SLAC-PUB-9009
November 2001

Testing Factorization [1]

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Abstract. We briefly review the status of factorization in b-decays. We discuss several experimental tests of its nature and stress their importance. We show that decays into mesons which have small decay constants or spin greater than one ('designer mesons') offer a variety of new opportunities.

INTRODUCTION

Major theory issues in b-physics are 1) Is the CKM description of CP violation correct or are there other sources of CP violation ? and 2) Is the Standard Model the correct effective theory up scales of order ~ 1 TeV ? The latter could be probed for example with Flavor-changing-neutral current (FCNC) decays such as $b \to s\gamma$, $b \to s\ell^+\ell^-$ and $b \to sq\bar{q}$. Both questions can be addressed in b-physics in a unique way, which has stimulated many experimental and theoretical activities. However, there is another one 3) Is our understanding of non-perturbative QCD good enough to answer the above questions ? which is part of the whole picture. Among effects due to hadronization, those related to the factorization of matrix elements of hadronic 2-body decays are of peak importance. Their understanding and knowledge of the limitations in their theoretical description will become more urgent in the near future since the 'QCD background' limits the potential of precision tests of the Standard Model. Fortunately, there are many decay modes, observables and facilities where this can be further explored and checked.

FACTORIZATION CONCEPT

Naive factorization is a working hypothesis [1], which allows one to express the matrix elements of hadronic 2-body decays in terms of known objects, with the product (decay constant $\times$ form factor). Diagrammatically, it amounts to cutting the amplitude across the W-boson line and resembles the description of semileptonic decays. The picture of color transparency (CT) [2] justifies this for some decays when the meson emitted

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[1] Invited Talk at the 9th International Symposium on Heavy Flavor Physics, Caltech, Pasadena, September 10-13, 2001.

[2] Work supported by the Department of Energy, Contract DE-AC03-76SF00515

from the weak vertex is fast in the rest frame of the decaying parent. An example is $\bar{B}_0 \to D^+\pi^-$. The CT explanation however must fail e.g. for $\bar{B}_0 \to D^-\pi^+$. If $1/N_c$ counting arguments [3] are at work, then factorization would still hold here. There exist no general theory for all 2-body decays, but they have been classified into color allowed, suppressed, heavy-light, etc. QCD based approaches [4, 5] differ in their treatment of α_s and $1/m_b$ power corrections. Thus it is important to test experimentally where (naive) factorization holds and where corrections arise to understand its dynamical origin (CT, $1/N_c$, ...).

status

Factorization has been tested with tree level dominated modes, i.e. where possible New Physics effects are tiny. Currently, the factorization concept in color allowed B-decays rules:

- Heavy-to-light $\bar{B}_0 \to D^{(*)+}(\pi,\rho,a_1)^-$ decays can be described by one universal coefficient $|a_1| = 1.1 \pm 0.1$, see e.g. [4]; factorization is ok up to the $O(10\%)$ level.
- In $\bar{B}_0 \to D^{(*)+}X^-$ decays, where $X = 4\pi, \omega\pi$ the factorization hypothesis can be tested as a function of the hadronic mass m_X of the emitted $n\pi$ state [6]. Its 'decay constant' $\langle X|\bar{d}\Gamma u|0\rangle$ is obtained from hadronic τ-data. CT holds if X is fast, so one expects corrections to factorization for growing m_X, but no kinematical dependence in the $1/N_c$ approach. Current data indicate no factorization breaking but further experimental studies should be pursued.
- In $\bar{B}_0 \to D^-_{(s)}\pi^+$ decays there is no CT explanation of factorization. The factorizable amplitude is proportional to $A_{fac} \sim V_{ub}F^{B\to\pi}(m^2_{D(s)})\, f_{D_s}$ and quantitative tests need good control over all parameters on the r.h.s. Experimentally, to date an upper bound exists, $B(\bar{B}_0 \to D_s^-\pi^+) < 1.1 \cdot 10^{-4}$ @90% C.L. [7] which is ok with factorization.
- In heavy-to-heavy $B \to D^{(*)}D_s^{(*)}$ decays factorization holds within errors [8]; confirmed by study including penguins [9]. The dominant uncertainty in these analyses comes from the decay constants, e.g. $f_{D_s} = 280 \pm 48$ MeV from $D_s \to \mu\nu_\mu$ [10].

