B DECAYS, AN INTRODUCTORY SURVEY.

A. Le Yaouanc, L Oliver, O.Pène, J.-C. Raynal
LPTHE, F 91405 Orsay, France,[1]

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Presented by O. Pène.

Abstract

To start the b-decay session we briefly introduce and comment some
important theoretical tools which are currently used in b physics. Heavy
Quark Symmetry and its consequences for heavy to heavy and heavy to
light semi-leptonic decays, as well as for leptonic decays, are briefly sum-
marised. It is stressed that symmetry must be completed with dynamical
calculations. A critical discussion of the nearest pole dominance (VMD)
assumption is performed. Parton model and its higher twist corrections
are discussed on the example of lifetimes. Finally non-leptonic decays are
considered via the example of the exclusive calculation of $\Delta\Gamma$ in the $B_s - \overline{B}_s$
system. The popular factorization assumption is discussed and seems to
be rather good.

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1 What is so exciting about beauty?

This talk should be taken as a short introduction to the following ones on beauty decay. Beauty physics has become one of the most active fields. It would be difficult to quote one large experimental device able to produce b's which is not making of the study of b decays one of its priority. Several thousand physicists are actively engaged in this field. What is the reason for this growing enthusiasm? Let us try some answers.

Beauty is heavy, while charm is not so heavy and top will not produce hadrons. This implies several theoretical niceties: Heavy Quark Symmetries, validity of parton model, etc. It also implies that there are many final states and hence a rich phenomenology.

Beauty is rather stable. The coupling of the third generation to the other two turns out to be rather small, $(O(\lambda^2))$ in Wolfenstein's parameterization. This lucky feature raises serious hopes that CP violation may be measured in B decay. In fact, a long standing intimacy has existed between beauty and CP violation, since the third generation was postulated by Kobayashi and Maskawa because their mechanism for CP violation needed it. But CP violation is out of the scope of this talk and we shall leave it aside, after having reminded you that it is presumably the main reason of the widely spread enthousiam for B physics.

The worst known CKM parameters concern the third generation: V_{ub}, $\sin\delta$, .. We need these parameters, for the sake of SM itself, and hopefully to learn something unexpected beyond it.

2 Main Theoretical tools for b decays.

We will restrict ourselves to heavy-light hadrons: $Q\bar{q}$ mesons and Qqq' baryons where Q represents any heavy quark and q, q' any light quark. Let us make a list of the main concepts, principles, rigourous methods, models, etc. that are commonly used:

- Heavy Quark Symmetry

- Duality and Parton Model

- Lattice QCD

- QCD Sum Rules

- Quark Models

- Analiticity, Vector Meson Dominance,...

- Factorization assumption for non-leptonic decays.

We will try to say a few words on these items, except for lattice calculations that will be considered later by Asmaa Abada [1] and QCD sum rules on which Stephan Narison will give a review. For lack of time we will also skip quark models

although they are able to give a precious physical insight. Recent analyses of the latter may be found in [3].

3   Heavy Quark Symmetry (HQS)

It is strange that the HQS has only been understood recently, although it is a direct consequence of QCD. It was anticipated by some works in the late eighties and fully emphasized only four years ago. It is impossible to quote but a few among the huge number of publications it has triggered in such a short period: [5]-[7]. Although you must all have heard of HQS, it is unavoidable to say some words about it.

The basic idea may be explained through the "atomic picture": Up to small corrections, the properties of an atom depend only on the electric charge of the nucleus (the atomic number), not of its atomic mass. This is because the nucleus is so heavy vz the electron that it is practically at rest in the center of mass of the atom, and it acts as a static electric charge. Mutatis mutandis, this happens when a heavy quark is bound with a light quark. Up to $O(1/m_Q)$ corrections, the heavy quark acts as a triplet static source of color.

