Spectroscopy of D Mesons

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Abstract. The scenario of heavy quark meson spectroscopy underwent recently a major revolution, after the observation of BABAR and CLEO, confirmed by BELLE, of D_{sJ} L=1 excited states, and by further evidences by SELEX. These experimental results have cast doubts on the incarnations of the ideas of Heavy Quark Effective Theory in heavy quark spectroscopy. I shall review the status of experimental data, discuss implications and sketch an outlook.

INTRODUCTION

This paper reports on recent experimental results on D meson spectroscopy, discussing the recent events that brought to cast doubts to our current understanding of the overall picture. I shall discuss excited non-strange D mesons, namely the observation of $j_q = 1/2$ broad states, the revolutionary observations of excited strange D_{sJ} mesons which are forcing us to switch the paradigm of HQ spectroscopy, discuss the status of debated $D_{sJ}(2632)$ meson observed by SELEX at Fermilab, finally sketch an outlook and draw conclusions. For a detailed review on charm physics including spectroscopy the reader is referred to Ref.[1], for other charm spectroscopy issues such as charmonium states etc. see other up-to-date reviews such as [2, 3, 4].

Let me pay a tribute to cosmic ray physicists and show the — possibly — very first D meson observed by human eye $(D^+ \to K^+\pi^0)$, in nuclear emulsions exposed to cosmic rays in 1971 [5]. After 35 years, here is where we are.

HEAVY-LIGHT QUARK SPECTROSCOPY, THE GLOBAL PICTURE

A global interpretation scheme for heavy quark meson spectroscopy is provided by the idea of Heavy Quark Symmetry (HQS). In the infinite heavy-quark mass limit, the heavy-light meson can be described as formed by a the still heavy quark, with all the orbital degrees of freedom being due to the light quark. This means that good conserved quantum numbers are the spin of the heavy quark, and the angular momentum j_q.

Experimentally, for each of the $c\bar{u}$, $c\bar{d}$ and $c\bar{s}$ systems four P-wave and two $n = 2$ radial excitations have been studied. There are four $L = 1$ states, namely two with $j_q = 1/2$ and total spin $J = 0,1$ and two with $j_q = 3/2$ and $J = 1,2$. These four states are named respectively D_0^*, $D_1(j_q = 1/2)$, $D_1(j_q = 3/2)$ and D_2^* (Fig.2). Parity and angular momentum conservation force the $(j_q = 1/2)$ states to decay to the ground states via

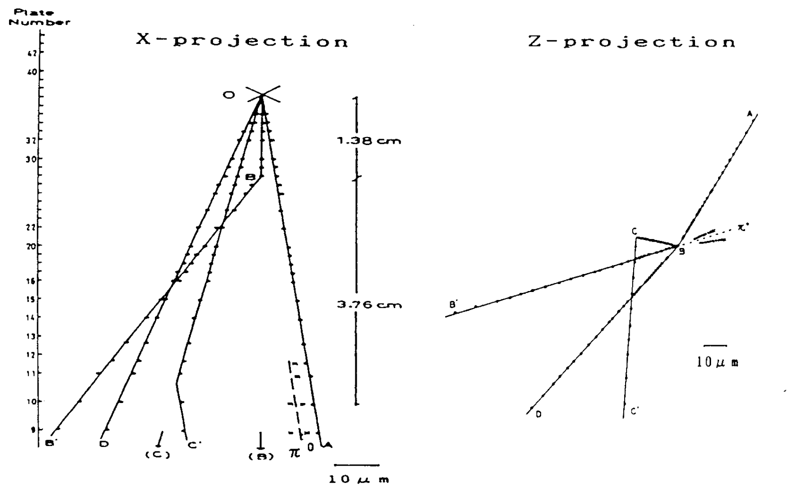

FIGURE 1. First charm candidate event in nuclear emulsions [5]. Figure from Ref. [6].