Significant improvement in precision is required to isolate factorization breaking effects in the above decays. Alternatively, one can study factorization in those decays, where the corrections to factorization are not hidden behind a large factorizable contribution [11, 12]. Then less precision is required, although for the price of less events.

NEW WAYS

Recently, it has been proposed to explore factorization with final states whose coupling to the W-boson is suppressed either because the spin > 1 or the decay constant is suppressed [11]. Examples of such 'designer mesons' are given in Table 1. The relevant property in the context of factorization tests is that amplitudes in *naive* factorization are

TABLE 1. Examples of ‘designer’ mesons.

X	a_0	b_1	π	a_2	a_0	π_2	ρ_3	χ_{c0}	K_0^*	K_2^*	D_2^*
m_X [MeV]	985	1230	1300	1318	1474	1670	1691	3415	1412	1426	2459
J^{PC}	0^{++}	1^{+-}	0^{-+}	2^{++}	0^{++}	2^{-+}	3^{--}	0^{++}	0^{+}	2^{+}	2^{+}

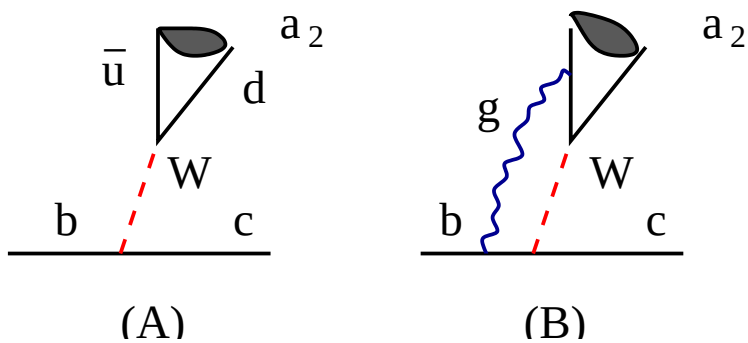

FIGURE 1. Examples of a diagram which does not (A) and does (B) contribute to $b \to c a_2^-$.

suppressed. In the case of a vanishing decay constant, they even vanish e.g. $B_{naive}(\bar{B}_0 \to D^+ a_2^-) = 0$, see Fig. 1 (A). However, corrections e.g. induced by hard gluon exchange, see Fig. 1 (B) circumvent suppression, because the a_2^- is now produced from a non-local vertex, which allows for higher spins. Other mechanisms that avoid the suppression include annihilation topologies, interactions with the spectator and those induced by charm [13]. Thus non-factorizable effects can be highlighted by the choice of specific ‘designer’ final states.

decay constants

Decay constants for scalars S with momentum p are defined as $\langle S(p)|\bar{q}\gamma_\mu q'|0\rangle = -i f_S p^\mu$. For $q = q'$ the decay constant vanishes by charge conjugation e.g. $f_{a_0^0}, f_{\chi_{c0}} = 0$. The decay constant of the charged a_0 is proportional to $m_d - m_u$ and thus isospin suppressed and small compared to e.g. $f_\pi = 131$ MeV. Analogous arguments apply to the axial vector b_1. Also a 1^+ single charm meson $D_{J=1}(j = 3/2)$ with vanishing decay constant in the heavy quark limit is predicted [14]. The decay constants of the mesons in Table 1 are only poorly known. The current theory spread as compiled in [11] reads as

$$\begin{aligned} f_{a_0(980)} &= 0.7 - 2.5\,\text{MeV} \\ f_{\pi(1300)} &= 0.5 - 7.2\,\text{MeV} \\ f_{K_0^*} &= 33 - 46 \;\; \text{MeV} \end{aligned} \tag{1}$$

As expected, $f_{K_0^*} > f_{a_0}$ due to larger quark mass splitting. No estimate of the b_1 (longitudinal) decay constant has been reported. The decay constants of $a_0, \pi(1300)$, b_1, K_0^* mesons could be determined in hadronic τ-decays. Estimates of the corresponding

TABLE 2. Theory estimates of decay constants as complied in [11] and the corresponding $\tau \to \nu_\tau X$ branching ratios.

