Weak B Decays into Orbitally Excited Charmed Mesons

C. Albertus, **J. Segovia**, D.R. Entem, F. Fernández, E. Hernández and M.A. Pérez-García

The XIV International Conference on Hadron Spectroscopy (Hadron 2011)
München, 13-17th of June 2011

Universidad de Salamanca
Spain

Contents

1.- Introduction

1.1.- Overview

- Accuracy on the knowledge of $|V_{cb}|$ and $|V_{ub}|$ demands detailed measurements of b-hadron decays
- A substantial contribution to the semileptonic decay width of b-hadrons is provided by decays including orbitally excited charmed mesons in their final state
- Additionally, the analysis of signals and backgrounds of inclusive and exclusive measurements of b-hadron decays calls for an improved understanding of these processes
- In this scenario, data reported by Belle and BaBar offer new theoretical possibilities to test meson models as far as they include both weak and strong decays

1.- Introduction

1.2.- Belle and BaBar measurements

	Belle [1] ($\times 10^{-3}$)	BaBar [2] ($\times 10^{-3}$)
$D_2^*(2460)$		
$\mathcal{B}(B^+ \to D_2^{*0} l^+ \nu_l)\mathcal{B}(D_2^{*0} \to D^+ \pi^-)$	$2.2 \pm 0.3 \pm 0.4$	$1.4 \pm 0.2 \pm 0.2^{(*)}$
$\mathcal{B}(B^+ \to D_2^{*0} l^+ \nu_l)\mathcal{B}(D_2^{*0} \to D^{*+} \pi^-)$	$1.8 \pm 0.6 \pm 0.3$	$0.9 \pm 0.2 \pm 0.2^{(*)}$
$\mathcal{B}(B^0 \to D_2^{*-} l^+ \nu_l)\mathcal{B}(D_2^{*-} \to D^0 \pi^-)$	$2.2 \pm 0.4 \pm 0.4$	$1.1 \pm 0.2 \pm 0.1^{(*)}$
$\mathcal{B}(B^0 \to D_2^{*-} l^+ \nu_l)\mathcal{B}(D_2^{*-} \to D^{*0} \pi^-)$	< 3	$0.7 \pm 0.2 \pm 0.1^{(*)}$
$\mathcal{B}_{D/D^{(*)}}$	0.55 ± 0.03	0.62 ± 0.03
$D_1(2420)$		
$\mathcal{B}(B^+ \to D_1^0 l^+ \nu_l)\mathcal{B}(D_1^0 \to D^{*+} \pi^-)$	$4.2 \pm 0.7 \pm 0.7$	$2.97 \pm 0.17 \pm 0.17$
$\mathcal{B}(B^0 \to D_1^- l^+ \nu_l)\mathcal{B}(D_1^- \to D^{*0} \pi^-)$	$5.4 \pm 1.9 \pm 0.9$	$2.78 \pm 0.24 \pm 0.25$

1 *D. Liventsev et al. (Belle Collaboration), Phys. Rev. D* **77**, *091503 (2008)*
2 *B. Aubert et al. (BaBar Collaboration), Phys. Rev. Lett.* **103**, *051803 (2009)*

2.- Theoretical framework

2.1.- Constituent quark model. Main features

- Spontaneous chiral symmetry breaking (Goldstone-Boson exchange):

$$L = \bar{\psi}\left(i\gamma^\mu\partial_\mu - MU^{\gamma_5}\right)\psi \rightarrow \quad U^{\gamma_5} = 1 + \frac{i}{f_\pi}\gamma^5\lambda^a\pi^a - \frac{1}{2f_\pi^2}\pi^a\pi^a + \ldots$$

$$M(q^2) = m_q F\left(q^2\right) = m_q\left[\frac{\Lambda^2}{\Lambda^2+q^2}\right]^{1/2}$$

