Charm and $\tau$ Decays: Review of BaBar and Belle Results

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A review of recent results concerning decays of charmed mesons, charmed baryons and $\tau$ leptons for the Belle and BaBar Experiments is given. The review was presented at the 43$^{rd}$ Rencontres de Moriond (QCD and High Energy Interactions), La Thuile, March 8-15, 2008.

The $B$ meson factories can in fact also be considered as charm and $\tau$ factories, as (a) $\sim$99% of all $B$ mesons decay to charm final states, and (b) the cross sections of charm and $\tau$ production in the continuum, i.e. $e^+e^-\to q\bar{q}$ ($q=u,d,s,c$) and $e^+e^-\to \tau^+\tau^-$, are as high as the cross section for $B$ meson production ($\sim$1 nb) in the $Y(4S)$ decay. Details of the BaBar and Belle detectors can be found elsewhere.

At the time of this review, the integrated luminosities are 512.2 fb$^{-1}$ for BaBar and 773.7 fb$^{-1}$ for Belle.

1 Charm Decays

1.1 $D_{sJ}$ states

Earlier two new $D_{sJ}$ states have been observed: the $D_{s0}(2317)$ by BaBar in the decay $D_{s0}^+(2317)\to D_s^+\pi^0$, and the $D_{s1}(2460)$, by CLEO in the decay $D_{s1}^+(2460)\to D_s^{*+}\pi^0$. In both cases, due to the $D_{s}$ in the final state, the most probable assignment is a $(c\bar{s})$ state with $L=1$. However, the measured masses were found $\sim$100 MeV too low compared to early quark models and inspired more theoretical and experimental work. Recent analyses have investigated decays of higher-mass $D_{sJ}$ states not only into $D_s\pi$, but also into $D^{(*)}K$, i.e. corresponding to a Feynman diagram with an internally (rather than externally) created $u\bar{u}$ pair.

1.2 $D_{sJ}$ decays into $D^*K$

This category of decays (assuming $L=0$) favors the production of vector or axial-vector $D_{sJ}$ states due to the $D^*$ vector meson in the final state. Recently BaBar reported the first observation of $D_{s1}(2536)$ in $B$ decays. A data set of 347 fb$^{-1}$ was used to investigate the decays $D_{s1}(2536)\to D^{*+}K^0$ and $D_{s1}(2536)\to D^{*0}K^+$. An analysis of the $D_{s1}(2536)$ helicity was performed in order to confirm the historically assigned PDG quantum numbers of $J^P=1^+$, which is the natural expectation in the heavy charm-quark limit for the lower member of an $L=1$, $j_q=3/2$ doublet. $J^P=1^+$ in a pure S-wave as well as $J^P=2^+$ and $J^P=2^-$ were disfavoured, whereas fits for $J^P=1^-$ in a pure P-wave and $J^P=1^+$ with S/D-wave admixture both describe the observed angular distribution well. On the other hand, Belle reported an analysis of $D_{s1}(2536)\to D^{*+}K^0_s$, but using continuum production $e^+e^-\to D_{s1}(2536)X$. A partial wave analysis on a data set of 462 fb$^{-1}$ was performed, in order to study the mixing of the ($j_q=1/2$) $D_{s1}(2460)$ and the ($j_q=3/2$) $D_{s1}(2536)$ states. Heavy Quark Effective Theory (HQET) predicts, that ($j_q=3/2$) $\to D^{*}K$ should be a pure D-wave decay, and ($j_q=1/2$) $\to D^{*}K$ should be a pure S-wave decay. If HQET is not exact, mixing between the S and D-waves would be possible by LS interaction:

$|D_{s1}(2460)> = \cos\theta|j_q=1/2> + \sin\theta|j_q=3/2>$ and $|D_{s1}(2536)> = -\sin\theta|j_q=1/2> + \cos\theta|j_q=3/2>.$

The fit result yields an admixture of $D/S=0.63\pm0.07$(stat.)$\cdot exp(\pm i(0.77\pm0.03$(stat.))). The result indicates that the S-wave dominates in the decay $D_{s1}(2536)\to D^{*}K$ with a fraction of

*Throughout this paper charge conjugations are implied if not noted otherwise.
Example, the result of a recent Lattice QCD calculation\cite{17} is estimates. However, theoretical calculations seem to indicate a lower value of $\Delta m \approx 76$ MeV. As a by-product of this analysis, Belle reported the first observation of a three-body decay mode of the $D_{sJ}(2536)$, in the decay $D_{sJ}(2536) \rightarrow D^{*0} K^+ \pi^−$.