X	$a_0(980)$	$a_0(1450)$	$\pi(1300)$	$K_0^*(1430)$
f_X [MeV]	1.1	0.7	7.2	42
$B(\tau \to \nu_\tau X)$	$3.8 \cdot 10^{-6}$	$3.7 \cdot 10^{-7}$	$7.3 \cdot 10^{-5}$	$7.7 \cdot 10^{-5}$

branching ratios are given in Table 2. Note that the bound $B(\tau \to (\pi(1300) \to 3\pi)\nu_\tau) < 1 \cdot 10^{-4}$ [10] implies $f_{\pi(1300)} < 8.4$ MeV.

flavor selection

Not every decay into a designer final state is suppressed. Instead one needs flavor selection criteria to find the designer modes. It is crucial that the spectator does not end up in the designer. An example where this condition does not hold is the decay $B^- \to D^0 a_0^-$. It proceeds via two different topologies. The color allowed one has a suppressed amplitude, because the a_0^- is emitted from the weak vertex. The color suppressed contribution to the amplitude however produces the a_0^- from the spectator. Since form factors for designer mesons are not anomalous, this topology escapes suppression. Examples of modes which satisfy the criteria and do have a suppressed factorizable contribution are given in Table 3, (for the full listing and details see [11]). There are many decays of $B_0, B^\pm, B_s$ mesons and Λ_b, Ω_b baryons, many final states, which cover a wide range of masses (every particle can be replaced by another one with the same flavor content and W-coupling features), many topologies (tree, annihilation, penguin annihilation,...), and many classifications (color allowed, color suppressed). Heavy-light, light-light and decays into charmonium should factorize according to CT while light-heavy and heavy-heavy not. Note that baryons differ in quark content and in particular in annihilation topologies from mesons, i.e. they cannot be fully annihilated by 4-Fermi operators. They also offer more degrees of freedom accessible to experiments such as polarization and have no background from the decay of the CP conjugate parent into the same final state (this is a problem for e.g. $\bar{B}_0 \to \pi^+ a_0^-$, because $B_0 \to \pi^+ a_0^-$ is unsuppressed).

existing data

Experimental information on some designer modes from Table 3 is already available. The Belle collaboration has reported recently [15]

$$\begin{aligned} B(B^+ \to \chi_{c0} K^+) &= (6.0^{+2.1}_{-1.8} \pm 1.1) \cdot 10^{-4} \\ R = \frac{B(B^+ \to \chi_{c0} K^+)}{B(B^+ \to J/\Psi K^+)} &= 0.60^{+0.21}_{-0.18} \pm 0.05 \pm 0.08 \end{aligned} \tag{2}$$

TABLE 3. Some color allowed, color suppressed and baryon decays which satisfy the flavor selection criteria specified in text, adapted from [11]. The magnitude of the amplitudes is given in powers of the Wolfenstein parameter $\lambda \simeq 0.22$.

example decay	**factorizing contribution**			**annihilation**	
	quark level	**tree**	**penguin**	**tree**	**penguin**
$\bar{B}^0 \to D^+ a_0^-$	$\bar{d}b \to \bar{d}(c\bar{u}d)$	λ^2		λ^2	
$B^- \to \pi^0 D_2^{*-}$	$\bar{u}b \to \bar{u}(u\bar{c}d)$	λ^4		λ^4	
$\bar{B}_s \to D_s^+ D_2^{*-}$	$\bar{s}b \to \bar{s}(c\bar{c}d)$	λ^3	λ^3		λ^3
$B^- \to \pi^- K_2^{*0}$	$\bar{u}b \to \bar{u}(d\bar{d}s)$		λ^2	λ^4	λ^2
$B^- \to K^- K_2^{*0}$	$\bar{u}b \to \bar{u}(s\bar{s}d)$		λ^3	λ^3	λ^3
$\bar{B}^0 \to \pi^0 D_2^{*0}$	$\bar{d}b \to \bar{d}(d\bar{u}c)$	λ^2		λ^2	
$B^- \to K^- \chi_{c0}$	$\bar{u}b \to \bar{u}(s\bar{c}c)$	λ^2	λ^2	λ^4	λ^2
$\bar{B}_s \to K^0 a_2^0$	$\bar{s}b \to \bar{s}(d\bar{u}u)$	λ^3	λ^3		λ^3
$\Lambda_b \to nD_2^{*0}$	$udb \to ud(c\bar{u}d)$	λ^2		λ^2	
$\Lambda_b \to \Lambda_c D_{sJ}^-, \Lambda\chi_{c0}$	$udb \to ud(c\bar{c}s)$	λ^2	λ^2	λ^4	λ^2
$\Omega_b \to \Omega_c a_0^-, \Xi^- D_2^{*0}$	$ssb \to ss(c\bar{u}d)$	λ^2			