- QCD perturbative effects (One-Gluon Exchange):

$$L = i\sqrt{4\pi\alpha_s}\,\bar{\psi}\gamma_\mu G^\mu\lambda^c\psi$$

- Confinement (screened potential):

$$V_{CON}^C(\vec{r}_{ij}) = \left[-a_c(1-e^{-\mu_c r_{ij}}) + \Delta\right](\vec{\lambda}_i^c\cdot\vec{\lambda}_j^c)$$

$$\begin{cases} V_{CON}^C(\vec{r}_{ij}) = \left(-a_c\mu_c r_{ij} + \Delta\right)(\vec{\lambda}_i^c\cdot\vec{\lambda}_j^c) & r_{ij}\rightarrow 0 \\ V_{CON}^C(\vec{r}_{ij}) = (-a_c + \Delta)(\vec{\lambda}_i^c\cdot\vec{\lambda}_j^c) & r_{ij}\rightarrow\infty \end{cases}$$

2.- Theoretical framework

2.1.- Constituent quark model. Some applications

- **N-N interaction**
  - D.R. Entem, F. Fernández and A. Valcarce, Phys. Rev. C **62**, 034002 (2000)
  - B. Julia-Diaz, J. Haidenbauer, A. Valcarce and F. Fernández, Phys. Rev. C **65**, 034001 (2002)
- **Baryon spectrum**
  - H. Garcilazo, A. Valcarce and F. Fernández, Phys. Rev. C **63**, 035207 (2001)
  - H. Garcilazo, A. Valcarce and F. Fernández, Phys. Rev. C **64**, 058201 (2001)
- **Meson spectrum**
  - J. Vijande, A. Valcarce and F. Fernández, J. Phys. G **31**, 481 (2005)
  - J. Segovia, D.R. Entem and F. Fernández, Phys. Rev. D **78** 114033 (2008)
  - J. Segovia, D.R. Entem and F. Fernández, accepted by Phys. Rev. D
- **Molecular states**
  - P. G. Ortega, J. Segovia, D. R. Entem and F. Fernández, Phys. Rev. D **81**, 054023 (2010)

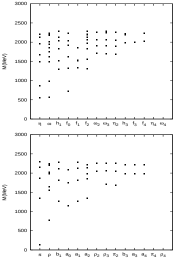
2.- Theoretical framework

2.1.- Constituent quark model. Some applications (Continuation)

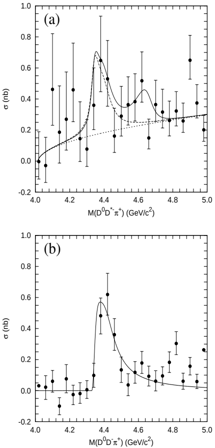
Deuteron

	CQM	NijmII	Bonn B	Exp.
ϵ_d (MeV)	-2.2242	-2.2246	-2.2246	-2.224575
P_D (%)	4.85	5.64	4.99	-
Q_d (fm^2)	0.276	0.271	0.278	0.2859 ± 0.0003
A_S (fm$^{-1/2}$)	0.891	0.8845	0.8860	0.8846 ± 0.0009
A_D/A_S	0.0257	0.0252	0.0264	0.0256 ± 0.0004

Light mesons



Charmonium reactions



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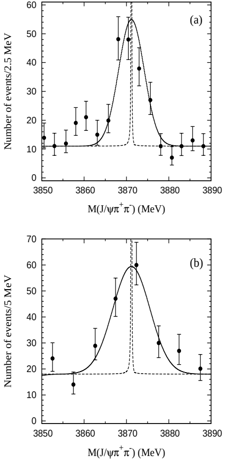


2.- Theoretical framework

2.1.- Constituent quark model. Mass predictions involved in the reactions

Quark masses	m_n (MeV)	313
	m_c (MeV)	1763
	m_b (MeV)	5110
Confinement	a_c (MeV)	507.4
	μ_c (fm^{-1})	0.576
	Δ (MeV)	184.432
	a_s	0.81
One-gluon exchange	α_0	2.118
	Λ_0 (fm^{-1})	0.113
	μ_0 (MeV)	36.976
	$\hat{r}_0$ (fm)	0.181
	$\hat{r}_g$ (fm)	0.259
GBE	taken from Ref. [1]	