1.3 $D_{sJ}$ decays into $DK$

This category of decays (assuming $L=0$) favors the production of scalar $D_{sJ}$ states due to the two pseudoscalar mesons in the final state. Recently Belle reported the observation of a new $D_{sJ}$ meson, tentatively called $D_{sJ}(2700)$, in $B^+ \rightarrow D^0 K^+$ decays with a data set of 414 fb$^{-1}$. The $D_{sJ}(2700)$ was found to be the dominating resonance in this $B$ decay. The mass was determined as $m=2708\pm9$ (stat.) $^{+11}_{-10}$ (syst.) MeV, the width as $\Gamma=108\pm23$ (stat.) $^{+36}_{-31}$ (syst.) MeV. The signal yield was reported as 182±30 events with a statistical significance of 8.4$σ$. In order to determine the quantum numbers, a helicity analysis was performed. A fit to the distribution of the helicity angle between the $D^0$ and the $D_{sJ}$ prefers an assignment of $J=1$. In this case, a $J=1 \rightarrow 0^− 0^−$ decay would imply $L=1$, and thus a negative parity assignment. Two possible interpretations of a $J^P=1^−$ $D_{sJ}(2700)$ state were proposed, i.e. (a) a radial $n=2$ excitation $(2^3S_1)$, predicted\cite{10} by potential models at $m\approx 2720$ GeV, or (b) a chiral doublet state $J^P=1^−$ as a partner to the $J^P=1^+$ $D_{sJ}(2536)$, predicted\cite{11} from chiral symmetry considerations at $m=2721\pm10$ MeV. The new Belle result could be compared to a prior search\cite{12} for higher $D_{sJ}$ states in the $ee^−$ continuum by BaBar with a data set of 240 fb$^{-1}$. Three structures were observed: (a) the known $D_{s2}(2573)$ state, (b) a new $D_{sJ}(2860)$ state, and (c) a broad structure peaking around 2.7 GeV, which could be identical to the $D_{sJ}(2700)$. As the $D_{sJ}(2860)$ is not seen in the Belle data, this might indicate that probably a higher $J$ should be assigned, and thus it is only produced in continuum, but not in $B$ decays.

1.4 $D_s^+ \rightarrow \mu^+ \nu_\mu$

The purely leptonic decay $D_s^+ \rightarrow \mu^+ \nu_\mu$ is theoretically rather clean, as in the standard model the decay is mediated by a single virtual $W$ boson. The decay rate is given by

$$\Gamma(D_s^+ \rightarrow l^+ \nu_l) = \frac{G_F^2}{8\pi} f_{Ds}^2 m_l^2 m_{Ds} (1 - \frac{m_l^2}{m_{Ds}^2})^2 |V_{cs}|^2$$

(1)

using the Fermi coupling constant $G_F$, the masses of the lepton and of the $D_s$ meson, $m_l$ and $m_{Ds}$, respectively, and the CKM matrix element $V_{cs}$. All effects of the strong interaction are accounted for by the decay constant $f_{Ds}$. The measurement of the branching fraction allows the determination of $f_{Ds}$ and the comparison to theoretical or Lattice QCD calculations. Recently several measurements of $f_{Ds}$ were performed. An overview is given in Tab. 1. BaBar reported\cite{13} a signal yield of $489\pm55$ (stat.) $D_s^+ \rightarrow \mu^+ \nu_\mu$ events in a data sample of 230 fb$^{-1}$. Belle reported\cite{14} a signal yield of $169\pm16$ (stat.) $\pm8$ (syst.) $D_s^+ \rightarrow \mu^+ \nu_\mu$ events in a data sample of 548 fb$^{-1}$. The reconstruction procedures show a few technical differences, i.e. the signal either peaks in (a) the mass difference of $m(\mu\nu\gamma)-m(\mu\nu)=143.5$ MeV, corresponding to the photon energy in the $D_s^+ \rightarrow D_{sJ} \gamma$ transition, or peaks in (b) the recoil mass $m(DKX\gamma\mu)=0$, where $X=\pi\pi$ and $\geq 1\gamma$ with $n=1,2,3$. In addition, while Belle determines an absolute branching fraction, the BaBar experiment provides a measurement of the partial width ratio $\Gamma(D_s^+ \rightarrow \mu^+ \nu_\mu)/\Gamma(D_s^+ \rightarrow \phi\pi^+)$. The recent measurements of $f_{Ds}$ of Belle, BaBar and also CLEO-c\cite{15} are consistent within the error estimates. However, theoretical calculations seem to indicate a lower value of $f_{Ds}$\cite{16}. As an example, the result of a recent Lattice QCD calculation\cite{17} is $f_{Ds}=241\pm3$ MeV. The discrepancy