Because it has a small radius, CT is expected to work for charmonium despite the fact it is not light. However, problems of factorization with color suppressed decays are no surprise, since radiative corrections come in without color suppression and are large [4, 11]. Indeed, eq. (2) represents an $O(1)$ violation of naive factorization since $R_{naive} = 0$.

The branching ratio into a light-light final state has been measured by Belle $B(B^+ \to (K_X(1400) \to K^+\pi^-)\pi^+) = (12.7^{+3.5+1.8+2.9}_{-3.4-1.8-5.8}) \cdot 10^{-6}$ [16]. This is comparable in magnitude with the one into the corresponding unsuppressed mode, $B(B^+ \to K^0\pi^+) = (13.7^{+5.7+1.9}_{-4.8-1.8}) \cdot 10^{-6}$ (Belle) [17] and $B(B^+ \to K^0\pi^+) = (18.2^{+3.3}_{-3.0} \pm 2.0) \cdot 10^{-6}$ (BaBar) [18]. Both decays are dominated by QCD penguins. In particular, they receive large contributions from scalar penguins $(\bar{q}(1-\gamma_5)b)(\bar{s}(1+\gamma_5)q)$, which are parametrically enhanced by factors

$$r_K = \frac{2m_K^2}{m_b m_s}\,, \qquad r_{K_0^*} = \frac{2m_{K_0^*}^2}{m_b m_s}$$

for pseudoscalar K and scalar K_0^* mesons, respectively. Since the penguin enhancement $r_{K_0^*}/r_K = m_{K_0^*}^2/m_K^2$ compensates for the decay constant suppression $f_{K_0^*}/f_K \sim 1/4$, the hypothesis $K_X(1400) = K_0^*$ is consistent with factorization [11, 19]. Note that both contributions remain finite in the chiral limit – for the Goldstone bosons because $m_K \to 0$ in the same limit and for the scalars because $f_{K_0^*} \sim m_s$ which multiplies $r_{K_0^*}$ vanishes. Measurement of the branching ratio into the tensor would be much more exciting since in naive factorization $B_{naive}(B^\pm \to K_2^*\pi^\pm) = 0$. Thus, one would directly probe the factorization breaking corrections, an issue in light-light decays that is controversial between perturbative QCD [5] and QCD factorization [4, 20] (Some problems in the pQCD approach have been pointed out recently in Ref. [21]). Experimentally, angular analysis is required to discriminate the nearby kaon resonances $K_0^*, K^*(1410), K_2^*$.

quantitatively: color allowed $B \to D^{(*)}X$ decays
$X = a_0, a_2, b_1, \pi(1300), \pi_2, \rho_3$ and K_0^*, K_2^*

Generically we have the branching ratios $B(B \to D^{(*)}(\pi, \rho, a_1)) \sim 10^{-3}$. Assuming $O(10)\%$ corrections to factorization arising from $1/N_c^2$ and/or Λ_{QCD}/m_b one expects for the $I = 1$ designer mesons $B(B \to D^{(*)}X) \sim 10^{-5} - 10^{-6}$. The branching ratios can be calculated in QCD factorization [4] from evaluation of the matrix element [11]

$$\langle D^{(*)+}X^-|H_{eff}|B\rangle \sim a_1(\mu) f_X + \frac{\alpha_s(\mu)}{4\pi} C_2(\mu) \frac{C_F}{N_c} \int_0^1 du F(u) \varphi(u;\mu) \tag{3}$$

