pm 1.2 \pm 1.9)\% \tag{50}$$

one concludes

$$|V(cb)| \simeq \begin{cases} 0.040 \pm 0.007 \\ 0.055 \pm 0.01 \end{cases} \tag{51}$$

in pleasantly good agreement with Eq. (48). By the way, this is one major reason why I find it hard to believe that the same models could fail by a factor two to three in $D \to \ell\nu K^*$ vs. $\ell\nu K$. Putting everything together one obtains

$$|V(cb)| \simeq \begin{cases} 0.040 \pm 0.007 & \text{GIW} \\ 0.045 \pm 0.008 & \text{quark level} \\ 0.055 \pm 0.01 & \text{BSW} \end{cases} \tag{52}$$

The models thus exhibit a roughly 20% internal uncertainty by themselves. Yet the real message of Eq. (52) is that the true overall uncertainty is much larger, namely

$$|V(cb)| \sim 0.033 - 0.065 \tag{53}$$

i.e., a factor of two – despite the more optimistic PDG claims! I sincerely hope that PDG will state a more realistic evaluation of the uncertainties in their next report. Eq. (52) also shows that the duality concept as implemented by Eq. (44) is not failing – after all $|V(cb)| = 0.045 \pm 0.008$ is consistent with both the GIW and BSW value – yet it does not provide us with a surgical tool either. One should also note that so far nobody has presented a proof why Eq. (44) should work better and better for increasing m_b.

B. $V(ub)$ in Semi-leptonic Decays.

Two methods have been used to distinguish $b \to u$ from $b \to c$ transitions.

1. One tries to exploit kinematical differences as exemplified by $m_c > m_u$. No clear signal has been found by CLEO or ARGUS. A great deal of model uncertainty enters when one translates this into a limit on $V(ub)$:

$$\left|\frac{V(ub)}{V(cb)}\right| \lesssim 0.1 - 0.2 \ . \tag{54}$$

2. One attempts to identify the hadronic final state. CLEO has searched for $B^+ \to \ell^+ \nu_\ell \rho^0$ and found no signal. Hence one concludes

$$|V(ub)| \lesssim \begin{cases} 0.0082 & \text{GIW} \\ 0.0068 & \text{BSW} \ . \end{cases} \tag{55}$$

It is tempting, though less than rigorous, to relate this to the ARGUS findings on $B \to \ell\nu D^*$. Since

$$\frac{\Gamma(B^+ \to \rho^0 \ell^+ \nu)}{\Gamma(B^0 \to D^{*-} \ell^+ \nu)} \simeq \begin{Bmatrix} 0.39 \\ 1.2 \end{Bmatrix} \times \left| \frac{V(ub)}{V(cb)} \right|^2 \qquad \begin{matrix} \mathrm{GIW} \\ \mathrm{BSW} \end{matrix} \tag{56}$$

one obtains

$$\left| \frac{V(bu)}{V(cb)} \right| \lesssim \begin{cases} 0.19 & \mathrm{GIW} \\ 0.11 & \mathrm{BSW} \ . \end{cases} \tag{57}$$

quite consistent with Eq. (54).

One important caveat is in order here: At our present level of understanding (or limitation thereof) one has to exhibit "brand name loyalty," i.e., stay within **one** hadronization scheme (GIW or BSW, etc.) when quoting numbers on the KM parameters. For otherwise one can fall into the following trap: combining $|V(cb)| \lesssim 0.07$ as obtained from BSW with the GIW bound $|V(ub)| \lesssim 0.2$ leads to $|V(ub)| \lesssim 0.014$. While this value might happen to be correct, its derivation was inconsistent as shown by Eq. (55).