Meson	J^{PC}	CQM (MeV)	EXP (MeV)
B	0^-	5275	5279.34 ± 0.21
D	0^-	1896	1867.22 ± 0.11
D^*	1^-	2017	2008.60 ± 0.11
$D_1(2420)$	1^+	2466	2422.15 ± 1.6
$D_2^*(2460)$	2^+	2513	2461.4 ± 2.3
π	0^{-+}	138	137.27339 ± 0.00035

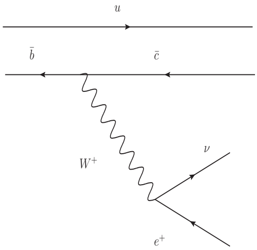
[1] *J. Vijande, F. Fernández and A. Valcarce J. Phys. G* **31** *481 (2005)*

2.- Theoretical framework

2.2.- Weak decays. Total decay width

Study of the weak process based on

- *E. Hernández, J. Nieves and J.M. Verde-Velasco, Phys. Rev. D* **74**, *074008 (2006)*
- *M.A. Ivanov, J.G. Körner and P. Santorelli, Phys. Rev. D* **73**, *054024 (2006)*



2.- Theoretical framework

2.2.- Weak decays. Case $0^- \to 2^+$

$$\langle D(2^+), \lambda\vec{P}_D \left| J^{cb}_\mu(0) \right| B(0^-)\vec{P}_B \rangle = \epsilon_{\mu\nu\alpha\beta}\epsilon^{\nu\delta *}_{(\lambda)}(\vec{P}_D)P_\delta P^\alpha q^\beta T_4(q^2)$$
$$- i\left\{\epsilon^*_{(\lambda)\mu\delta}(\vec{P}_D)P^\delta T_1(q^2) + P^\nu P^\delta \epsilon^*_{(\lambda)\nu\delta}(\vec{P}_D)\left[P_\mu T_2(q^2) + q_\mu T_3(q^2)\right]\right\}$$

$$T_1(q^2) = -i\frac{2m_D}{m_B|\vec{q}\,|}A^1_{T\lambda=+1}(|\vec{q}\,|),$$

$$T_2(q^2) = i\frac{1}{2m_B^3}\left\{-\sqrt{\frac{3}{2}}\frac{m_D^2}{|\vec{q}\,|^2}A^0_{T\lambda=0}(|\vec{q}\,|) - \sqrt{\frac{3}{2}}\frac{m_D^2}{|\vec{q}\,|^3}(E_D(-\vec{q}\,) - m_B)A^3_{T\lambda=0}(|\vec{q}\,|)\right.$$
$$\left.+\frac{2m_D}{|\vec{q}\,|}\left(1 - \frac{E_D(-\vec{q}\,)(E_D(-\vec{q}\,) - m_B)}{|\vec{q}\,|^2}\right)A^1_{T\lambda=+1}(|\vec{q}\,|)\right\}$$

$$T_3(q^2) = i\frac{1}{2m_B^3}\left\{-\sqrt{\frac{3}{2}}\frac{m_D^2}{|\vec{q}\,|^2}A^0_{T\lambda=0}(|\vec{q}\,|) - \sqrt{\frac{3}{2}}\frac{m_D^2}{|\vec{q}\,|^3}(E_D(-\vec{q}\,) + m_B)A^3_{T\lambda=0}(|\vec{q}\,|)\right.$$
$$\left.+\frac{2m_D}{|\vec{q}\,|}\left(1 - \frac{E_D(-\vec{q}\,)(E_D(-\vec{q}\,) + m_B)}{|\vec{q}\,|^2}\right)A^1_{T\lambda=+1}(|\vec{q}\,|)\right\}$$

