Study of $B \to D_{sJ}^{(*)+}\overline{D}^{(*)}$ Decays

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(Received 11 August 2004; published 25 October 2004)

We report a study of $D^*_{sJ}(2317)^+$ and $D_{sJ}(2460)^+$ meson production in B decays. We observe the decays $B^+ \to D^{(*)+}_{sJ}\overline{D}^{(*)0}$ and $B^0 \to D^{(*)+}_{sJ}D^{(*)-}$ with the subsequent decays $D^*_{sJ}(2317)^+ \to D^+_s\pi^0$, $D_{sJ}(2460)^+ \to D^+_s\gamma$, and $D_{sJ}(2460)^+ \to D^{*+}_s\pi^0$. Based on a data sample of 122.1×10^6 $B\overline{B}$ pairs collected with the *BABAR* detector at the PEP-II B factory, we obtain branching fractions for these modes, including the previously unseen decays $B \to D^{(*)+}_{sJ}D^*$. 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.

DOI: 10.1103/PhysRevLett.93.181801 PACS numbers: 13.25.Hw, 14.40.Lb

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 [5–8], although other interpretations [9–13] cannot be ruled out, and are referred to in the following as $D_{sJ}^*(2317)^+$ and $D_{sJ}(2460)^+$ mesons.

The new states were first observed in $e^+e^- \to c\bar{c}$ collisions. Their observation in exclusive $B \to D_{sJ}^{(*)+}\overline{D}^{(*)}$ decays allows additional properties of the $D_{sJ}^{(*)+}$ states to be studied: the $D_{sJ}(2460)^+ \to D_s^+\gamma$ helicity angle distribution in B decays can be used to obtain information on the $D_{sJ}(2460)^+$ spin J [14], and the measurement of the different branching fractions can help clarify the nature of these states.

In this Letter we consider the $D_{sJ}^{(*)+}$ production modes $B^+ \to D_{sJ}^{(*)+}\overline{D}^{(*)0}$ and $B^0 \to D_{sJ}^{(*)+}D^{(*)-}$ with the subsequent decays $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$, $D_{sJ}(2460)^+ \to D_s^{*+}\pi^0$, and $D_{sJ}(2460)^+ \to D_s^+\gamma$. Our intention is to observe previously unseen decay chains, measure branching fractions for all channels, and determine the $D_{sJ}(2460)^+$ spin by means of an angular analysis. Charge-conjugate reactions are assumed throughout this Letter.

The measurements reported here use 113 fb^{-1} of data, corresponding to $(122.1 \pm 1.3) \times 10^6$ $B\overline{B}$ pairs, collected at the $\Upsilon(4S)$ resonance with the *BABAR* detector [15] at the PEP-II asymmetric-energy B factory.

We reconstruct $\overline{D}$ and D_s^+ mesons in the modes $\overline{D}^0 \to K^+\pi^-$, $K^+\pi^-\pi^0$, $K^+\pi^-\pi^+\pi^-$; $D^- \to K^+\pi^-\pi^-$; and $D_s^+ \to \phi\pi^+$ ($\phi \to K^+K^-$), $\overline{K}^{*0}K^+$ ($\overline{K}^{*0} \to K^-\pi^+$). The reconstructed mass of the $\overline{D}$ and D_s^+ candidates is required to be within 2.5σ (3σ for $K^+\pi^-$, $K^+\pi^-\pi^-$, and $\phi\pi^+$) of the nominal D masses, where the D mass resolution σ, found in the data, is close to 12 MeV/c^2 for $\overline{D} \to K^+\pi^-\pi^0$ decays and varies from 5.3 to 6.3 MeV/c^2 for the other decay modes.

The D^* candidates are reconstructed in the decay modes $D^{*+} \to D^0\pi^+$, $D^{*0} \to D^0\pi^0$, $D^0\gamma$, and $D_s^{*+} \to D_s^+\gamma$. The mass difference Δm between the D^* and D candidates is required to be within 2 MeV/c^2 of its nominal value [16] for $D^{*+} \to D^0\pi^+$ and $D^{*0} \to D^0\pi^0$ (10 MeV/c^2 for $D^{*0} \to D^0\gamma$ and $D_s^{*+} \to D_s^+\gamma$), corresponding to about $5\sigma_{\Delta m}$ for D^{*+} and $2\sigma_{\Delta m}$ for D^{*0} and D_s^{*+}.