C. Non-leptonic Decays and the Impact of Strong Interactions.

As in D decays, it is useful to distinguish between class I, II, and III transitions. In the following table, I list BSW predictions for some typical modes together with present experimental numbers:

Mode	$BR[\%]\, BSW$	$BR[\%]\, EXP.$
$Class\ I\ :\ a_1$		
$\bar{B}^0 \to D^+\pi^-$	$0.5\ \left\|\frac{V(cb)}{0.05}\right\|^2$	0.59 ± 0.3
$\bar{B}^0 \to D^{+*}\pi^-$	$0.45\ \left\|\frac{V(cb)}{0.05}\right\|^2$	$0.35 \pm 0.13 \pm 0.13$
$\bar{B}^0 \to D^{*+}\pi^-\pi^0$	$1.4\ \left\|\frac{V(cb)}{0.05}\right\|^2$	$2.0 \pm 1.1 \pm 1.1$
	$if\ \pi^-\pi^0 = \rho^-$	
$Class\ II\ :\ a_2;\ \xi = 0$		
$B^0 \to \psi K^{0*}$	$0.25\ \left\|\frac{V(cb)}{0.05}\right\|^2$	0.33 ± 0.18
$Class\ III\ :\ a_1, a_2,\ \xi = 0$		
$B^- \to D^0\pi^-$	$0.4\ \left\|\frac{V(cb)}{0.05}\right\|^2$	$0.47 \pm 0.15 \pm 0.10$

Considering the rather limited experimental information one cannot draw firm conclusions from this juxtaposition. Yet the following tentative statements are suggested:

- We appear to be off to a good start in describing non-leptonic B decays consistently with $|V(cb)| \sim 0.05$.
- $\xi \cong 0$ is strongly favored — like in D decays, despite the vast differences in kinematics, prominence of FSI, etc.
- Relatively little negative interference occurs in the two-body modes of B^- decays.

Since two-body modes do not dominate non-leptonic B decays as they do with D decays, I estimate

$$1 \lesssim \frac{\tau(B^+)}{\tau(B^0)} \lesssim 1.2 \ . \tag{58}$$

Extrapolating from $\tau(D^+)/\tau(D^0)$, I expect weak annihilation to be fairly unimportant in $\Gamma(B)$: $\tau(B^0)$ should not be shortened by more than $\sim 10\%$. However not everybody agrees with this expectation and in any case it has to be checked experimentally.

D. Baryonic Decays of B Decays.

Beauty mesons are sufficiently heavy to allow decays into a baryon-antibaryon pair possibly together with other mesons. Furthermore the weak decay produces already two quarks and two antiquarks

$$b\bar{q} \rightarrow cd\bar{u}\bar{q} \ .$$

Thus only one more $q\bar{q}$ pair has to be created from the vacuum to form a baryon-antibaryon pair and such baryonic decays should not be particularly suppressed. The drawback is that it poses a non-trivial problem to make these statements more quantitative.

Two prescriptions have been put forward to predict the inclusive baryonic branching ratio: both use di-quark production as a starting point although they treat it in a different manner. The results are[15]

$$BR(B \rightarrow \Lambda_c + X) = \begin{cases} 8 \pm 4\,\% & \text{Ref. } \ 15 \\ > 2\%\,, \sim 6\% & \text{Ref. } \ 6 \end{cases} \tag{59}$$

in fine agreement with the CLEO findings

$$BR(B \to \Lambda_c + X) = (7.4 \pm 2.9)\% \ . \tag{60}$$

That is nice, but so what – these prescriptions are still semi-quantitative at best.