The first term corresponds to the expression in naive factorization. It vanishes if $f_X = 0$. In terms of light cone distribution amplitudes (DA) $\varphi(u;\mu)$, where u denotes the momentum fraction carried by the quark in X, the decay constant is given as

$$f_X = \int_0^1 du \varphi(u)$$

However, a small or vanishing zeroth moment $f_X \simeq 0$ does not imply that the DA is small or vanishing. The contribution from hard gluon exchange, which is given by the second term in eq. (3), thus escapes the suppression mechanism [11]. From charge conjugation, the following symmetry properties for meson DA's hold up to isospin breaking

$$\begin{aligned} \pi, \pi(1300), \pi_2, \rho_3 &: \quad \varphi(u) = +\varphi(1-u) \\ a_0, a_2, b_1, K_0^*, K_2^* &: \quad \varphi(u) = -\varphi(1-u) \end{aligned} \tag{4}$$

The leading coefficients in the expansion of the DA in Gegenbauer polynomials $C_n^{3/2}$

$$\varphi(u;\mu) = f^\varphi 6u(1-u)\Big[B_0 + \sum_{n=1}^{\infty} B_n(\mu) C_n^{3/2}(2u-1)\Big]$$

are estimated for mesons X with Fock space normalization techniques a la pion as

$$\begin{aligned} |f^\varphi B_1|_{a_0, b_1, a_2, K_0^*, K_2^*} &\approx 75 \text{ MeV} \\ |f^\varphi B_2|_{\pi(1300), \pi_2, \rho_3} &\approx 50 \text{ MeV} \end{aligned} \tag{5}$$

at the renormalization scale $\mu = m_b = 4.4$ GeV ($B_0 = 1$ and $f^\varphi = f_X$ for spin$(X) \leq 1$, otherwise $B_0 = 0$) [11]. Resulting branching ratios are given in Table 4. Similar ones are expected for $B_s \to D_s X$ decays accessible at the Tevatron and LHC. The QCD factorization result shows an enhancement over the one obtained in the naive factorization approach. However, the branching ratios are still much smaller than the ones of the corresponding 'non-designer' modes like $B \to D\pi$, but within experimental reach. Since QCD factorization picks up hard α_s contributions which are enhanced in the designer decays, their amplitude is more sensitive to the renormalization scale and gains large strong phases. Current dominant uncertainties are due to the decay constants, which could be measured in hadronic τ decays, see Table 2. Furthermore, information on the DA's of the neutral $a_0, a_2, \pi(1300), \pi_2$ could be obtained from $\gamma\gamma^*$ collisions in $e^+e^- \to e^+e^-X$ processes similar to the analysis performed by CLEO for π, η, η' [22].

TABLE 4. Branching ratios obtained in QCD factorization for two choices of the renormalization scale μ and in the naive factorization approach, taken from [11]. †With $f_{b_1} = 0$.