In other words, let us write the heavy quark momentum as $p^\mu = m_Q v^\mu + k^\mu$ where m_Q is the heavy quark mass, v_μ is the hadron four velocity (momentum divided by the mass), and k_μ is a momentum that represents the effect of the wave function, and it is of the order of the QCD scale, remaining constant when $m_Q \to \infty$.

$$\frac{i m_Q \not{p} + \not{k}}{(m_Q v + k)^2 - m_Q^2} \simeq \frac{i \not{p} + 1}{2 v \cdot k} \tag{1}$$

where the $\simeq$ symbol here means up to $O(1/m_Q)$ corrections. Flavor symmetry is obvious since no dependence on the heavy mass is left. Let us now assume many soft gluons emitted from the heavy line:

$$\bar{u}(s,v) \frac{i\not{p}+1}{2} it_a \gamma^\mu \frac{i\not{p}+1}{2} it_b \gamma^\nu \frac{i\not{p}+1}{2} \dots =$$
$$\bar{u}(s,v) \frac{i\not{p}+1}{2} t_a t_b \dots v^\mu v^\nu \dots$$

No dependence on the heavy quark spin is left, and we end up with a $SU(2N_F)_v$ symmetry where N_F is number of heavy flavors. One should notice however that the symmetry acts inside a sector corresponding to one heavy hadron velocity. This is the meaning of the index v.

4   Scaling laws and symmetry relations in the heavy quark limit.

We turn to the phenomenological consequences of HQS on leptonic decays, heavy to heavy semi-leptonic decays and finally heavy to light semi-leptonic decays. Although the second one is the best known, the other two are also very useful for phenomenology. In all this section we will neglect anomalous dimensions.

4.1 Scaling laws for letponic decay constants: $B, D \to l\nu$

Let us simply state the result [5]. The leptonic decay constant of a heavy pseudoscalar meson P composed of a heavy quark Q and a light one $\bar{q}$ scales like

$$F_P M_P^{1/2} \underset{m_Q \to \infty}{\longrightarrow} \text{contant} + O(\frac{1}{M_P}) \tag{2}$$

and, of course $M_P \simeq m_Q$. The same is true for a vector meson with the same constant. But the symmetry does not tell us:

How much is the constant?

How large are the $1/M_P$ corrections? what is their sign?

For the answer we need to ask Lattice QCD and QCD sum rules [1],[2]. These two methods yield the same result: the $1/m_Q$ are such as *to soften the* $1/\sqrt{M_P}$ *decrease of* F_P as a function of M_P. In practice, the predictions for F_B are not very different from those for F_D while scaling rules without corrections would predict $F_B/F_D \simeq 0.6$.

4.2 Scaling laws for Semi-leptonic decay $B \to Dl\nu$

$$< D(v')|V_\mu|B(v) > \underset{m_Q \to \infty}{\longrightarrow} \sqrt{M_B M_D} \, \xi(v \cdot v')(v + v')_\mu$$

$$< D^*(v')|V_\mu|B(v) > \underset{m_Q \to \infty}{\longrightarrow} \sqrt{M_B M_D} \, \xi(v \cdot v')\epsilon_{\mu\nu\alpha\beta}\epsilon^{*\nu}v'^\alpha v^\beta$$

$$< D^*(v')|A_\mu|B(v) > \underset{m_Q \to \infty}{\longrightarrow} \sqrt{M_B M_D} \, \xi(v \cdot v')(v \cdot v' + 1 - \epsilon^* \cdot v v'_\mu) \tag{3}$$

where $\xi(v.v')$ is the celebrated Isgur-Wise function [7], with $\xi(1) = 1$ (corresponding to $v' = v$). But:

$\xi(y)$ is unknown for $y \neq 1$

How large are the $)(1/m_Q)$ corrections?

This scaling law has already proven to be very useful for phenomenology. Neubert [8] has proposed a direct use of the relations (3) and of the normalization $\xi(1) = 1$ to measure $|V_{cb}|$ from $B \to D^*l\nu$. Using this method CLEO [9] obtains $|V_{cb}| = 0.037 \pm 0.005 \pm 0.004$.

4.3 Scaling laws for Semi-leptonic decay $B \to K(^*), \pi, \rho l\nu$

In the rest frame of the initial (heavy) meson [6]:

$$\frac{< K(^*), \vec{p}|J_\mu|B >}{\sqrt{M_B}} \simeq \frac{< K(^*), \vec{p}|J_\mu|D >}{\sqrt{M_D}}$$

if

$$|\vec{p}|, M_K, M_{K^*} \ll M_D, M_B$$

Notice that small $|\vec{p}|$ means $q^2 \sim q_{max}^2$. Once again,
the symmetry provides a relation between matrix elements, but not their values neither the size and sign of the corrections.

Lattice QCD [1] gives a preliminary answer: for A_1 and V the corrections tends to soften the M_P dependence of the dominant term (similarly to the case of F_P), A_2 presents the opposite trend but with large errors, and f_+ is close to the uncorrected scaling. A phenomenological analysis [3] of $B \to \Psi K^*$ tends to confirm the general trend of a "soft" scaling which can be understood very simply in the quark models [3], [4].