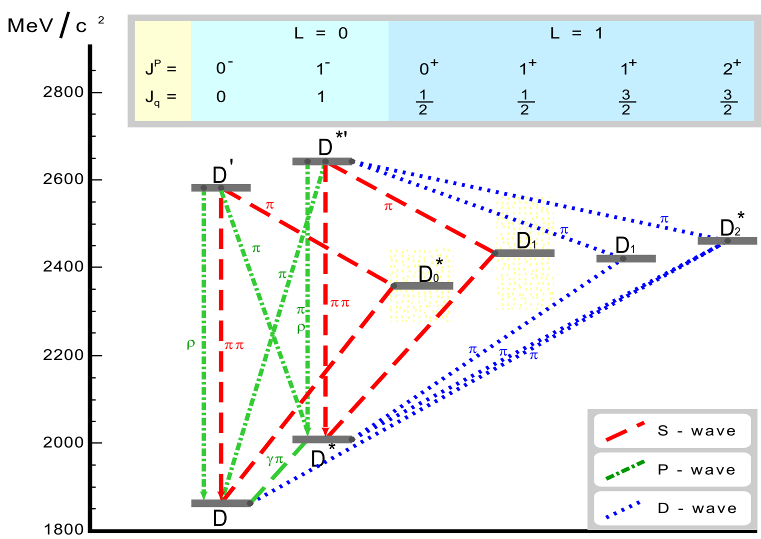

FIGURE 2. *Masses and transitions predicted for the excited non-strange D meson states.*

S-wave transitions (broad width), while $(j_q = 3/2)$ states decay via D-wave (narrow width). To be more specific, for the $1/2$ one predicts widths of ~ 100 MeV and for the $3/2$ of about ~ 10 MeV with the exception of the $D_{s1}(j_q = 3/2)(2536)$ which is kinematically forced to a ~ 1 MeV width.

Therefore, the HQS picture has two consequences, which turn to be direct predictions:

1. each L level is split in two J-degenerate doublets, in each doublet one broad and one narrow state;
2. flavour symmetry does exist. In principle in the heavy-quark infinite mass limit one is allowed to use the same chart tfor $c\overline{q}, c\overline{s}, b\overline{q}, b\overline{s}$ mesons, just changing quark

labels and absolute mass energy scale.

However, the HQS paradigm was recently put in discussion by BABAR's and CLEO's discovery of D_{sJ} states.

L=1 NON-STRANGE EXCITED D MESONS

All six $L=1, j=3/2$ non-strange *narrow* states are well established, with precisions on masses at the 1 MeV level and on widths at the few MeV level. This is due to the fact that excited D states are abundantly produced both at FT experiments, in e^+e^- continuum production, in B decays and at the Z^0 [7].

Table 1 shows the experimental data available for $c\overline{q}$ L=1 mesons, masses and widths, as showing on Ref.[8] updated to 2005, as well as recent measurements not appearing in PDG world averages. In bold I listed measurements that are somehow new or debated.

Let me first of all mention a long-standing dilemma, the $D^{*\prime}$. Called $D^*(2640)^{\pm}$ by PDG, the first L=1 radial excitation was seen by DELPHI [9] in the $D^{*+}\pi^-\pi^+$ final state; it has not been confirmed by any experiment (OPAL[10], CLEO[11], ZEUS[12]). Final disproof or confirmation is needed, and it should be considered as a relatively easy task considered the level of statistics currently available to contemporary experiments.

The status of the *broad* L=1 states is not clear at all, as well. The assignments of the quantum numbers are largely based on theory expectations for their masses and widths. In 1998 CLEO [13] showed evidence for the $D_1(j_q=1/2)$ broad state. Two results, by BELLE [14] and photoproduction experiment FOCUS [15], have appeared in 2003 and are now included in the average of PDG 2005. BELLE have studied the $D^{*+}\pi^-$ and $D^+\pi^-$ final states, while FOCUS have studied both isospin channels $D^+\pi^-$ and $D^0\pi^+$. They both claim observation for broad states. Due to the presence of feeddown satellite peaks due to missing neutral kinematics, FOCUS do not claim conclusively that the broad state observed is the D_0^* predicted by HQS. The mass values found are in disagreement at the $\sim 2\sigma$ level, and consistent with many predictions out of the huge number of papers on the subject. The BELLE mass value is notably close to what predicted a long time ago [16]. More experimental results are needed.