The selected pairs of $D_s^{(*)+}$ and $\overline{D}^{(*)}$ candidates are combined with a photon or a π^0 to form B candidates. The photon energy is required to be greater than 100 MeV. The neutral pions are built from pairs of photons with energies above 30 MeV and an invariant mass between 115 and 150 MeV/c^2. A mass-constrained kinematic fit is applied to all the intermediate particles. In order to suppress combinatorial background, we require the $\overline{D}^{(*)}\pi^0/\gamma$ invariant mass to be greater than 2.3 and 2.4 GeV/c^2 for $\overline{D}$ and $\overline{D}^*$ final states, respectively. Events compatible with being two-body decays $B \to D_s^{(*)+}\overline{D}^{(*)}$ are rejected.

We define a B signal region in terms of the beam energy substituted mass, $m_{\mathrm{ES}} \equiv \sqrt{s/4 - p_B^{*2}}$, 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. We require $5.272 < m_{\mathrm{ES}} < 5.288$ GeV/c^2 and $|\Delta E| < 32(40)$ MeV for π^0 (γ) final states. The width of the signal box is approximately $\pm 3\sigma$ in m_{ES} and $\pm 2\sigma$ in ΔE. We also define in the $D_s^{(*)+}\pi^0/\gamma$ mass spectra a signal region $|m(D_s^{(*)+}\pi^0/\gamma) - m(D_{sJ}^{(*)+})| < 2.5\sigma$ and a sideband region from 4σ to 12σ away from the nominal value, with $m(D_{sJ}^{(*)+}) = 2.317$ GeV/c^2 (2.460 GeV/c^2) for $D_s^+\pi^0$ ($D_s^{*+}\pi^0$, $D_s^+\gamma$). The resolution $\sigma = 8$ MeV/c^2 (12 MeV/c^2) for π^0 (γ) final states is obtained from simulated signal events.

The ΔE, m_{ES}, and $D_s^{(*)+}\pi^0$ or $D_s^+\gamma$ mass spectra of the selected events are shown in Fig. 1 for each of the three $D_{sJ}^{(*)+}$ final states after combining the charged and neutral $B \to D_{sJ}^{(*)+}\overline{D}^{(*)}$ modes and summing over all the $\overline{D}^{(*)}$ and $D_s^{(*)+}$ decays. Data points in each plot show the distribution of one variable in the signal regions of the other two. We also show (cross-hatched histograms) the ΔE and m_{ES} spectra of events in the $D_{sJ}^{(*)+}$ sidebands.

Only one B signal candidate per event, based on the smallest $|\Delta E|$, is entered in the $D_s^{(*)+}\pi^0$ and $D_s^+\gamma$ mass spectra and kept for further analysis. The $D_{sJ}^{(*)+}$ yields, masses, and resolutions, obtained from fitting a Gaussian signal function and an exponential background to these spectra, are given in Table I. The measured resolutions are compatible with expectations from the simulation, assuming zero intrinsic width for $D_{sJ}^{(*)+}$. We have also confirmed that the yields obtained from fits to the m_{ES} and ΔE spectra are in good agreement with the yields fitted from the $D_{sJ}^{(*)+}$ mass spectra.

The branching fraction measurement is based on the individual $D_s^+\pi^0$, $D_s^{*+}\pi^0$, and $D_s^+\gamma$ mass spectra for each of the 12 $D_s^{(*)+}\overline{D}^{(*)}\pi^0/\gamma$ final states. As shown in Fig. 2, signals for $B \to D_{sJ}^{(*)+}\overline{D}^{(*)}$ are observed in all channels. The results of likelihood fits to these distributions, using

