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Studies of $D_{sJ}^{(*)}$ Production in B Decays and $e^+e^- \to c\bar{c}$ Events

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Abstract. We report a study of $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ meson production in B decays. We observe and measure branching fractions for the decays $B^+ \to D_{sJ}^{(*)+}\bar{D}^{(*)0}$ and $B^0 \to D_{sJ}^{(*)+}\bar{D}^{(*)-}$ with the subsequent decays $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$, $D_{sJ}(2460)^+ \to D_s^{*+}\pi^0$, and $D_{sJ}(2460)^+ \to D_s^+\gamma$. In addition, we perform an angular analysis of $D_{sJ}(2460)^+ \to D_s^+\gamma$ decays to test the different $D_{sJ}(2460)^+$ spin hypotheses.

From a dataset of $e^+e^- \to c\bar{c}$ events we measure the masses of the $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ mesons and the $D_{sJ}(2460)^+ \to D_s^+\gamma$ and $D_{sJ}(2460)^+ \to D_s^+\pi^+\pi^-$ branching fractions. A search is performed for neutral and doubly-charged partners.

We have also searched for the $D_{sJ}^*(2632)^+$ reported by the SELEX collaboration at FNAL. The resulting $D_s^+\eta$ and D^0K^+ mass spectra show no evidence for the $D_{sJ}^*(2632)^+$ state. In addition, no signal is observed in the $D^{*+}K_s$ mass spectrum.

All the above studies are performed on data samples collected with the BaBar detector at the SLAC PEP-II B factory.

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INTRODUCTION

The unexpected observation of a narrow $D_s^+\pi^0$ resonance with a mass of 2317 MeV/c^2 was recently reported by the BaBar collaboration [1] and confirmed by the CLEO experiment [2]. CLEO observed a second $D_s^{*+}\pi^0$ resonance with a mass close to 2460 MeV/c^2 [2], previously suggested [1] and later confirmed [3] by BaBar. The Belle collaboration confirmed both resonances and found two additional decay modes for the higher-mass state [4], $D_s^+\gamma$ and $D_s^+\pi^+\pi^-$. These resonances are usually interpreted as P-wave $c\bar{s}$ quark states [5, 6, 7, 8, 9], although other interpretations [10, 11, 12, 13, 14] cannot be ruled out, and will be referred to in the following as $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ mesons.

In the framework of the heavy quark effective theory, an analogy is made between the $c\bar{s}$ system and a hydrogen atom. The approximation consists to consider a light quark (s quark) spinning around a heavy quark (c quark), such as the heavy quark is regarded as fixed. In this case, the quantum number of the s quark, $j = s_s + L$, where s_s is the spin of the s quark and L the orbital quantum number, is considered as good quantum number. The total quantum number of the $c\bar{s}$ system is defined as $J = j + s_c$, where s_c is the spin of the c quark. In this context, 2 S-wave states are predicted, identified as the $D_s(1968)^+$ and the $D_s^*(2112)^+$ mesons, and 4 P-wave states are predicted, where the states with $j = 3/2$ are identified with the $D_{s1}(2536)^+$ and $D_{s2}^*(2573)^+$ mesons. The agreement

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between the mass prediction of this model [15] and the real masses of the resonances is good. The 2 P-wave states with $j = 1/2$ (with $J^P = 0^+, 1^+$) are predicted with a mass between 2400 and 2600 MeV/c^2, and with a very large width (with a decay to $D^{(*)}K$).

This contradicts with the smaller masses and the narrow widths of the $D^*_{sJ}(2317)^+$ and $D_{sJ}(2460)^+$ mesons. It is then very important to measure further the properties of these 2 new resonances, and in particular to try to measure their quantum number.

The analyses presented below were performed using a 113 fb^{-1} and a 125 fb^{-1} data sample (depending if off-resonance data were used) collected on or near the $\Upsilon(4S)$ resonance with the BaBar detector at the PEP-II asymmetric-energy e^+e^- storage ring. The BaBar detector, a general-purpose, solenoidal, magnetic spectrometer, is described in detail elsewhere [16].