New players in the D meson spectroscopy game could be the experiments at hadron colliders, which have greatly improved charm physics capabilities with impact paramenter trigger which uses silicon vertex detectors. As instance, CDF at the Fermilab Tevatron showed results in 2003 [17] with high statistic peaks of L=1 mesons sitting on huge combinatoric backgrounds, due to high multiplicity of primary interaction vertex. Clearly, hadroproduction is not the best place to look for L=1 mesons. However, more recent unpublished results [18] show great improvements, with $D\pi$ distributions clearly evidencing clean L=1 mesons peaks. We expect interesting news from CDF and D0, possibly at this same conference.

TABLE 1. Summer 2005 status of (L=1, n=1) and (L=0, n=2) $c\bar{q}$ mesons (MeV). Statistical and systematical errors added in quadrature, unless noted. Preliminary data from CDF are from [17][18].

j_q	$1/2$	$1/2$	$3/2$	$3/2$	$1/2$	$1/2$
J^P	0^+	1^+	1^+	2^+	0^-	1^-
L,n	$1,1$	$1,1$	$1,1$	$1,1$	$0,2$	$0,2$
	$D_0^*(2400)$	$D_1(2430)$	$D_1(2420)$	$D_2^*(2460)$	D'	$D^{*\prime}\,[D^*(2640)]$
Decay Mode	$D\pi$	$D^*\pi$	$D^*\pi$	$D\pi, D^*\pi$		$D^*\pi\pi$
Mass (MeV)						
PDG 0	**2352** $\pm$ **50**	2427 $\pm$ 36	2422 $\pm$ 2	**2461.1** $\pm$ **1.6**		
PDG $\pm$	2403 $\pm$ 38		2427 $\pm$ 5	**2464.9** $\pm$ **3.0**		2637 $\pm$ 7
CDF prel. $\pm$				**2463.6** $\pm$ **2.7** $\pm$ **x**		
CDF prel. 0			**2421.7** $\pm$ **0.9**	**2463.3** $\pm$ **1.0**		
Width (MeV)						
PDG 0	**261** $\pm$ **50**	384 $\pm$ 117	19 $\pm$ 4	**32** $\pm$ **4**		
PDG $\pm$	283 $\pm$ 42		28 $\pm$ 8	29 $\pm$ 5		<15
CDF prel. 0			**20** $\pm$ **2**	**49** $\pm$ **3**		
Isospin Mass Splitting(MeV)						
PDG			$4^{+2}_{-3} \pm 3$	**2.4** $\pm$ **1.7**		

L=1 STRANGE EXCITED D MESONS, OR: NEED TO CHANGE PARADIGM OF D SPECTROSCOPY ?

Before Spring 2003 we thought we could use the same $c\bar{q}$ chart in Fig.2 for $c\bar{s}$, thanks to flavour symmetry of HQS. The narrow D_{s1} and D_{s2}^* states have been very well established since a long time, and we would expect the two missing broad $c\bar{s}$ states to lie somewhere above the DK and D^*K threshold, respectively.

Instead, surprisingly enough, BABAR finds[19] a prominent peak at 2317 MeVin $D_s\pi^0$ with width compatible to experimental resolution. They also find another narrow peak in $D_s^*\pi^0$, but are not sure whether it is a reflection or not, therefore do not claim observation for a second state. The analysis is complicated by the presence of two reflections from undetected neutrals. Following BABAR announcement, CLEO looked

