CHARMED MESON SPECTROSCOPY

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ABSTRACT
In the two years since HQL02, the long sought $j_{\ell} = 1/2$ states have been observed. In the charmed non-strange sector, these states have the expected properties but, in the charmed strange sector, the states have masses below threshold for the otherwise dominant decay modes, allowing their observation in suppressed modes. Improved measurements of the masses and widths of the well established P-wave charm states have also been published.

1 Introduction

These proceedings will discuss new results in the P-wave sector of the $c\bar{q}$ systems, where $q$ is one of $u$, $d$ or $s$. The spectroscopy of these mesons is described by coupling of the spins of the quark and anti-quark, $S_c$ and $S_{\bar{q}}$, with the orbital angular momentum, $L$, between the quark and anti-quark. When $L = 1$ this coupling produces 4 states, with $J^P = \{2^+, 1^+, 1^+, 0^+\}$. 
Until recently, all of the measured properties of the P-wave sector were well described by models which exhibit Heavy Quark Symmetry, HQS. In the limit that the mass of the charmed quark is >> $\Lambda_{QCD}$, the spin of the charmed quark decouples from the dynamics, leaving the total angular momentum of the light quark, $j_\ell = S_\bar{q} + L$, as an effective quantum number. In this limit, the $c\bar{u}$ and $c\bar{d}$ P-wave states are grouped into two doublets. One doublet, with $j_\ell = 3/2$, has members with $J^P = \{2^+,1^+\}$; these states decay to $D(\ast)\pi$ in a D-wave and have natural widths of order 20 MeV. The other doublet, with $j_\ell = 1/2$ has members with $J^P = \{1^+,0^+\}$; these states decay to $D(\ast)\pi$ in an S-wave and have natural widths of order a few hundred MeV. In the following the two $J^P = 1^+$ states will be denoted as $D_1$ and $D_1(j_\ell = 1/2)$, where the first notation is for the state with $j_\ell = 3/2$. To obtain the properties of the physical states, the finite mass of the charmed quark is introduced as a small perturbation on the HQS states.

The states with $j_\ell = 3/2$ are well established and have the predicted properties. The states with $j_\ell = 1/2$ have only recently been observed and are the topic of these proceedings. A more detailed discussion of HQS and a review of the data up to 10 years ago can be found in reference 1). The experimental results reviewed in these proceedings are the first significant new results since that time so the reference remains relevant.

Most models predicted a similar pattern for the $c\bar{s}$ mesons and the $j_\ell = 3/2$ states do indeed follow the pattern. There was, however, a model that predicted a rather different picture for the $j_\ell = 1/2$ $c\bar{s}$ mesons. In this model, which combines chiral symmetry with HQS, the $j_\ell = 1/2$ $c\bar{s}$ mesons were predicted to lie below threshold for decay to $D(\ast)K$. The decay modes available in this case are: $D_s(\ast)\pi^0$, which is isospin violating, $D_s(\ast)\pi\pi$, which is OZI suppressed, and $D_s(\ast)\gamma$, which are electromagnetic transitions. All of these decay modes have small partial widths of, at most, a few MeV. Refer to the transparencies of this talk for a bibliography of recent theoretical work on the $j_\ell = 1/2$ $D_s$ states.

2 P-wave Charmed Non-Strange Mesons

There are two new measurements in this sector. The FOCUS collaboration has presented measurements using the traditional method of looking at the inclusive $D^+\pi^-$ and $D^0\pi^+$ invariant mass spectra. The second set of new
measurements comes from the BELLE collaboration \cite{5}, who have pioneered a new technique, the measurement of excited charm resonances in the Dalitz plots of the decays $B \to D\pi\pi$ and $B \to D^{*}\pi\pi$.

In the $D\pi$ mass spectra presented by FOCUS one expects contributions from five processes plus combinatoric background. The five processes are: $D_2^* \to D\pi$, feed-down from $D_2^* \to D^{*}\pi$, feed-down from $D_1(2420) \to D^{*}\pi$, $D_0^* \to D\pi$, and feed-down from $D_1(j_\ell = 1/2) \to D^{*}\pi$. In the feed-down processes, the $D^{*}$'s decay to a $D$ plus unobserved neutrals, giving a final state of $D\pi$. Because of the small $Q$ values in these decay chains, the peaks from the feed-down processes suffer little kinematic broadening. In previous inclusive measurements, the first three processes, which give rise to narrow peaks, have been well established, but the final two processes, which produce broad peaks, could not be resolved above the combinatoric background.