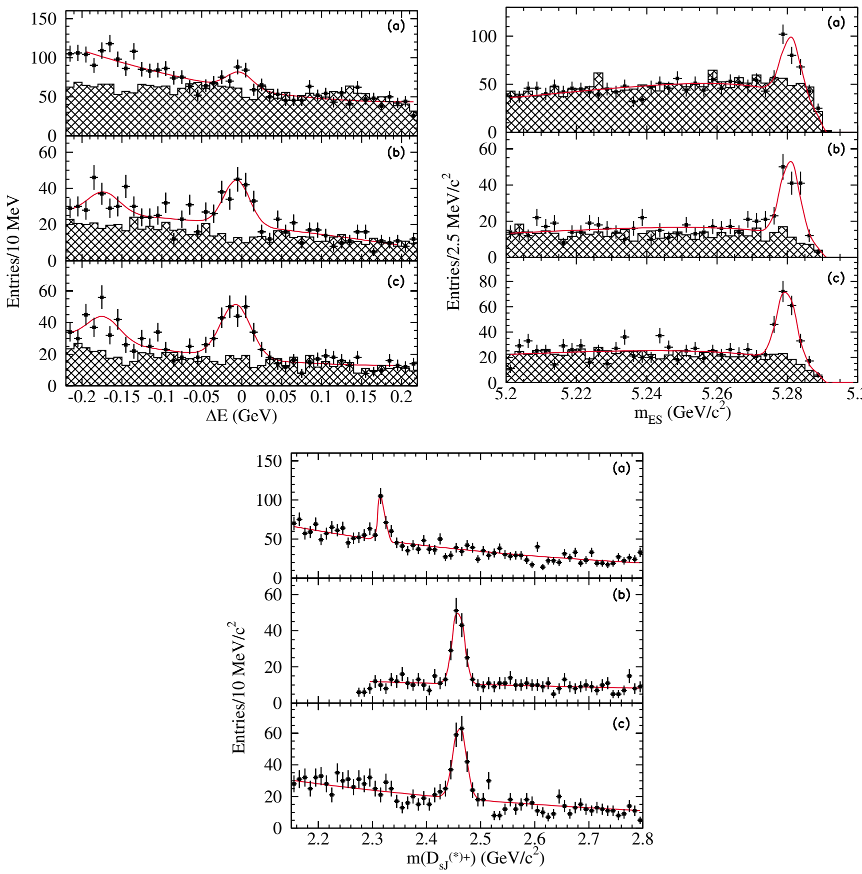

FIG. 1 (color online). ΔE (top left), $m_{\rm ES}$ (top right), and $m(D_{sJ}^{(*)+})$ (bottom) spectra for the $B \to D_{sJ}^{(*)+}\overline{D}^{(*)}$ candidates: (a) $D_{sJ}^*(2317)^+ \to D_s^+\pi^0$, (b) $D_{sJ}(2460)^+ \to D_s^{*+}\pi^0$, and (c) $D_{sJ}(2460)^+ \to D_s^+\gamma$. Data points in each plot show the distribution of one variable in the signal regions of the other two, as defined in the text. For ΔE and $m_{\rm ES}$, the cross-hatched histograms are from events from the $m(D_{sJ}^{(*)+})$ sideband regions defined in the text. For the $m(D_{sJ}^{(*)+})$ plots, only one B signal candidate per event has been selected. Curves correspond to fit results.

a Gaussian signal and an exponential background function, are overlaid. In these fits, the Gaussian mean value is fixed to 2317 (2460) MeV$/c^2$ for $D_{sJ}^*(2317)^+$ ($D_{sJ}(2460)^+$). Its width is fixed to 8 (12) MeV$/c^2$ for π^0 (γ) final states, as obtained from the simulation and confirmed with the data (Table I). The $D_{sJ}^{(*)+}$ event yields and the statistical significances are listed in Table II. The significance is defined as $\sqrt{-2\ln(\mathcal{L}_0/\mathcal{L}_{\rm max})}$, where $\mathcal{L}_{\rm max}$ and $\mathcal{L}_0$ are the likelihood values with the nominal and with zero signal yield, respectively. A significance larger than 4 is observed for 10 of the 12 modes.

From the $D_{sJ}^{(*)+}$ event yields in the data, we compute cross-feed-corrected branching fractions, using the signal efficiency and the relative contributions from cross feed between the different $D_{sJ}^{(*)+}$ decay modes as obtained from simulated signal events. The resulting branching fractions are given in Table II, together with the efficiencies, including the intermediate branching fractions, and the internal cross-feed contributions.