STUDY OF $B \to D^{(*)}_{SJ}\bar{D}^{(*)}$ DECAYS

The new states were first observed in $e^+e^- \to c\bar{c}$ collisions. Their observation in exclusive $B \to D^{(*)}_{sJ}\bar{D}^{(*)}$ decays allows additional properties of the $D^{(*)}_{sJ}$ state to be studied: the helicity angle distribution in B decays can be used to obtain information on the spin J, and the measurement of the different branching fractions can help clarify the nature of these states. This analysis [17] considers the production modes $B^+ \to D^{(*)+}_{sJ}\bar{D}^{(*)0}$ and $B^0 \to D^{(*)+}_{sJ}\bar{D}^{(*)-}$ with the subsequent decays $D^*_{sJ}(2317)^+ \to D^+_s\pi^0$, $D_{sJ}(2460)^+ \to D^{*+}_s\pi^0$, and $D_{sJ}(2460)^+ \to D^+_s\gamma$. After reconstruction of the $\bar{D}^{(*)}$ and $D^{(*)+}_s$ mesons, these candidates are combined with a photon or a π^0 to form B candidates. A B signal region is defined in terms of the beam energy substituted mass, $m_{ES} \equiv \sqrt{s/4 - p^{*2}_B}$, and the difference between the reconstructed energy of the B candidate and the beam energy, $\Delta E \equiv E^*_B - \sqrt{s}/2$, where $\sqrt{s}$ is the total energy in the $\Upsilon(4S)$ center-of-mass frame and E^*_B (p^*_B) is the energy (momentum) of the B candidate in the same frame.Different cuts are defined on these variables depending on the final state, and only one B candidate is selected per event. Signals are observed in the 3 decay modes: 88 $\pm$ 17 events with a mass of 2317.2 $\pm$ 1.3 MeV/c^2 for the $D^*_{sJ}(2317)^+\bar{D}^{(*)}$ $[D^+_s\pi^0]$ decay mode, 112 $\pm$ 14 events with a mass of 2458.9 $\pm$ 1.5 MeV/c^2 for the $D_{sJ}(2460)^+\bar{D}^{(*)}$ $[D^{*+}_s\pi^0]$ decay mode and 139 $\pm$ 17 events with a mass of 2461.1 $\pm$ 1.6 MeV/c^2 for the $D_{sJ}(2460)^+\bar{D}^{(*)}$ $[D^+_s\gamma]$ decay mode. Signals are also observed for each of the twelve $D^{(*)+}_s\bar{D}^{(*)}\pi^0/\gamma$ final states. A significance larger than 4 is observed for 10 of the 12 modes. From the $D^{(*)+}_{sJ}$ event yields in the data, the cross-feed-corrected branching fractions are computed, using the signal efficiency and the relative contributions from cross-feed between the different $D^{(*)+}_{sJ}$ decay modes as obtained from simulated signal events.

A helicity analysis of the $D_{sJ}(2460)^+$ state has been performed, using the decays $B \to D_{sJ}(2460)^+\bar{D}$ with $D_{sJ}(2460)^+ \to D^+_s\gamma$. The helicity angle θ_h is defined as the angle between the $D^{(*)+}_{sJ}$ momentum in the B meson rest frame and the D_s momentum in the $D^{(*)+}_{sJ}$ rest frame. A fit of the $D_s\gamma$ invariant mass is performed for five different $cos(\theta_h)$ regions. A good agreement is found with the $J = 1$ hypothesis.

STUDY OF $D_{SJ}^*(2317)^+$ AND $D_{SJ}(2460)^+$ IN CONTINUUM PRODUCTION

The properties of the $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ mesons are studied using $e^+e^- \to c\bar{c}$ events [18]. Searches are performed for the decay to the D_s^+ meson along with one or more π^0, π^+, or γ particles. A search is also performed for neutral and doubly-charged partners.