$$T_4(q^2) = i\frac{m_D}{m_B^2|\vec{q}\,|^2}V^1_{T\lambda=+1}(|\vec{q}\,|)$$

2.- Theoretical framework

2.2.- Weak decays. Case $0^- \to 1^+$

$$\langle D(1^+), \lambda \vec{P}_D | J_\mu^{cb}(0) | B(0^-), \vec{P}_B \rangle = \frac{-1}{m_B + m_D} \epsilon_{\mu\nu\alpha\beta} \epsilon_{(\lambda)}^{\nu *}(\vec{P}_D) P^\alpha q^\beta A(q^2)$$
$$- i \left\{ (m_B - m_D) \epsilon^*_{(\lambda)\mu}(\vec{P}_D) V_0(q^2) - \frac{P \cdot \epsilon^*_{(\lambda)}(\vec{P}_D)}{m_B + m_D} \left[P_\mu V_+(q^2) + q_\mu V_-(q^2) \right] \right\}$$

$$A(q^2) = - \frac{i}{\sqrt{2}} \frac{m_B + m_D}{m_B |\vec{q}\,|} A^1_{\lambda=-1}(|\vec{q}\,|)$$

$$V_+(q^2) = + i \frac{m_B + m_D}{2m_B} \frac{m_D}{|\vec{q}\,| m_B} \left\{ V^0_{\lambda=0}(|\vec{q}\,|) - \frac{m_B - E_D(-\vec{q}\,)}{|\vec{q}\,|} V^3_{\lambda=0}(|\vec{q}\,|) + \sqrt{2} \frac{m_B E_D(-\vec{q}\,) - m_D^2}{|\vec{q}\,| m_D} V^1_{\lambda=-1}(|\vec{q}\,|) \right\}$$

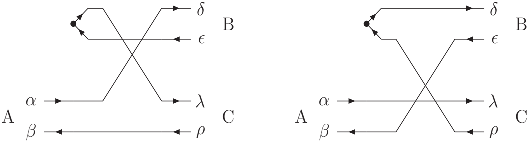
$$V_-(q^2) = - i \frac{m_B + m_D}{2m_B} \frac{m_D}{|\vec{q}\,| m_B} \left\{ - V^0_{\lambda=0}(|\vec{q}\,|) - \frac{m_B + E_D(-\vec{q}\,)}{|\vec{q}\,|} V^3_{\lambda=0}(|\vec{q}\,|) + \sqrt{2} \frac{m_B E_D(-\vec{q}\,) + m_D^2}{|\vec{q}\,| m_D} V^1_{\lambda=-1}(|\vec{q}\,|) \right\}$$

$$V_0(q^2) = + i\sqrt{2} \frac{1}{m_B - m_D} V^1_{\lambda=-1}(|\vec{q}\,|)$$

2.- Theoretical framework

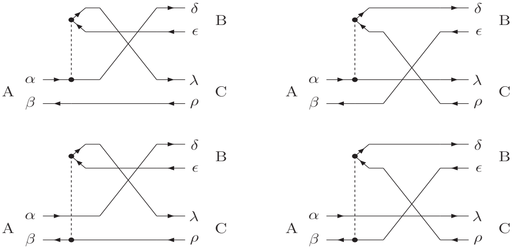
2.3.- Strong decays. $^3P_0$ and microscopic models

- $^3P_0$ decay model



$$H_I = g \int d^3x \, \bar{\psi}(\vec{x}) \, \psi(\vec{x})$$

- Microscopic decay model



$$H_I = \frac{1}{2} \int d^3x \, d^3y \, J^a(\vec{x}) \, K(|\vec{x} - \vec{y}|) \, J^a(\vec{y})$$

2.- Theoretical framework

2.3.- Strong decays. $^3P_0$ and microscopic models (Continuation)

- *$^3P_0$ decay model*
  - *L. Micu, Nucl. Phys. B* **10**, *521 (1969)*
  - *A. Le Yaouanc, L. Olivier, O. Pène, and J.C. Raynal, Phys. Rev. D* **8**, *2223 (1973)*
  - *R. Bonnaz, and B. Silvestre-Brac, Few-Body Syst.* **27**, *163 (1999)*