The dominant systematic errors come from the tracking efficiency (1.3% per track), γ and π^0 efficiencies (2.5% per γ), the Δm requirement on the D_s^{*+} and D^{*0} selections ($\approx$ 5% per D^*), efficiency of the ΔE requirement ($\approx$ 6%), $D_{sJ}^{(*)+}$ mass resolutions assumed in the fits (5% to 10%), and background fitting model (5%). We assume equal production rates for B^+B^- and $B^0\overline{B}^0$ pairs and do not include a systematic error related to this assumption. The errors from the individual $\overline{D}^{(*)}$ and $D_s^{(*)}$ branching fractions, as taken from [16], are given separately (Table II). They are dominated by the 25% relative error on $\mathcal{B}(D_s^+ \to \phi\pi^+)$.

From the measured branching fractions for $B \to D_{sJ}^+(2460)\overline{D}^{(*)}$ in the $D_s^{*+}\pi^0$ and in the $D_s^+\gamma$ final states, we compute the ratio

$$\frac{\mathcal{B}[D_{sJ}(2460)^+ \to D_s^+\gamma]}{\mathcal{B}[D_{sJ}(2460)^+ \to D_s^{*+}\pi^0]} = 0.274 \pm 0.045 \pm 0.020,$$

where the first and second uncertainties are statistical and

TABLE I. Event yields, reconstructed $D_{sJ}^{(*)+}$ masses, and resolutions in each final state for $B \to D_{sJ}^{(*)+}\overline{D}^{(*)}$ decays.

Decay mode	Yield	$m(D_{sJ}^{(*)+})$ (MeV$/c^2$)	σ_m (MeV$/c^2$)
$D_{sJ}^*(2317)^+\overline{D}^{(*)}$ $[D_s^+\pi^0]$	88 ± 17	2317.2 ± 1.3	5.9 ± 1.4
$D_{sJ}(2460)^+\overline{D}^{(*)}$ $[D_s^{*+}\pi^0]$	112 ± 14	2458.9 ± 1.5	10.8 ± 1.3
$D_{sJ}(2460)^+\overline{D}^{(*)}$ $[D_s^+\gamma]$	139 ± 17	2461.1 ± 1.6	12.1 ± 1.6