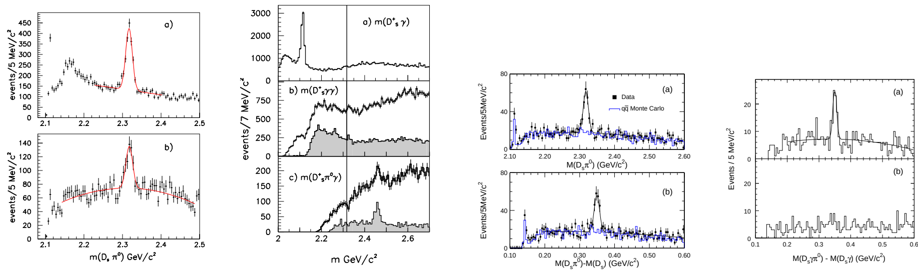

FIGURE 3. *New $D^*_{s0+}(2317)$ and $D^*_{s1+}(2463)$ states observed by BABAR (a,b) [19] and CLEO (c,d) [21].*

back to circa-1995 data, at the time when they published [20] the first evidence for isospin-violation decay $D^*_s \to D_s\pi^0$. At that time they had much less statistics, now they integrate all events and they also confirm[21] the BABAR state. By availing of a more trained analysis they find and interpret correctly the $D^*_s\pi^0$ state at 2463 MeVas another new state. BELLE joins the club by finding evidence[22, 23] of the $D_{sJ}(2463) \to D_s\gamma$ and determines the J^{PC}. A detailed historical account is reported in [1].

It seems natural to interpret $D^*_{sJ}(2317)$ and $D^*_{sJ}(2463)$ as 0^+ and 1^+ states, respectively. The decay distributions are consistent with such assignments, yet do not establish them. They together with the mass values would explain the narrow widths: for $D^*_{s1+}(2463) \to DK$ is forbidden by parity, $D^*_{s0+}(2317) \to DK$ and $D^*_{s1+}(2463) \to DK^*$ by kinematics and $D^*_{s0+}(2317) \to D^+_s\pi^0$ and $D^*_{s1+}(2463) \to D^{*+}_s\pi^0$ are isospin violating transition and thus suppressed. Also $D^*_{s0+}(2317) \to D^+_s\gamma$ is forbidden.

There are three puzzling aspects to these states:

- Why have no other decay modes been seen ? In particular CLEO places a low upper bound
$$BR(D^*_{s0+}(2317) \to D^{*+}_s\gamma) < 0.078 \;\; 90\%\, C.L. \tag{1}$$
Why is it not more prominent, when $D^*_{s0+}(2317) \to D_s\pi^0$ is isospin violating ?
- Why are their masses so much below predictions ? One should note that a deficit of ~ 160 and ~ 100 MeV is quite significant on the scale of $M(D^*_{sJ}) - M(D)$. Answers to this question have been proposed a long time ago[16]. Why is the mass splitting to the previously found narrow states $D_{s1}(2536)$ and $D_{sJ}(2573)$ so much larger than anticipated ?
- A related mystery is the following: where are the corresponding *non*-strange charm resonances ? They should be lighter, not heavier than $D^*_{s0+}(2317)$ and $D^*_{s1+}(2463)$.

PDG 2005 entries (reported in Table 2) are dominated by the BABAR measurements. Unpublished results not on PDG are the observation of the 2317 MeVstate by FOCUS, worth to be mentioned because it is the only observation of a D_{sJ} state outside e^+e^- colliders, and some results on 1^+ states.

What is really new is a couple of results from BELLE [27, 26] presented at (northern hemisphere) Summer conferences, most notably measurement of branching ratios, and observation of a nonresonant decay of $D^+_{s1}(2536)$. BELLE have studied the decay $B^0 \to$

TABLE 2. Summer 2005 status of (L=1, n=1) and (L=0, n=2) $c\bar{s}$ mesons (MeV). Statistical and systematical errors added in quadrature, unless noted. Preliminary results are from FOCUS[24][25] and BELLE[26].