$(72\pm3$ (stat.$)\pm1$ (syst.$))\%$, which contradicts HQET. The reason might be given by the fact, that HQET assumes the $c$ quark to be infinitely heavy. However, it should be noted that the interpretation is not trivial, as the $D$-wave might also be suppressed by the centrifugal barrier. In any case, there is strong indication that the $D_{s1}(2460)$ and the $D_{s1}(2560)$ in fact are mixing, which might be considered surprising for two very narrow states ($\Gamma \leq 1$ MeV) with a mass difference of $\Delta m \approx 76$ MeV. As a by-product of this analysis, Belle reported the first observation of a three-body decay mode of the $D_{sJ}(2536)$, in the decay $D_{sJ}(2536) \rightarrow D^{*0} K^+ \pi^−$. 

(72±3(stat.)±1(syst.)%)%
Table 1: Overview of recent measurements of the branching fraction for $D_s^+\rightarrow\mu^+\nu_\mu$ and $f_{D_s}$.

|               | $\text{Br}(D_s\rightarrow\mu^+\nu_\mu)$ | $f_{D_s}$ (MeV) |
|---------------|-----------------------------------------|-----------------|
| PDG06         | (6.1±1.9)·10^{-3}                       |                 |
| BaBar         | (6.74±0.83±0.26±0.66)·10^{-3}           | 283±17±7±14    |
| Belle         | (6.44±0.76±0.57)·10^{-3}                | 275±16±12      |
| CLEO-c        | (5.94±0.66±0.31)·10^{-3}               | 274±13±7       |

between experiment and theory gave rise to speculation as a possible indication of new physics. Note that charm quark loops are not included in the Lattice QCD calculation.

1.5 Decays of Charmed Baryons

Recently new studies of the $\Xi_c$ charmed baryon system\(^{[5]}\) were performed by both BaBar and Belle. Formerly, the $\Lambda_c K \pi$ final state has been used in the $B$ meson factories in searches for double charm baryon ground states. For these (ccq) states, this final state indicates weak decays. However, Belle formerly observed\(^{[18]}\) two new $\Xi^+_c$ states, i.e. the $\Xi^+_c(2980)^{+,0}$ and the $\Xi^+_c(3077)^{+,0}$ in $\Lambda^+_c K^- \pi^+$ and $\Lambda^+_c K^0_s \pi^-$. The doublet nature of these states clearly indicate the $\Xi^+_c$ interpretation. Contrary to double charm baryons, for $\Xi^+_c$ baryons these final states indicates strong decays. The discovery of these decays might be considered as a surprise, as (a) formerly only $\Xi^+_c$ decays to $\Xi_c^c\gamma$ and $\Xi_c\pi$ were observed, and (b) here the charm and the strange quarks are observed in different hadrons. Thus the decay reveals an interesting dynamics. Recently BaBar\(^{[19]}\) also published an updated $\Xi_c$ analysis based upon 384 fb\(^{-1}\). Besides the confirmation of the $\Xi_c(2980)$ and the $\Xi_c(3077)$, two new states were observed. In the analysis, the final state of $\Lambda_c K \pi$ (same as above) was required, however using a cut on the $\Sigma_c$ invariant mass in the $\Lambda_c \pi$ subsystem. The new states and observed decays are: $\Xi^+_c(3055)^{+,0}\rightarrow\Sigma^+_c(2455)^{++,0}(J^P=1/2^+)K^-\pi^+$ with a statistical significance of 6.4$\sigma$, and $\Xi^+_c(3122)^{+,0}\rightarrow\Sigma^+_c(2520)^{++,0}(J^P=3/2^+)K^-\pi^+$ with a statistical significance of 3.6$\sigma$. The observation of these decays imposes a new question to the understanding of the dynamics in the decay, namely why the $\Xi_c$ states decay into a $\Sigma_c$ with an isospin 1. Again, the charm and the strange quark are observed in different hadrons, i.e. ($u_suc\rightarrow(u_suc)(\pi s)$). Belle recently continued\(^{[20]}\) the investigation of the $\Xi_c(2980)$ with a data set of 414 fb\(^{-1}\) in order to try to determine the nature of this state. The $\Xi_c(2980)$ could be the first positive parity excitation of the $\Xi_c$, or a higher ($n\geq2$) radial excitation. A new decay mode $\Xi^+_c(2980)^{+,0}\rightarrow\Xi^+_c(2645)^{+,0}\pi^-$ was observed. Single pion transitions of such kind can give important hints for the assignment of quantum numbers. For example, the transition $\Xi^+_c(2815)^{++,0}(J^P=3/2^-)\rightarrow\Xi^+_c(2645)^{+,0}(\text{ground state})\pi^-$ is forbidden, but the transition $\Xi^+_c(2815)^{++,0}(J^P=3/2^-)\rightarrow\Xi^+_c(2645)^{+,0}\pi^-$ is allowed. On the other hand, the double pion transition $\Xi^+_c(2815)^{++,0}(J^P=3/2^-)\rightarrow\Xi^+_c(\text{ground state})\pi\pi^-\pi^-$ is allowed in any case and thus less indicative for quantum number assignments. Assuming S-wave, the newly observed decay mode is predicted\(^{[21]}\) dominant for the $\Xi^+_c(1/2^+)\rightarrow\Xi^+_c(2815)^{++,0}(J^P=1/2^-)$ state, and thus might favour an assignment of a positive parity.