Firstly, $\frac{1}{N}$ arguments can be invoked to improve the theoretical underpinning of the arguments sketched above. Secondly, data on exclusive baryonic modes would help tremendously to refine these concepts. Thirdly, the very new ARGUS data on charmless B decays force this issue upon us

$$\begin{aligned} BR(B^+ \to p\bar{p}\pi^+) &= (3.7 \pm 1.3 \pm 1.4) \times 10^{-4} \\ BR(B^0 \to p\bar{p}\pi^+\pi^-) &= (6.0 \pm 2.0 \pm 2.2) \times 10^{-4} \end{aligned} \tag{61}$$

compared to the upper limits obtained by CLEO

$$BR(B^0 \to \pi^+\pi^-) \, , \quad BR(B^0 \to p\bar{p}) \leq 2 \times 10^{-4} \ . \tag{62}$$

Since Penguin transitions can be ruled out rather conclusively as the origin of Eq. (61), these data, if confirmed, establish

$$|V(ub)| \neq 0 \ .$$

Alas, only guestimates are at present available to relate Eq. (61) to a more specific statement. The arguments can typically be phrased as follows

$$\Gamma(b \to u) = A_u \cdot B_u \cdot C_u \cdot \Gamma(B^0 \to p\bar{p}\pi^+\pi^-) \tag{63}$$

with

$$C = \frac{\Gamma(B \to N\bar{N}\pi\pi)}{\Gamma(B^0 \to p\bar{p}\pi^+\pi^-)}\,, \qquad B = \frac{\Gamma(B \to N\bar{N} + X)}{\Gamma(B \to N\bar{N}\pi\pi)}$$
$$A = \frac{\Gamma(b \to u)}{\Gamma(B \to N\bar{N}X)}\ . \tag{64}$$

Just counting the number of available states one arrives at order of magnitude estimates

$$C_u \sim 4\,, \qquad B_u \sim 5 - 10\ . \tag{65}$$

B_u is modelled after baryonic decays of the J/ψ.[16]

A_u is equated with the corresponding number in $b \to c$ transitions, Eq. (60):

$$A_u \sim A_c \sim 10\ . \tag{66}$$

Then one obtains $|V(ub)/V(cb)| \sim 0.3$. Making "reasonable" variations in our assumptions one arrives at a rather wide range[17]

$$\left|\frac{V(ub)}{V(cb)}\right| \sim 0.1 - 0.4\ . \tag{67}$$

This strongly suggests – though does not prove conclusively – that $|V(ub)/V(cb)|$ would be as large as it is still (barely) compatible with the analysis of semi-leptonic decays.

$$\left| \frac{V(ub)}{V(cb)} \right| \sim 0.2 - 0.25 \ . \tag{68}$$

I had emphasized before that in a state-of-the-art discussion of $|V(ub)/V(cb)|$ one has to specify the hadronization scheme adopted. I have refrained from doing so in Eq. (68) basically because there is no well-developed such scheme yet for baryonic B decays. All the parameters A, B, C are rather uncertain.

1. Naive di-quark pictures tend to yield $A_u \leq A_c$; $\frac{1}{N}$ arguments lead to $A_u \sim A_c$ and there is no conclusive argument against $A_u > A_c$ even.

2. Resonance effects clearly affect B_u, C_u in a very significant way.

ARGUS observes a low mass enhancement in the $p\pi$ spectra in Eq. (61) which appears consistent with $\Delta \to p\pi$. This raises some highly intriguing questions.

1. It is virtually impossible that a significant part of $B^0 \to p\bar{p}\pi^+\pi^-$ is fed from $B^0 \to \Delta\bar{\Delta}$ modes.

   $BR(\Delta^0 \to p\pi^-) = \frac{1}{3}$; furthermore it is almost unavoidable that

$$B^0 \not\to \Delta^{++}\overline{\Delta^{++}}, \quad \Delta^-\overline{\Delta^-} \ . \tag{69}$$

   Therefore

$$BR(B^0 \to \Delta\bar{\Delta}) \simeq 2BR(B^0 \to \Delta^0\bar{\Delta}^0) = 18BR(B^0 \to p\bar{p}\pi^+\pi^-) \tag{70}$$

   i.e., unacceptably huge!