j_q	1/2	1/2	3/2	3/2	1/2	1/2
J^P	0^+	1^+	1^+	2^+	0^-	1^-
L,n	1,1	1,1	1,1	1,1	0,2	0,2
	$D^*_{sJ}(2317)$	$D_{sJ}(2460)$	$D_{s1}(2536)$	$D^*_{s2}(2573)$	D'_s	$D^{*\prime}_s$
Decay Mode	$D_S^+\pi^0$	$D_S^+\gamma, D_S^{*+}\pi^0, D_S^+\pi^+\pi^-$	$D^*K, D\pi K$	DK		
		Mass (MeV)				
PDG $\pm$	2317 ± 0.6	2458.9 ± 0.9	2535.35 ± 0.6	2573.5 ± 1.7		
FOCUS prel. $\pm$	2323 ± 2		2535.1 ± 0.3	2567.3 ± 1.4		
		$BR(D\pi K)/BR(D^*K)$				
BELLE prel. $\pm$			$2.8 \pm 0.2 \pm 0.4\%$			
		Width (MeV)				
PDG $\pm$	<4.6	<5.5	<2.3 90 % cl	15 ± 5		
FOCUS $\pm$			1.6 ± 1.0	28 ± 5		

$D_{sJ}(2317)^+K^-$ which is an interesting decays because quark content of final state is totally different from B meson, suggesting non-trivial decay mechanisms: W-exchange, final state interactions, tree diagram if the D_{sJ} has a 4-quark structure. The new measurement improves previous low-statistics results. BELLE find a very large isospin breaking, namely that the rate for $\bar{B}^0$ decays to $D_{sJ}(2317)$ is about three times larger than rate to $D_{sJ}(2460)$. BELLE also study the resonant structure of $D_{s1}(2536)^+ \to D^+\pi^-K^+$ decay, finding a small but non-zero fraction of non-resonant $D^+\pi^-K^+$ component relative to resonant $D^{*+}K_s^0$. Besides, they studied the presence of an S-wave component, which may give informationon mixing between the two newly discovered 1^+ states. I expect BELLE to report on this at this Conference.

THE $D_{SJ}(2632)^+$

Following the discovery of D_{sJ} states by BABAR and CLEO, SELEX (fixed target hadroproduction at Fermilab with Σ^- and π^- beams) looked for signals in strangess-rich channels with a charm meson, such as $D_s^+\eta, D^0K^+$ [28]. They found evidence for a state at 2632 MeV, with a width $\Gamma < 17$ MeV. They also found a very strong isospin breaking, *i.e.,* the D^0K^+ is severely depressed with respect to $D_s^+\eta$.

Given the interest of the SELEX results, quite immediately all other active charm experiments looked for confirmation. Photoproduction experiment FOCUS looked [29] in D^+K_s, D^0K^+, BABAR[30] in $D_s^+\eta, D^0K^+, D^{*+}K_s$, BELLE [31] in $D_s^+\eta, D^0K^+$. All three experiments saw no evidence. Unless a peculiar production mechanism related to the hyperon beam is in place here, one should consider the SELEX evidence not confirmed. Results from hadron beam experiments (CDF/D0 at Tevatron, and COMPASS at CERN) would be useful to shed light and revive the case for the $D_{sJ}(2632)$.

CHANGING PARADIGMA OF HQ SECTROSCOPY - A PLETHORA OF IDEAS

Needless to say, the BABAR and CLEO discoveries spurred a plethora of theory papers. My personal list of favourite topics sees the idea of Ref. [32] in top position: combine HQS and chiral invariance, form doublets by pairing (D_s^+, D_s^{*+}) with $(D^*_{s0^+}(2315), D_{s1^+}(2460))$. By applying chiral dynamics they find that the splitting between doublets should follow the prediction, indeed verified,

$$\Delta M \equiv M(D^*_{s0^+}(2315)) - M(D_s)\; M(D_{s1^+}(2460)) - M(D^*_s)\; m_N/3 \tag{2}$$

An interesting comment was made [33] on the relative production rate of 3/2 versus 1/2 states. Sum rules predict dominance of 3/2 states (such as D_1 and D_2^*) versus 1/2 states (such as broad D_0^* and D_1). Since experimentally the opposite is observed, the author suggests the discrepancy be reconciled with lower mass 1/2 states, compatible to those found by BABAR and CLEO.[1]

As for the SELEX evidence, it was noted[37] how, if the SELEX $D_{sJ}(2632)$ state was confirmed experimentally, the very strong isosping breaking could be explained by a 4q structure $[cd][ds]$.