- *Microscopic decay model*
  - *E. Eichten et al. Phys. Rev. D* **17** *3090 (1978);* **21** *203 (1980)*
    → update: Phys. Rev. D **73** *014014 (2006)*
  - *E.S. Ackleh et al. Phys. Rev. D* **54**, *6811 (1996)*
  - *Yu.A. Simonov arXiv:1103.4028v1 [hep-ph] 21 Mar 2011*
  - *Bao-Fei Li et al. arXiv:1105.1620v1 [hep-ph] 9 May 2011*

$$\Gamma_{A\to BC} = 2\pi \frac{E_B E_C}{M_A k_0} \sum_{J_{BC},l} |\mathcal{M}_{A\to BC}(k_0; J_{BC}, l)|^2$$

$$\mathcal{M}_{A\to BC} = M_{A\to BC} + (-1)^{l_B+l_C-l_A+J_B+J_C-J_{BC}+l} M_{A\to CB}$$

$$M_{A\to BC} = \mathcal{I}_{color}\ \mathcal{I}_{flavor}\ (\mathcal{I}_{signature}\ \mathcal{I}_{spin-space})$$

2.- Theoretical framework

2.3.- Strong decays. Factors for the $^3P_0$ model

- Color term ⇒

$$\mathcal{I}_{color} = \frac{1}{\sqrt{3}}$$

- Flavor term ⇒

$$\mathcal{I}_{flavor} = (-1)^{t_\alpha + t_\beta + I_A} \delta_{f_\alpha f_\delta} \delta_{f_\beta f_\rho} \delta_{f_\mu f_\lambda} \delta_{f_\nu f_\epsilon} \sqrt{(2I_B+1)(2I_C+1)(2t_\mu+1)} \begin{Bmatrix} t_\beta & I_C & t_\mu \\ I_B & t_\alpha & I_A \end{Bmatrix}$$

- Spin-space term ⇒

$$\begin{aligned} \mathcal{I}_{spin-space} = & \frac{1}{\sqrt{1+\delta_{BC}}} \int d^3K_B d^3K_C d^3p_\alpha d^3p_\beta d^3p_\mu d^3p_\nu \delta^{(3)}(\vec{K} - \vec{K}_0) \\ & \delta^{(3)}(\vec{K}_B - \vec{P}_B)\delta^{(3)}(\vec{K}_C - \vec{P}_C)\delta^{(3)}(\vec{p}_\mu + \vec{p}_\nu)\delta^{(3)}(\vec{P}_A)\frac{\delta(k-k_0)}{k} \\ & \langle \{ [[\phi_B(\vec{p}_B)(s_\alpha s_\nu)S_B]\, J_B\, [\phi_C(\vec{p}_C)(s_\mu s_\beta)S_C]\, J_C]\, J_{BC}\, Y_l(\hat{k})\}\, J_A | \\ & \{[\phi_A(\vec{p}_A)(s_\alpha s_\beta)S_A]\, J_A\, [\gamma_{\mu,(1)} \left(\frac{\vec{p}_\mu - \vec{p}_\nu}{2}\right) (s_\mu s_\nu)1]\, 0\}\, J_A \rangle \end{aligned}$$

2.- Theoretical framework

2.3.- Strong decays. Factors for the microscopic model

- Color term ⇒

$$\mathcal{I}_{color} = \frac{2^2}{3^{\frac{3}{2}}}$$

- Flavor term ⇒

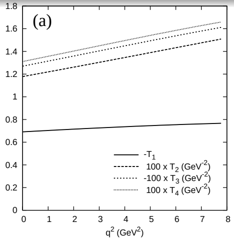
$$\mathcal{I}_{flavor} = (-1)^{t_\alpha + t_\beta + I_A} \delta_{f_\alpha f_\delta} \delta_{f_\beta f_\rho} \delta_{f_\mu f_\lambda} \delta_{f_\nu f_\epsilon} \sqrt{(2I_B+1)(2I_C+1)(2t_\mu+1)} \begin{Bmatrix} t_\beta & I_C & t_\mu \\ I_B & t_\alpha & I_A \end{Bmatrix}$$