mode	**naive factorization**	**QCD factorization**	
		$\mu = m_b$	$\mu = m_b/2$
$\bar{B}^0 \to D^+ a_0(980)$	$1.1 \cdot 10^{-6}$	$2.0 \cdot 10^{-6}$	$4.0 \cdot 10^{-6}$
$\bar{B}^0 \to D^+ a_0(1450)$	$8.6 \cdot 10^{-8}$	$5.8 \cdot 10^{-7}$	$2.1 \cdot 10^{-6}$
$\bar{B}^0 \to D^+ a_2, D^+ b_1{}^\dagger$	0	$3.5 \cdot 10^{-7}$	$1.7 \cdot 10^{-6}$
$\bar{B}^0 \to D^+ \pi(1300)$	$9.1 \cdot 10^{-6}$	$9.3 \cdot 10^{-6}$	$9.6 \cdot 10^{-6}$
$\bar{B}^0 \to D^+ \pi_2, D^+ \rho_3$	0	$1.4 \cdot 10^{-9}$	$8.1 \cdot 10^{-9}$
$\bar{B}^0 \to D^+ K_0^*(1430)$	$2.0 \cdot 10^{-5}$	$2.0 \cdot 10^{-5}$	$2.1 \cdot 10^{-5}$
$\bar{B}^0 \to D^+ K_2^*$	0	$1.9 \cdot 10^{-8}$	$9.2 \cdot 10^{-8}$
$\bar{B}^0 \to D^{*+} a_0(980)$	$1.0 \cdot 10^{-6}$	$1.8 \cdot 10^{-6}$	$3.7 \cdot 10^{-6}$
$\bar{B}^0 \to D^{*+} a_0(1450)$	$7.9 \cdot 10^{-8}$	$5.2 \cdot 10^{-7}$	$1.9 \cdot 10^{-6}$
$\bar{B}^0 \to D^{*+} a_2 D^{*+} b_1{}^\dagger$	0	$2.9 \cdot 10^{-7}$	$1.5 \cdot 10^{-6}$
$\bar{B}^0 \to D^{*+} \pi(1300)$	$8.3 \cdot 10^{-6}$	$8.4 \cdot 10^{-6}$	$8.4 \cdot 10^{-6}$
$\bar{B}^0 \to D^{*+} \pi_2, D^{*+} \rho_3$	0	$5.7 \cdot 10^{-10}$	$3.2 \cdot 10^{-9}$
$\bar{B}^0 \to D^{*+} K_0^*(1430)$	$1.8 \cdot 10^{-5}$	$1.9 \cdot 10^{-5}$	$1.9 \cdot 10^{-5}$
$\bar{B}^0 \to D^{*+} K_2^*$	0	$1.5 \cdot 10^{-8}$	$7.7 \cdot 10^{-8}$

measure strong phases as a byproduct of $2\beta + \gamma$

Time dependent measurements in $B \to D^\pm \pi^\mp$ decays allow the extraction of CKM angles $2\beta + \gamma$ together with strong phases without model assumptions on strong dynamics [23]. Unfortunalty, the effect scales with a tiny $\sim 1\%$ asymmetry. Choosing instead $B \to D^\pm X^\mp$ decays, where $X = a_0, a_2, b_1, \pi(1300), \pi_2, \rho_3$ the CKM hierarchy of the amplitudes is compensated by the decay constants and large [24], for example for the a_0

$$\frac{A(B_0 \to D^+ a_0^-)}{A(\bar{B}_0 \to D^+ a_0^-)} \simeq \frac{f_D}{f_{a_0}} \frac{V_{cd} V_{ub}^*}{V_{cb} V_{ud}^*} \sim O(1) \tag{6}$$

Therefor designer mesons are competitive with $B \to D^\pm \pi^\mp$ decays and help to resolve ambiguities because different and large strong phases are involved.

CONCLUSIONS

Factorization successfully works in color allowed b-decays within present errors. This includes $B \to DD_s$ decays where the color transparency explanation is absent. More data are needed to see to what accuracy it works and perhaps to understand why it works. I discussed new strategies to explore factorization with modes where the factorizable contribution is suppressed such that the corrections show up isolated. This is similar to pure annihilation decays $B_0 \to K^+K^-$, $B_s \to \pi^+\pi^-, \pi^0\pi^0$ and $B \to baryon\, baryon$. These measurements could be carried out at operating and future high luminosity e^+e^--facilities [25]. A dedicated factorization study requires improved knowledge of non-perturbative

input such as decay constants and distribution amplitudes. Their determination should be part of such an experimental program. A qualitatively and quantitatively accurate description of hadronic matrix elements in B-decays is particularly important for the extraction of the CKM unitarity angles γ and α. Finally, 'designer' final states and modes are also promising to study CP violation and to search for New Physics effects in rare FCNC processes. Steps in this direction have already been undertaken [24, 26, 27].

ACKNOWLEDGMENTS

It is a pleasure to thank the organizers for the invitation to this exciting symposium and Dr. Diehl for joyful collaboration on parts of the work presented here. I am grateful to David E. Kaplan for useful comments on the manuscript.

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