Reviewing the theory ideas put forward is beyond the scope of this paper, the interested reader can avail of several reviews, such as [38].

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[1] *Note added in proof* - Recent BELLE results [34] seem to suggest that the semileptonic decay $B \to X_c \ell \overline{\nu}$ is predominatly due to $X_c = D(L = 1, j_q = 3/2)$ states. For a recent review see [35].

OUTLOOK AND CONCLUSIONS

We should be aware of the exciting era we are living, at least as far heavy quark spectroscopy is concerned. A lot of new results from all charm experiments active today have urged the need for a critical revision of the basic assumptions in the paradigma used so far.

The discoveries of D_{sJ} states by BABAR and CLEO ask for a critical revision of the HQS paradigma. BELLE entered the game with confirmation of states, new decay modes, and a flurry of new results. Non-strange broad states have now been established, with FOCUS and BELLE confirming the 1998 evidence by CLEO. The PDG average for the newly observed states sums up mass values in mild disagreement, more data is needed and results should come soon.

The intriguing evidence of $D_{sJ}(2632)$ by SELEX is not confirmed by FOCUS, BABAR, BELLE. We could be experiencing a peculiar production mechanism connected to the strangeness-rich beam, or simply a statistical fluctuation. There is real opportunity for hadron beam experiments (CDF/D0 at Tevatron, COMPASS at CERN) to say the last word on the issue. As a lot of work is being done presently world-wide, we should expect a wealth of new results in plenary (Mueller[39], Trabelsi[40], Maciel[41]) and parallel (Kopar[42], Poireau[43], Cumalat[44], Lesiak[45]) session talks.

Where are we going next ? Of course the list of open problems is fairly large, just to quote some:

- establish the non-strange broad states. In particular all channels with neutrals are unobserved so far;
- measure the widths of D_{sJ} states;
- measure the relative production of 1/2 versus 3/2 states;
- solve the mystery of the existence of the radial excitations.
- investigate the *Terra Incognita*: the beauty L=1 mesons, verify the little data available[46], mainly dating back to LEP, and check the validity of flavour symmetry, if any.

Most of this shopping list will be addressed by experiments at B-factories. Hadroproduction (CDF/D0) may contribute, as well fixed target (COMPASS at CERN). In the far future I see only SuperBELLE as a player, after the cancellation of the flavour programme in the US. LHC-b seems to be ruled out by the choice of not triggering on charm decays. PANDA [47] will be a major player in charmonium spectroscopy, but seems to me problematic in taming the huge minimum bias background in the search of charm decay verteces. As for the B spectroscopy sector, which is crucial to verify the extent to which one can still apply flavour symmetry, it should be playground of LHC-b at CERN. In any case, the field literally bursts with enigmas, and loads of good data are coming in.