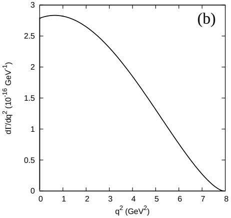
- Spin-space term ⇒

$$\mathcal{I}_{spin-space} = \frac{-2}{\sqrt{1+\delta_{BC}}} \int d^3K_B d^3K_C \sum_{m,M_{BC}} \langle J_{BC} M_{BC} lm | J_A M_A \rangle \, \delta^{(3)}(\vec{K} - \vec{K}_0) \delta(k - k_0)$$
$$\frac{Y_{lm}(\hat{k})}{k} \sum_{M_B, M_C} \langle J_B M_B J_C M_C | J_{BC} M_{BC} \rangle \int d^3p_\delta d^3p_\epsilon d^3p_\lambda d^3p_\rho \, \delta^{(3)}(\vec{K}_B - \vec{P}_B)$$
$$\delta^{(3)}(\vec{K}_C - \vec{P}_C) \phi_B(\vec{p}_B) \phi_C(\vec{p}_C) \delta_{\rho\beta} \delta^{(3)}(\vec{p}_\rho - \vec{p}_\beta) \delta^{(3)}(\vec{p}_\lambda + \vec{p}_\epsilon + \vec{p}_\delta - \vec{p}_\alpha)$$
$$K(|\vec{p}_\lambda + \vec{p}_\epsilon|) \lim_{v/c \to 0} [\bar{u}_\lambda(\vec{p}_\lambda) \Gamma v_\epsilon(\vec{p}_\epsilon)] \lim_{v/c \to 0} [\bar{u}_\delta(\vec{p}_\delta) \Gamma u_\alpha(\vec{p}_\alpha)]$$
$$\int d^3p_\alpha d^3p_\beta \, \delta^{(3)}(\vec{P}_A) \phi_A(\vec{p}_A)$$

3.- Results

3.1.- Semileptonic $B \to D_2^* l \nu_l$ decay





- Semileptonic decay widths

$\Gamma(B^+ \to \bar{D}_2^{*0} l^+ \nu_l) = 1.3388 \times 10^{-15}\,\text{GeV} \Rightarrow \mathcal{B}(B^+ \to \bar{D}_2^{*0} l^+ \nu_l) = 3.3320 \times 10^{-3}$

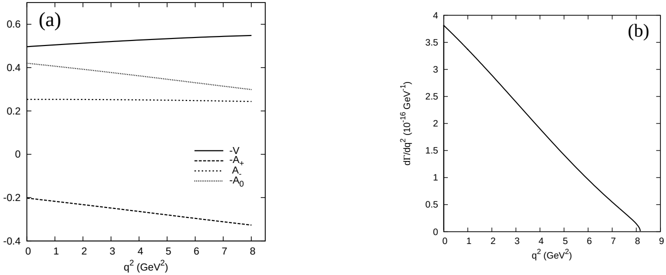
$\Gamma(B^0 \to D_2^{*-} l^+ \nu_l) = 1.3454 \times 10^{-15}\,\text{GeV} \Rightarrow \mathcal{B}(B^0 \to D_2^{*-} l^+ \nu_l) = 3.1172 \times 10^{-3}$

- Some results about strong decays

B	Exp.	$^3P_0$	Microscopic
$\frac{\Gamma(D_2^{*+} \to D^0 \pi^+)}{\Gamma(D_2^{*+} \to D^{*0} \pi^+)}$	$1.9 \pm 1.1 \pm 0.3$	1.80	1.97
$\frac{D_2^{*0} \to \Gamma(D^+ \pi^-)}{\Gamma(D_2^{*0} \to D^{*+} \pi^-)}$	1.56 ± 0.16	1.82	1.97
$\frac{\Gamma(D_2^{*0} \to D^+ \pi^-)}{\Gamma(D_2^{*0} \to D^{(*)+} \pi^-)}$	$0.62 \pm 0.03 \pm 0.02$	0.64	0.66