In this analysis, each D_s^+ candidate is constructed by combining a K^+K^- candidate pair with a π^+ candidate in a geometrical fit to a common vertex. Once a D_s^+ candidate is obtained, a search is performed for all accompanying π^0, γ and $\pi^\pm$ particles. Each final state is restricted to the same minimum center-of-mass momentum (p^*) value of 3.2 GeV/c^2.

The kinematic is complex, and leads to competing contributions and mutual cross-feeds between different modes.

$D_s^+\pi^0$ **final states:** to form $D_s^+\pi^0$ combinations, each D_s^+ candidate is combined with one π^0 candidate (the π^0 momentum is required to be greater than 400 MeV/c). A clear peak signal is seen at the mass of the $D_{sJ}^*(2317)^+$ resonance. Three types of background are present: the combinatorial background, background coming from the contribution of $D_s^*(2112)^+ \to D_s^+\gamma$ (where an unassociated γ forms a fake π^0 candidate), and background coming from the contribution of $D_{sJ}(2460)^+ \to D_s^*(2112)^+\pi^0$. These background contributions must be accurately determined from the simulation in order to extract the properties of the $D_{sJ}^*(2317)^+$. After taking into account these contributions, the results give a $D_{sJ}^*(2317)^+$ mass of 2318.9 $\pm$ 0.3 MeV/c^2, and $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ yields of 1275 $\pm$ 45 and 3 $\pm$ 26 mesons (statistical errors only).

$D_s^+\gamma$ **final states:** to form $D_s^+\gamma$ combinations, each D_s^+ candidate is combined with γ candidate with energy greater than 500 MeV/c. A clear peak is seen in the invariant mass distribution for the $D_{sJ}(2460)^+$. There is also a lower mass structure composed of $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$ and of $D_{sJ}(2460)^+ \to D_s^+\pi^0\gamma$, which could be described by the simulation. A $D_{sJ}(2460)^+$ mass of 2457.2 $\pm$ 1.6 MeV/c^2 and yield of 509 $\pm$ 46 mesons is obtained (statistical errors only). The fit, which allows the signal yield to fluctuate to negative values, obtains -107 $\pm$ 84 $D_{sJ}^*(2317)^+$ decays.

$D_s^+\pi^0\gamma$ **final states:** D_s^+, π^0 and γ particles are combined together, with the requirement that the minimum π^0 momentum is 400 MeV/c and that the minimum γ energy is 135 MeV. The $D_{sJ}(2460)^+$ signal can be better isolated by requiring the $D_s^+\gamma$ invariant mass to reside within 2 MeV/c^2 of the $D_s^*(2112)^+$ mass. This procedure isolates clearly the $D_{sJ}(2460)^+$ signal, but also introduces some peaking background in the invariant mass distribution ($D_s^*(2112)^+ \to D_s^+\gamma$ and $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$). A fit is then performed on this distribution, taking into account all contributions: the fit obtains a $D_{sJ}(2460)^+$ mass of 2459.1 $\pm$ 1.3 MeV/c^2 and yield of 292 $\pm$ 29 mesons (statistical errors only). It has also been shown that the decay $D_{sJ}(2460)^+ \to D_s^+\pi^0\gamma$ can be successfully described as proceeding entirely through the channel $D_s^*(2112)^+\pi^0$.

$D_s^+\pi^+\pi^-$ **final states:** to form $D_s^+\pi^+\pi^-$ candidates, each D_s^+ is combined with π^+ and π^- candidates with momentum above 230 MeV/c. The resulting invariant mass distribution has two distinct, narrow peaks, which correspond to the decays of the

$D_{sJ}(2460)^+$ and $D_{s1}(2536)^+$ mesons. The result of the fit of the invariant mass is a $D^*_{sJ}(2317)^+$ yield of 0.6 ± 1.8 decays; a $D_{sJ}(2460)^+$ mass and yield of 2460.1 ± 0.3 MeV/c^2 and 67 ± 11 decays.

$D^+_s\pi^\pm$ final states: there has been some conjecture [14, 10] that the $D^*_{sJ}(2317)^+$ may be a four-quark hybrid state. It might be expected, if it was true, that neutral and doubly-charged partners should exist with a similar mass. The $D^+_s\pi^\pm$ system can be used to test this possibility. To form $D^+_s\pi^\pm$, each D^+_s candidate is combined with $\pi^\pm$ candidates with momentum greater than 300 MeV/c. No resonant structure is observed in the resulting mass distribution.