Following the earlier experiments, the FOCUS collaboration first tried to fit their $D\pi$ mass spectra without including the last two processes. Their experiment, however, has an order of magnitude higher statistics than previous experiments and, after trying many models of the combinatoric background, none was able to produce a good fit to their data. Inspection of the residuals of the fits suggested that the fit would be improved by introducing a contribution from a broad resonance. Such a contribution was parameterized using S-wave Breit-Wigner\footnote{This work does not give any information about the $J^P$ of the broad states. The choice of an S-wave Breit-Wigner was driven by the expectation that any broad peak would be dominated by the $D_0^*$.} with a free mass, width and yield. This contribution is intended to model the sum of the contributions from an unknown mixture of $D_0^*$ and feed-down from the $D_1(j_\ell = 1/2)$. When this term was added, the fit produced an acceptable $\chi^2$. However it was never possible to resolve separately contributions from the $D_0^*$ and the $D_1(j_\ell = 1/2)$.

It has long been anticipated that the $e^+e^-\ B$-factory experiments would open a new window on charm spectroscopy through the analysis of the Dalitz plots in $B$ decay. The first hint at the power of this technique was presented by CLEO\footnote{This work does not give any information about the $J^P$ of the broad states. The choice of an S-wave Breit-Wigner was driven by the expectation that any broad peak would be dominated by the $D_0^*$.}, in which they used a partial reconstruction technique to perform a multi-dimensional fit to the decay $B^- \to D^{*+}\pi^-\pi^-$. BELLE has presented the first example of this technique using full reconstruction of the final state. They presented a fit to the Dalitz plot of the decay
$B^- \to D^+ \pi^- \pi^-$ and a 4 dimensional fit to the decay $B^- \to D^{*+} \pi^- \pi^-$. A key component of their analysis is that the energy of the $B$ mesons in the $e^+e^-$ center-of-mass frame is fully determined and they require that the energy of their $B$ candidates be consistent with this energy. This requirement removes the feed-down processes which complicate the FOCUS analysis. Compared with the FOCUS data, the BELLE data has an improved signal to background ratio, at the expense of signal yield.

The power of multi-dimensional fits is that interference among the contributing amplitudes gives rise to structures with distinctive shapes that are readily distinguished from backgrounds. For example the presence of the $D^*_{00}$ is established by observing its interference with the $D_2^*$ in the $D^+ \pi^- \pi^-$ Dalitz plot. Moreover these interference effects are powerful probes of the $J^P$ of the intermediate states and BELLE establishes that the $D^*_{00}$ and $D^*_{10}(j_\ell = 1/2)$ states do indeed have $J^P = 0^+$ and $J^P = 1^+$, as expected. In neither fit does BELLE find a significant contribution from a constant amplitude; that is, the data are fully described by a sum of resonant contributions, including virtual processes via the $D^*$ and $B^*$.

FOCUS and BELLE also presented new measurements of the parameters of the $D_2^*$ mesons. These measurements have errors that are comparable to those of the previous world averages.

All of the masses and widths discussed above, along with the PDG 2002 averages and new world averages, are shown in figure 11. Inspection shows that the new results are consistent with the PDG 2002 values, albeit barely consistent in a few cases. It does seem that the new results do prefer broader widths for both the of the $D_2^*$ charge states. Perhaps this indicates a bias toward narrow widths in early, statistically weaker observations. Because the FOCUS measurements of the $j_\ell = 1/2$ states are for an unknown mixture of the $D^*_{00}$ and feed-down from the $D_1(j_\ell = 1/2)$, the author recommends that the best values for the properties of the $D^*_{00}$ are the BELLE results alone.

There are several reasons why the $B$ decay results might differ systematically from the inclusive measurements. The line shape of the resonances is a matrix element squared multiplied by a phase-space factor. In the inclusive measurements it is difficult to write down the phase-space factor and it has always been ignored, motivated by the assumption that it varies only slowly over the region of interest. In $B$ decays it is straightforward to write down
the phase space factors and BELLE includes them. Presumably this is a small effect for the narrow states but an important effect for the broad states. A second difference is that the inclusive analyses always assume that the resonances are produced incoherently. While this is likely, is not certain.

The author looks forward to BaBar entering the field with Dalitz analyses of their B decays. He also looks forward to both B-factories presenting updated results with much larger datasets. In the longer term, both BTeV and LHCb should contribute to charm spectroscopy through the Dalitz analysis of B decays.

3 P-wave Charmed Strange Mesons

In the charmed strange sector, the $D_{s2}^*$ and the narrow $D_{s1}(2536)$ have been well established for more than a decade. It was long presumed that the the $D_{s0}^*$ and the $D_{s1}(j\ell = 1/2)$ would lie above threshold for decay to $DK$ and $D^*K$. In such a case this sector would look much like the non-strange sector, differing only in detail.

This picture was overthrown when the BaBar collaboration published the surprising observation of a new, narrow resonance at a mass of about 2317 MeV which decays to $D_s\pi^0$. Their paper also hinted at a second narrow resonance at a mass near 2456 MeV which decays to $D_s^*\pi^0$. Shortly afterward the first state was confirmed by CLEO, who also claimed a definite observation of the second state. Both BaBar and CLEO observed these states in continuum $e^+e^-$ production. Both states were soon confirmed by BELLE, who observed them both in continuum $e^+e^-$ and in $B$ decay. BELLE observed new decay modes of the $D_s(2456)$, to $D_s\gamma$ and $D_s\pi^+\pi^-$, and a new decay mode of one of the well established states, $D_{s1}(2536) \to D_s\pi^+\pi^-$. BaBar has since confirmed the $D_s(2456)$. Finally, FOCUS has observed the state at 2317 MeV in $D_s\pi^0$, which represents the first observation of either state outside of the $e^+e^-$.