5 q^2 dependence of form factors : Beware of Vector Meson Dominance !

Little is known about the q^2 dependence of the form factors (q^2 is the invariant squared mass of the final leptons). The scaling laws described in section 4.2 predict only the q^2 dependence of the *ratio* between different heavy to heavy form factors. But this limited piece of information is missing in the case of heavy to light form factors. There is a wide-spread belief that the nearest pole dominance should not be a bad approximation, i.e.

$$F(q^2) \propto \frac{1}{q^2 - M_{B'}^2} \tag{4}$$

where we call B' the lightest state which has the quantum numbers exchanged in the t channel, for example $B^*, B^{**}, \ldots$. If we consider, say, $B \to \pi l \nu$, the physical region corresponds to $0 \le q^2 \le q_{max}^2 = (M_B - M_\pi)^2 < M_{B'}^2$. Pole dominance is valid only in the vicinity of the pole. It may be valid near q_{max}^2 when the pole is not too far away, but it is certainly not valid in the whole range. Many other poles, cuts, etc contribute. If lattice estimates [1] seem to favor form factors that increase with q^2 near q_{max}^2, QCD sum rules seem to indicate no pole dominance for axial form factors[10], and a phenomenological analysis of $B \to \Psi K^*$ [3] also seems to discard pole dominance in favor of a differentiated behaviour for the various form factors. A weak binding relativistic quark model predicts A_1 to be flatter than f_+ [3], [4].

6 Duality and parton model, life times.

6.1 Plain parton model.

Parton model assumes that the total width $\Gamma(B \to \text{everything}) \simeq \gamma(b \to cq\bar{q}, cl\bar{\nu})$. It is based on the idea that the spectator quark plays no role because the final quarks are hard. Plain parton model then predicts

$$\tau_{B^0} = \tau_{B^-} = \tau_{\Lambda_b}$$

as it would predict $\tau_{D^0} = \tau_{D^+} = \tau_{\Lambda_c}$ if charm was assumed to be heavy. The latter assumption is in total contradiction with present experimental values:

$$\tau_{D^0} = 4.20 \pm 0.08\, 10^{-13}s, \quad \tau_{D^+} = 10.66 \pm 0.23\, 10^{-13}s, \quad \tau_{\Lambda_c} = 1.91\,^{+0.15}_{-0.12} 10^{-13}s$$

and $\tau_{\Xi_c} = 3.20\,^{+0.9}_{-0.8} 10^{-13}s$ [11]. We see that charm cannot be considered as heavy under this respect.

What about beauty? The present situation [12] is:

$$\frac{\tau_{B^-}}{\tau_{B^0}} = 1.14 \pm 0.15, \quad \frac{\tau_{B_s}}{\tau_{B^0}} = 1.11 \pm 0.18, \quad \frac{\tau_{\Lambda_b}}{\tau_{B^0}} = 0.75 \pm 0.12. \qquad (5)$$

This looks much better than for the charm, but $\tau_{\Lambda_b}/\tau_{B^0}$ is two sigmas away from the uncorrected parton model prediction.

6.2 How to compute the corrections to parton model?

A recent series of papers [13] propose a generalization of parton model:

$$\Gamma(H_Q \to X) \propto G_F^3 < H_Q |Im\hat{T}(Q \to X \to Q)|H_Q > \qquad (6)$$

is expanded into matrix elements of the operators $v_\mu \overline{Q}\gamma^\mu Q$, $\quad \overline{Q}(D^2 - (v \cdot D)^2)Q$, $\overline{Q}\sigma^{\mu\nu}G_{\mu\nu}Q$, $\quad \overline{Q}\Gamma q\bar{q}\Gamma Q$, etc.

The first operator, $\overline{Q}\not{v}Q$, of dimension three, gives the parton model. Next, there are no $1/m_Q$ corrections.