After taking into account the systematic errors, and combining the different results of this analysis, the $D^*_{sJ}(2317)^+$ and $D_{sJ}(2460)^+$ masses are measured to be 2318.9 ± 0.3 (stat.) $\pm$ 0.9 (syst.) MeV/c^2 and 2459.4 ± 0.3 (stat.) $\pm$ 1.0 (syst.) MeV/c^2, respectively.

SEARCH FOR THE $D^*_{SJ}(2632)^+$

The SELEX collaboration at FNAL has recently reported the existence of a narrow state at a mass of 2632 MeV/c^2 decaying to $D^+_s\eta$ [20]. Evidence for the same state in the corresponding D^0K^+ mass spectrum was also presented. In the present analysis [19], inclusive production of the $D^+_s\eta$, D^0K^+ and $D^{*+}K_s$ systems in $e^+e^- \to c\bar{c}$ collisions is investigated in a search for the $D^*_{sJ}(2632)^+$ state.

Search for $D^*_{sJ}(2632)^+ \to D^+_s\eta$: each D^+_s candidate is constructed by combining a K^+K^- candidate pair with a π^+ candidate. For events containing a D^+_s candidate, η candidates are selected in the $\gamma\gamma$ decay mode. The precise cuts for this reconstruction are defined in the original paper [19]. The center-of-mass momentum $p^*(D^+_s\eta)$ of the $D^+_s\eta$ system is required to be at least 2.5 GeV/c to suppress background. In order to establish the presence of an excess of events in the correlated D^+_s and η production, a two-dimensional subtraction is performed in the $D^+_s - \eta$ invariant mass plane. After this subtraction is done, and looking at the invariant mass of the $D^+_s\eta$ system, no evidence of a signal has been found.

Search for $D^*_{sJ}(2632)^+ \to D^0K^+$: a D^0 candidate is constructed by combining a $\pi^+ - K^-$ pair in a geometric fit to a common vertex. A good D^0 candidate is combined with a well-identified K^+ track in a fit to a common vertex. The D^0K^+ mass spectrum is obtained after requiring $p^*(D^0K^+) > 4.0$ GeV/c. There is no evidence for structure in the 2.632 GeV/c^2 mass region.

Search for $D^*_{sJ}(2632)^+ \to D^{*+}K_s$: a D^0 candidate with mass within 25 MeV/c^2 of the central mass value is combined with a well-identified π^+ track in a fit to a common vertex. A candidate K_s track is reconstructed by vertexing a well-identified $\pi^+\pi^-$ pair. The center-of-mass momentum of the $D^{*+}K_s$ system is required to be greater than 4 GeV/c. There is no evidence for production of the $D^*_{sJ}(2632)^+$ state in the data.

CONCLUSION

Given the previous results, it is possible to make some assumptions on the spin of the $D^*_{sJ}(2317)^+$ and $D_{sJ}(2460)^+$ resonances. The J^P quantum numbers of the $D^*_{sJ}(2317)^+$

resonance is probably 0^+ since it does not decay to $D_s^* \pi^0$, to $D_s \gamma$ and to $D_s^* \pi^+ \pi^-$, as expected for a 0^+ state. The $D_{sJ}(2460)^+$ is probably a 1^+ state since it decays to $D_s \gamma$ and $D_s \pi^+ \pi^-$, and does not decay to $D_s \pi^0$ and DK. In addition, the helicity measurement in the exclusive analysis confirms this hypothesis.

Thus, on the experimental point of view, one natural possibility would be to identify the $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ with the two missing states 0^+ and 1^+ of the $c\bar{s}$ system.

In summary, the properties of the resonances $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ were studied. Masses, spin assignments, decay modes and branching fractions were determined using the data collected by the BaBar detector. In addition, no evidence for the $D_{sJ}^*(2632)^+$ state was found.

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