2 $\tau$ Decays

In the simplest tree diagram, hadronic $\tau$ decays are given by a $\tau\rightarrow\nu W$ transition, in which the virtual $W$ boson forms a quark anti-quark pair $q\bar{q'}$ with $q$ and $q'$ carrying different flavor. As any additional gluon might be soft, $\alpha_s\approx0.35$ is quite large, and therefore these decays are an interesting tool to study non-perturbative QCD.

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\(^{[5]}\) The valence quark contents of the $\Xi^+_c$ and the $\Xi^0_c$ are given by ($u_suc$) and ($d_suc$), respectively.
2.1 $\tau$ decays with an $\eta$ in the final state

Belle recently improved\textsuperscript{22} known branching fractions for $\tau$ decays with $\eta$ and two additional pseudoscalar mesons by a factor 4-6 with a data set of 485 $fb^{-1}$. For the decays $\tau^{-} \to K^{-} \pi^{0} \nu_{\tau}$ and $\tau^{-} \to \pi^{-} \pi^{0} \nu_{\tau}$ branching ratios of $4.7 \pm 1.1 \,(\text{stat.}) \pm 0.4 \,(\text{syst.}) \cdot 10^{-5}$ and $4.7 \pm 1.1 \,(\text{stat.}) \pm 0.4 \,(\text{syst.}) \cdot 10^{-3}$ were measured, respectively. The measurement of the branching fractions is very important for understanding of low energy QCD. In the case of three pseudoscalar mesons the branching fraction could be increased by a factor $\geq 10$ by the Wess-Zumino-Witten anomaly\textsuperscript{23}.

2.2 $\tau$ decays with an $\phi$ in the final state

Recently BaBar published\textsuperscript{24} an analysis of $\tau$ decays into a $\phi$ and an additional pseudoscalar meson with a data set of 342 $fb^{-1}$. The decay $\tau^{-} \to \phi K^{-} \nu_{\tau}$ is Cabibbo suppressed by the CKM matrix element $V_{us} \simeq 0.2$. The measured branching fraction of $3.39 \pm 0.20 \,(\text{stat.}) \pm 0.28 \,(\text{syst.}) \cdot 10^{-5}$ is consistent with an earlier Belle result\textsuperscript{25}, and thus could be used as a reference for the branching fractions of even more rare processes. On the one hand, excluding the resonant $\phi$ contribution, an upper limit for the non-resonant $\tau^{-} \to K^{+} K^{-} K^{-} \nu_{\tau}$ of $< 2.5 \cdot 10^{-6}$ was obtained, indicating that the $\phi$ largely dominates the decay. On the other hand, a first measurement of the branching fraction of the OZI suppressed process $\tau^{-} \to \phi \pi^{-} \nu_{\tau}$ was performed with the result of $3.42 \pm 0.55 \,(\text{stat.}) \pm 0.25 \,(\text{syst.}) \cdot 10^{-5}$.

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