- There are further dynamical isospin selection rules suppressing $B \to \Delta\bar{\Delta}$. The (valence part of the) baryonic wavefunction is antisymmetric in color space. (This was the original motivation for introducing color.) Therefore it is only the (somewhat enhanced) Fierz antisymmetric operator 0_- that contributes here:

$$b \xrightarrow[0_-]{} ud\bar{u} \ . \tag{71}$$

The ud pair is then in a isosinglet state and only $I = \frac{1}{2}$ baryons can be generated from this vertex (in a one-step process):[16,17]

$$B = (\bar{b}q) \to \bar{N}\Delta \, , \bar{N}\Delta\pi's \tag{72}$$

- The two-body modes $B \to \Delta\bar{\Delta}$ are – as usual – suppressed in amplitude by a form factor, $F(q^2)$

$$F(q^2) \propto \left(1 + \frac{M^2}{q^2}\right)^{-n} \ . \tag{73}$$

Applying the QCD counting rules of Brodsky and Lepage, one arrives actually at $n \simeq 2$, i.e., a **dipole** (instead of monopole) form factor since the exchange of **two** hard momenta is required to produce $B \to$ baryon-antibaryon. Such a highly effective suppression can be balanced only by maximizing the mass-like parameter M. This leads to the very general expectation

$$\Gamma(B \to \widetilde{N}\bar{N}) \gg \Gamma(B \to \Delta\bar{\Delta}) \tag{74}$$

with

$$\widetilde{N} \to \Delta\pi \ . \tag{75}$$

2. A related selection rule can be stated for B^+ decays

$$\Gamma(B^+ \to \Delta^{++}\bar{p}) \gg \Gamma(B^+ \to p\bar{\Delta}^0) \tag{76}$$

which is further strengthened by $BR(\Delta^{++} \to p\pi^+) = 1$, $BR(\Delta^0 \to p\pi^-) = \frac{1}{3}$.

In all of this we should keep in mind that the apparent low-mass enhancement might not be a bona fide Δ resonance!

More theoretical work is necessary – and proceeding at different places.[19] But I have to add that further experimental input is of crucial importance for making progress:

(a) Check the selection rules (Eq. 72, 74, 75).

(b) Find or limit $B^+ \to p\bar{p}\pi^+\pi^-\pi^+$.

(c) Strife to identify final states containing a π^0.

(d) Find **exclusive** modes containing charm baryons like $B \to \Lambda_c\bar{N}\pi$ for (theoretical) calibration purposes.

IV. Summary

A. The Presence.

Over the last few years we have developed a rather decent understanding of charm decays — one that is better than for strange decays. This development has been made possible by the coincidence of three factors:

1. Nature has decided on a fairly undramatic dynamical pattern underlying charm decays. There is no striking feature like the $\Delta I = \frac{1}{2}$ rule.
2. There have been good, comprehensive data - the "MARK III legacy."[20]
3. Close feed-backs between experimentalists and theorists had developed.

Yet the success of our theoretical description has not been firmly established, improved data could reveal grave deficiencies.

Beauty physics on the other hand is still in its adolescent phase, characterized more by promise than completed achievement: We have started to draw a rough sketch of the overall picture and to extract the KM parameters.

B. The Future.

In charm decays

1. Important cross checks have to be performed, namely
   (a) Study $D^{+,0} \to VV$ transitions,
   (b) Determine absolute D_s branching ratios and find more of them.
   (c) Do the same for charm baryons.

2. We have to reach a higher level of sophistication in once and twice Cabibbo suppressed decays.

3. All of this should eventually lead to a more precise determination of $V(cs), V(cd)$.

In beauty decays we have to

1. Continue to map out B decays and start on the B_s,

2. Compare $\tau(B^{\pm})$ vs. $\tau(B_d)$ vs. $\tau(B_s)$, and

3. Develop a better understanding of baryonic decay modes.

Attaining these goals will enable us

1. To interpret $B^0 - \bar{B}^0$ mixing with rigor rather than just vigor, and

2. Analyse rare decays and CP violation with considerable more confidence.

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