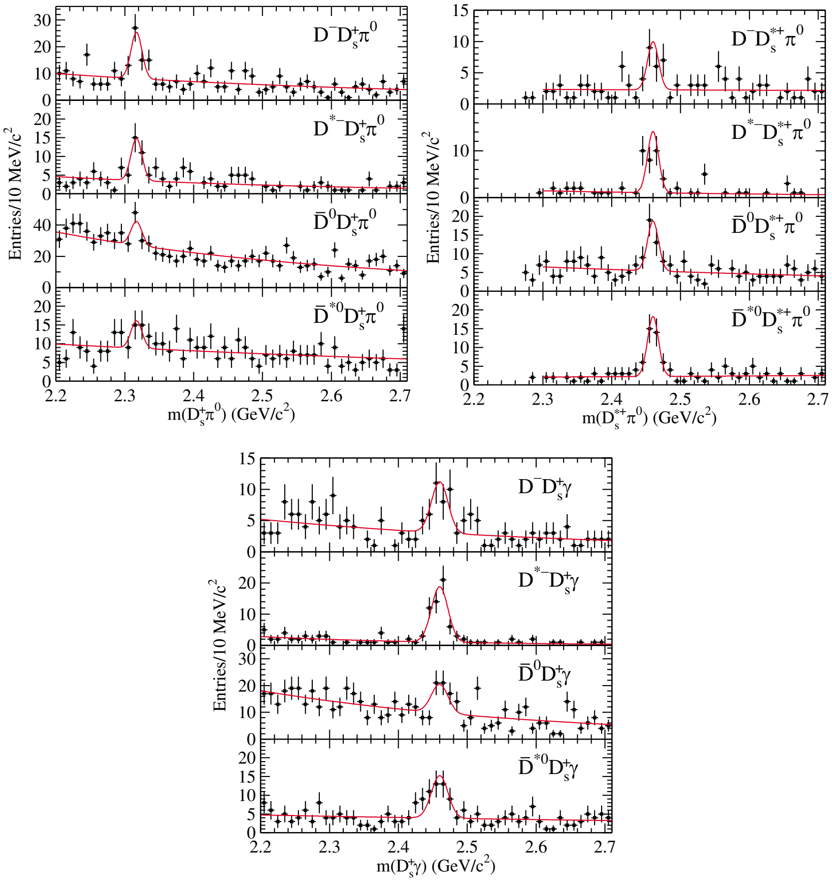

FIG. 2 (color online). $D_s^+\pi^0$ (top left), $D_s^{*+}\pi^0$ (top right), and $D_s^+\gamma$ (bottom) mass spectra of the selected B signal candidates for the 12 $\overline{D}^{(*)}D_{sJ}^{(*)+}$ final states. Curves are the results of the fits described in the text.

systematic, respectively. This is compatible with the prediction from [6].

We perform a helicity analysis of the $D_{sJ}(2460)^+$ state, using the decays $B^+ \to D_{sJ}(2460)^+\overline{D}^0$ and $B^0 \to D_{sJ}(2460)^+D^-$, 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. Since the $\overline{D}\gamma$ mass is correlated with the helicity angle, the selection requirement $m(\overline{D}\gamma) > 2.3$ GeV$/c^2$ is omitted for the angular analysis. We perform $m(D_s\gamma)$ fits for five different $\cos(\theta_h)$ regions, using the same fit functions and parame-

TABLE II. Event yields (including internal cross-feed contributions), number of events attributed to internal cross feed, efficiencies (including intermediate branching fractions), and final branching fractions, $\mathcal{B}$, for $B \to D_{sJ}^{(*)+}\overline{D}^{(*)}$ decays. The first error on $\mathcal{B}$ is statistical, the second is systematic, and the third is from the $\overline{D}$ and D_s^+ branching fractions.

B mode	Yield	Cross feed	Efficiency (10^{-4})	$\mathcal{B}(10^{-3})$	Significance
$B^0 \to D_{sJ}^*(2317)^+D^-$ $[D_s^+\pi^0]$	34.7 ± 8.0	0.3	1.6	$1.8 \pm 0.4 \pm 0.3^{+0.6}_{-0.4}$	5.5
$B^0 \to D_{sJ}^*(2317)^+D^{*-}$ $[D_s^+\pi^0]$	23.5 ± 6.1	0.0	1.3	$1.5 \pm 0.4 \pm 0.2^{+0.5}_{-0.3}$	5.2
$B^+ \to D_{sJ}^*(2317)^+\overline{D}^0$ $[D_s^+\pi^0]$	32.7 ± 10.8	0.3	2.6	$1.0 \pm 0.3 \pm 0.1^{+0.4}_{-0.2}$	3.1
$B^+ \to D_{sJ}^*(2317)^+\overline{D}^{*0}$ $[D_s^+\pi^0]$	17.6 ± 6.8	7.2	1.0	$0.9 \pm 0.6 \pm 0.2^{+0.3}_{-0.2}$	2.5
$B^0 \to D_{sJ}(2460)^+D^-$ $[D_s^{*+}\pi^0]$	17.4 ± 5.1	0.1	0.5	$2.8 \pm 0.8 \pm 0.5^{+1.0}_{-0.6}$	4.2
$B^0 \to D_{sJ}(2460)^+D^{*-}$ $[D_s^{*+}\pi^0]$	26.5 ± 5.7	0.0	0.4	$5.5 \pm 1.2 \pm 1.0^{+1.9}_{-1.2}$	7.4
$B^+ \to D_{sJ}(2460)^+\overline{D}^0$ $[D_s^{*+}\pi^0]$	29.0 ± 6.8	2.2	0.8	$2.7 \pm 0.7 \pm 0.5^{+0.9}_{-0.6}$	5.1
$B^+ \to D_{sJ}(2460)^+\overline{D}^{*0}$ $[D_s^{*+}\pi^0]$	30.5 ± 6.4	2.5	0.3	$7.6 \pm 1.7 \pm 1.8^{+2.6}_{-1.6}$	7.7
$B^0 \to D_{sJ}(2460)^+D^-$ $[D_s^+\gamma]$	24.8 ± 6.5	0.5	2.6	$0.8 \pm 0.2 \pm 0.1^{+0.3}_{-0.2}$	5.0
$B^0 \to D_{sJ}(2460)^+D^{*-}$ $[D_s^+\gamma]$	53.0 ± 7.8	0.1	1.9	$2.3 \pm 0.3 \pm 0.3^{+0.8}_{-0.5}$	11.7
$B^+ \to D_{sJ}(2460)^+\overline{D}^0$ $[D_s^+\gamma]$	31.9 ± 9.0	1.4	4.1	$0.6 \pm 0.2 \pm 0.1^{+0.2}_{-0.1}$	4.3
$B^+ \to D_{sJ}(2460)^+\overline{D}^{*0}$ $[D_s^+\gamma]$	34.6 ± 7.6	6.5	1.7	$1.4 \pm 0.4 \pm 0.3^{+0.5}_{-0.3}$	6.0