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REFERENCES

1. S. Bianco, F. L. Fabbri, D. Benson and I. Bigi, Riv. Nuovo Cim. **26N7** (2003) 1 [arXiv:hep-ex/0309021].
2. J. L. Rosner, arXiv:hep-ph/0508155.
3. K. K. Seth, “Exciting developments in hadron spectroscopy,” arXiv:hep-ex/0511061.
4. T. Barnes, “HADRON05 summary: Heavy quark hadrons and theory,” arXiv:hep-ph/0510365.
5. K. Niu, E. Mikumo, Y. Maeda, *Prog. Theor. Phys.* **46** (1971) 1644.
6. The story of the discovery of charm in Japan is narrated in: K. Niu, Proceed. Of the First Intern. Workshop on Nucl. Emulsion Techn., June 12-14, 1998, Nagoya, Japan, preprint DPNU-98-39.
7. P. Roudeau, “Charm, beauty and tau physics at LEP,” LAL-97-96 *Talk given at Int. School of Physics, ’Enrico Fermi’: Heavy Flavor Physics - A Probe of Nature’s Grand Design, Varenna, Italy, 8-18 Jul 1997*
8. S. Eidelman *et al.*, Phys. Lett. **B592**, 1 2004 and 2005 web updates.
9. P. Abreu *et al.* [DELPHI Collaboration], *Phys.Lett.* **B426** (1998) 231.
10. G. Abbiendi *et al.* [OPAL Collaboration], Eur. Phys. J. C **20** (2001) 445.
11. J. L. Rodriguez [CLEO Collaboration], arXiv:hep-ex/9901008.
12. F. Sefkow [H1 Collaboration], arXiv:hep-ex/0011034.
13. S. Anderson *et al.* [CLEO Coll.], Nucl. Phys. A **663**, 647 (2000).
14. K. Abe et al., Phts. Rev. **D69** 112002.
15. J.M. Link et al., Phys. Lett. **B586**, 11-20 (2004).
16. T. Matsuki and T. Morii, Phys. Rev. D **56** (1997) 5646.
17. M. Shapiro, presented at FPCP 2003, Paris.
18. CDF Coll., CDF-Note-7191, available at `www-cdf.fnal.gov`.
19. BABAR Collab., B. Aubert *et al.*, hep-ex/0304021.
20. J. Gronberg *et al.* [CLEO Collaboration], Phys. Rev. Lett. **75** (1995) 3232 [arXiv:hep-ex/9508001].
21. CLEO Collab., D. Besson *et al.*, hep-ex/0305017.
22. K. Abe *et al.*, arXiv:hep-ex/0307052.
23. K. Abe *et al.* [Belle Collaboration], arXiv:hep-ex/0307041.
24. E.Vaandering (for the FOCUS Coll.), hep-ex/0406044.
25. R. K. Kutschke [FOCUS Collaboration], Frascati Phys. Ser. **20** (2001) 321.
26. BELLE Coll., hep-ex/0507030.
27. A. Drutskoy (for the BELLE Coll.), HEP05 (EPS) Lisboa (Portugal) 2005. BELLE-Conf-0516, 0519.
28. A.V.Evdokimov et al., Phys. Rev. Lett. **93**, 242001 (2004).
29. R.Kutschke (FOCUS Coll.), E831-doc-701-v2, available at `www-focus.fnal.gov`.
30. BABAR Coll., hep-ex/0408087.
31. B. Yabsley (BELLE Coll.), hep-ex/0507028.
32. W. Bardeen, E. Eichten, C. Hill, Phys. Rev. **D68** 054024,2003.
33. N. Uraltsev, hep-ph/0406086.
34. K. Abe *et al.* [Belle Collaboration], arXiv:hep-ex/0507060.
35. I. I. Bigi *et al.*, arXiv:hep-ph/0512270.
36. F. Jugeau, A. Le Yaouanc, L. Oliver, J-C. Raynal, hep-ph/0504206.
37. L. Maiani, F. Piccinini, A.D. Polosa, V. Riquer, Phys. Rev. **D70** 054009, 2004.
38. P. Colangelo, F. De Fazio and R. Ferrandes, Mod. Phys. Lett. A **19** (2004) 2083 [arXiv:hep-ph/0407137].
39. D. Muller [BABAR Collaboration], arXiv:hep-ex/0510050.
40. K. Trabelsi, *these Proceedings*.
41. A.Maciel, *these Proceedings*.
42. J. Kopar, *these Proceedings*.
43. V. Poireau, *these Proceedings*.
44. J. Cumalat, *these Proceedings*.

45. T. Lesiak, *these Proceedings*.
46. F. L. Fabbri, “Heavy flavor spectroscopy,” *Prepared for Workshop on Hadron Spectroscopy (WHS 99), Rome, Frascati, Italy, 8-12 Mar 1999,* Frascati Phys. Ser. **15** 627, 1999.
47. G. Boca (for the PANDA Coll.), *these Proceedings*.