The $O(1/m_Q^2)$ **corrections** are generated by the dimension five operators. The $\overline{Q}(D^2 - (v \cdot D)^2)Q$ corresponds to the Fermi motion. The $\overline{Q}\sigma^{\mu\nu}G_{\mu\nu}Q$ matrix element is known from hyperfine splitting between meson masses. These dimension five operators do not split the meson life-time degeneracy. To $O(1/m_Q^2)$

$$\tau_{\Lambda_b} \neq \tau_{B^0} = \tau_{B^+} \Rightarrow \frac{\tau_{\Lambda_b} - \tau_{B^0}}{\tau_{\Lambda_c} - \tau_{D^0}} \simeq \frac{m_c^2}{m_b^2}. \qquad (7)$$

It is gratifying that experiment seems to confirm that $|\tau_{\Lambda_b} - \tau_{B^0}| > |\tau_{B^+} - \tau_{B^0}|$. However it is still unclear if this model can account for such a small $\tau_{\Lambda_b}/\tau_{B^0}$ ratio as 0.75.

The most interesting $O(1/m_Q^3)$ **operator** is $\overline{Q}\Gamma q\bar{q}\Gamma Q$ since it produces the first non-spectator effect (the light quark fields can act on the spectator quarks). It results:

$$\frac{\tau_{B^+} - \tau_{B^0}}{\tau_{D^+} - \tau_{D^0}} \simeq \frac{m_c^3}{m_b^3} \qquad (8)$$

Finally, this approach is new and still under discussion, however it has several nice features and certainly deserves further work.

7 Non-leptonic decays and factorization assumption

7.1 Some general remarks.

Non leptonic decays represent the dominant decay channels of the B's. But there exists no exact method to deal with them. One usually resorts to the factorization assumption which allows to express two body non leptonic decays as a product of a semi-leptonic amplitude and a purely leptonic one. It neglects the soft-gluon exchange between the two parts of the diagram. It is only valid when $N_c \to \infty$, but in B physics it often appears to be a reasonable approximation

with phenomenological coefficients, a_1, a_2, multiplying both relevant four quark operators. CLEO [14] has carefully checked factorization for N_c dominant decays, and the success of factorization seems to extend to their fit of the a_2/a_1 ratio which is $O(1/N_c)$.

There is an overwhelming number of studies of non-leptonic decays. We will give a recent example [15] noticeable, in the realm of non-leptonic decays, by the fact that a calculation of phenomenological interst turns out to be unexpectedly under control.

7.2 An example: exclusive computation of $\Delta\Gamma$ in $B_s - \overline{B}_s$

The $B_s - \overline{B}_s$ system has $\Delta M/\Gamma \gg 1$, which makes it difficult to measure [16] the too fast oscillations $\sim \sin(\Delta M t)$. What about $\Delta\Gamma$? Is $\Delta\Gamma/\Gamma$ large enough to allow it to be seen and used?[2]

Inclusive parton model calculations [17] give: $\Delta\Gamma/\Gamma \simeq 0.20$. The question is, what are the effects of the lightest exclusive channels? Should they be added to parton model contribution? Are they dual to it? The analysis [15] leads to the following conclusions:

- The dominant decay channels are $D_s\overline{D}_s$, $D_s^*\overline{D}_s$, $D_s\overline{D_s^*}$, $D_s^*\overline{D_s^*}$.
- These channel contribute mainly with the same sign to $\Delta\Gamma$. Their contribution is known in a model independent way from experimental [18] $B_d \to D_s^{(*)}\overline{D^{(*)}}$ branching ratios.
- Factorization is a reasonable assumption in this case.
- Exclusive and inclusive calculations are dual: they are not to be added, they should approximately agree, and they do !
- $\Delta\Gamma/\Gamma \simeq 0.15$

This is maybe the largest lifetime difference among the B's, and it is measurable [19] !

8   Conclusions

- Heavy Quark Symetry is a simple and powerful consequence of QCD. But it needs to be completed by dynamical computations of universal constants, universal functions, and $1/m_Q$ corrections.

- There are several instances where the $1/m_Q$ corrections tend to soften the dependence on the heavy mass indicated by the dominant term.

- The corrections to parton model for inclusive processes may be understood via a systematic expansion in higher dimension operators.

- Lattice QCD predicts leptonic decays and semi-leptonic ones (for not too large momenta).

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[2]Remember how useful has been, in the $K - \overline{K}$ system, the fact that $\Gamma(K_S) \gg \Gamma(K_L)$ and hence the fact that only K_L's fly a few meters before decaying.

- The q^2 dependence of the form factors is still largely unknown. Nearest pole dominance has no theoretical grounding and there are indications of other behaviours. QCD sum rules may help in this problem.

- Non-leptonic decays are tractable, using the factorization assumption which seems not too bad. Improvement needs an understanding of the corrections to it, and of duality.

Acknowledgments :

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