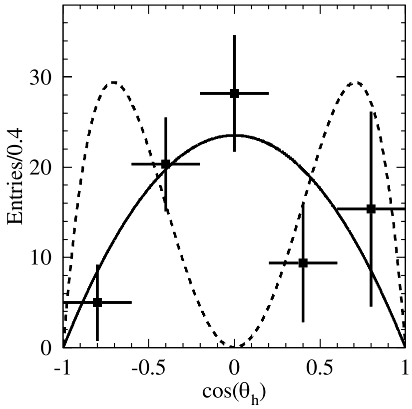

FIG. 3. Helicity distribution obtained from $m(D_s\gamma)$ fits in bins of $\cos(\theta_h)$ for data (points) in comparison with the expectations for a $D_{sJ}(2460)^+$ spin $J = 1$ (solid line) and $J = 2$ (dashed line), respectively, after normalizing the predicted spectra to the data.

ter values as in the corresponding branching fraction measurements.

The resulting angular distribution, after applying corrections for detector acceptance and selection efficiency, is shown in Fig. 3. The predicted spectra for two different assumptions for the $D_{sJ}(2460)^+$ spin, which have been normalized to the data, are overlaid. We exclude the $J = 2$ hypothesis ($\chi^2/\mathrm{d.o.f.} = 36.4/4$) and find good agreement with $J = 1$ ($\chi^2/\mathrm{d.o.f.} = 4.0/4$). A $D_{sJ}(2460)^+$ spin $J = 0$ is ruled out by parity and angular momentum conservation in the decay $D_{sJ}(2460)^+ \to D_s^+\gamma$.

In summary, we have observed and measured the branching fractions for the decays $B \to D_{sJ}^*(2317)^+\overline{D}^{(*)}$ ($D_{sJ}^*(2317)^+ \to D_s^+\pi^0$) and $B \to D_{sJ}(2460)^+\overline{D}^{(*)}$ ($D_{sJ}(2460)^+ \to D_s^{*+}\pi^0$, $D_s^+\gamma$). The modes involving a $\overline{D}^*$ have been seen for the first time. The angular analysis of the decay $B \to D_{sJ}(2460)^+\overline{D}$ with $D_{sJ}(2460)^+ \to D_s^+\gamma$ excludes $J^P = 2^+$ and supports the hypothesis that the $D_{sJ}(2460)^+$ is a $J^P = 1^+$ state.

We are grateful for the excellent luminosity and machine conditions provided by our PEP-II colleagues and for the substantial dedicated effort from the computing organizations that support *BABAR*. The collaborating institutions wish to thank SLAC for its support and kind hospitality. This work is supported by DOE and NSF (USA), NSERC (Canada), IHEP (China), CEA and CNRS-IN2P3 (France), BMBF and DFG (Germany), INFN (Italy), FOM (The Netherlands), NFR (Norway), MIST (Russia), and PPARC (United Kingdom). Individuals have received support from CONACyT (Mexico), A. P. Sloan Foundation, Research Corporation, and Alexander von Humboldt Foundation.

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