In the following these states will be referred to as the $D_{s0}^*(2317)$ and the $D_{s1}(2536)$.

The analysis of the two states is more subtle than is hinted at by the previous paragraph. Consider the decay chain, $D_{s1}(2536) \to D_s^*\pi^0, D_s^* \to D_s\gamma$. If the $\gamma$ is missed and the state is reconstructed as $D_s\pi^0$, it produces a narrow feed-down peak in the $D_s\pi^0$ mass spectrum at a mass very close to that of the $D_{s0}^*(2317)$. Now consider starting with the decay $D_{s0}^*(2317) \to D_s\pi^0$,
adding a random photon, requiring that the $D_s\gamma$ invariant mass fall within
the experimental resolution on the $D_s^*$ mass, and then plotting the $D_s\gamma\pi^0$
invariant mass. This feed-up process will produce a narrow peak in the $D_s^*\pi^0$
invariant mass spectrum at a mass close to that of the $D_s(2456)$. A typical mass peak
in any of the BaBar, BELLE or CLEO analysis contains about 75% from the
signal being looked for and about 25% from either the feed-up or feed-
down background. The three experiments have developed different methods
for unfolding the true signals from these backgrounds and all experiments get
consistent results.

None of the experiments observe a non-zero natural width for these states
and the best upper limit comes from BELLE $^{13}$, $\Gamma(D_s^{*0}(2317)) < 4.6$ MeV and
$\Gamma(D_s(2456)) < 5.5$ MeV, both at the 90% confidence level.

The quantum numbers of these states are already well constrained. The
observation of $D_{s1}(2456) \rightarrow D_s\gamma$, forbids $J = 0$ and the BELLE analysis of
angular distributions in the decay $B \rightarrow DD_{s1}(2456)$ prefers $J = 1$ over $J = 2$.
The decay $D_{s1}(2456) \rightarrow D_s\pi^0$ is not observed, even though phase space favors
it over $D_s^*\pi^0$. This is most easily explained if the $D_s(2456)$ has $J^P$ from the
unnatural sequence, $0^-, 1^+, 2^- \ldots$ So the spin parity assignment of $J^P = 1^+$ is
strongly preferred for the $D_s(2456)$. Because the $D_s(2317)$ is observed to decay
to two pseudo-scalars, and presuming that parity is conserved in its decay, the
$D_s(2317)$ must have $J^P$ from the natural spin parity sequence, $0^+, 1^-, 2^+ \ldots$.

4 Summary and Conclusions

In the $c\bar{u}$ and $c\bar{d}$ sectors most of the $j_\ell = 1/2$ states have been observed;
only the $D_{s1}^+(j_\ell = 1/2)$ remains unobserved. These states have the properties
predicted by HQS and the $J^P$ quantum numbers are established using the
multi-dimensional analysis presented by BELLE. The results from the old in-
clusive technique and the new exclusive technique agree with each other but, in
a few cases, the agreement is only marginal. Perhaps this is an indication that
small effects, which could be ignored in the past can no longer be ignored in
high statistics, high precision experiments. The author looks forward to many
years of new results in charm spectroscopy from the multi-dimensional analysis
of B decays.

In the $c\bar{s}$ sector both $j_\ell = 1/2$ states have now been established. The
$D_{s1}(2456)$ has $J^P = 1^+$ strongly favored while the $D_s^{*0}(2317)$ is known to have
$J^P$ from the natural sequence, consistent with the expectation of $0^+$. Although many people considered the low masses of these states a surprise, if you accept the masses then all of the other properties of these states make sense. For example the narrow widths arise because only suppressed decay modes are kinematically allowed.

5 Acknowledgments

The author would like to thank the organizers of the conference for an exciting program, presented in comfortable and pleasant surroundings. He also thanks them for their patience in waiting for these proceedings.

6 References

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Figure 1: Masses and widths of charmed non-strange P-wave mesons. The first two errors are statistical and systematic. For BELLE the third error comes from the choice of contributions to the decay amplitude and for CLEO it comes from the parameterization of the strong phase. Parts a) through d) show the results for the well established $D_{s}^{*}$ and $D_{1}(2420)$ states. Parts e) and f) show the results for the newly observed broad $D_{1}$ and $D_{0}^{*}$ states. The averages are taken by the author; the CL notation gives the confidence level that the data are self consistent. As discussed in the text, no average is taken for the broad states and the BELLE results from the $D_{0}^{*}$ should be preferred over the FOCUS ones.