3.- Results

3.2.- Semileptonic $B \to D_1 l \nu_l$ decay



- Semileptonic decay widths

$$\Gamma(B^+ \to \bar{D}_1^0 l^+ \nu_l) = 1.5490 \times 10^{-15}\,\text{GeV} \Rightarrow \mathcal{B}(B^+ \to \bar{D}_1^0 l^+ \nu_l) = 3.8552 \times 10^{-3}$$
$$\Gamma(B^0 \to D_1^- l^+ \nu_l) = 1.5445 \times 10^{-15}\,\text{GeV} \Rightarrow \mathcal{B}(B^0 \to D_1^- l^+ \nu_l) = 3.5785 \times 10^{-3}$$

Only one open-charm decay $\Rightarrow \mathcal{B}(D_1^0 \to D^{*+}\pi^-) = \mathcal{B}(D_1^- \to D^{*0}\pi^-) = 2/3$

3.- Results

3.3.- Comparison with experiment

	Belle $(\times 10^{-3})$	BaBar $(\times 10^{-3})$	$^3P_0$ $(\times 10^{-3})$	Mic. $(\times 10^{-3})$
$D_2^*(2460)$				
$\mathcal{B}(B^+ \to D_2^{*0} l^+ \nu_l)\mathcal{B}(D_2^{*0} \to D^+ \pi^-)$	2.2 ± 0.5	1.42 ± 0.21	1.43	1.47
$\mathcal{B}(B^+ \to D_2^{*0} l^+ \nu_l)\mathcal{B}(D_2^{*0} \to D^{*+} \pi^-)$	1.8 ± 0.7	0.87 ± 0.21	0.79	0.75
$\mathcal{B}(B^+ \to D_2^{*0} l^+ \nu_l)\mathcal{B}(D_2^{*0} \to D^{(*)+} \pi^-)$	4.0 ± 0.9	2.29 ± 0.31	2.22	2.22
$\mathcal{B}(B^0 \to D_2^{*-} l^+ \nu_l)\mathcal{B}(D_2^{*-} \to D^0 \pi^-)$	2.2 ± 0.6	1.10 ± 0.19	1.34	1.38
$\mathcal{B}(B^0 \to D_2^{*-} l^+ \nu_l)\mathcal{B}(D_2^{*-} \to D^{*0} \pi^-)$	< 3	0.67 ± 0.19	0.74	0.70
$\mathcal{B}(B^0 \to D_2^{*-} l^+ \nu_l)\mathcal{B}(D_2^{*-} \to D^{(*)0} \pi^-)$	< 5.2	1.77 ± 0.28	2.08	2.08
$\mathcal{B}_{D/D^{(*)}}$	0.55 ± 0.03	0.62 ± 0.04	0.64	0.66
$D_1(2420)$				
$\mathcal{B}(B^+ \to D_1^0 l^+ \nu_l)\mathcal{B}(D_1^0 \to D^{*+} \pi^-)$	4.2 ± 1.0	2.97 ± 0.24	2.57	2.57
$\mathcal{B}(B^0 \to D_1^- l^+ \nu_l)\mathcal{B}(D_1^- \to D^{*0} \pi^-)$	5.4 ± 2.1	2.78 ± 0.35	2.39	2.39

4.- Summary and conclusions

- We have studied semileptonic B decays into orbitally excited charmed mesons
- These data offer new theoretical possibilities to test meson models as far as they include weak and strong processes
- Weak decays: Studied within spectator aproximation and in the helicity formalism.
- Strong decays: We study these processes within the context of the $^3P_0$ and microscopic models
- Predictions for $B \to D_2^* l \nu_l$ and $B \to D_1 l \nu_l$: very good agreement with BaBar data which are the latest measurements. All theoretical results within the error bars
- In both cases the theoretical predictions are smaller than the Belle data