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Hadronic B Decays to Charm and Charmonium with the BaBar Experiment

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The *BABAR* experiment has recorded the decays of more than 465×10^6 $B\bar{B}$ pairs since 1999, and is reaching an unprecedented precision in the measurement of hadronic B decays. The following results are presented: tests of QCD factorization with the decays $B\to\chi_{c0}K^*$, $B\to\chi_{c1,2}K^{(*)}$, and $\bar{B}^0\to D^{(*)0}h^0$, $h^0=\pi^0,\ \eta,\ \omega,\ \eta'$, study of the decays to charmonium $B\to\eta_cK^{(*)}$, $\eta_c(2S)K^{(*)}$ and $h_cK^{(*)}$, measurement of the mass difference between neutral and charged B's, measurement of the "r" parameters for the extraction of the CKM angles $\sin(2\beta+\gamma)$ with the decays $B\to D_s^{(*)}h,\ h=\pi^-,\ \rho^-,\ K^{(*)+}$, study of the three-body rare decays $B\to J/\psi\phi K$, study of the baryonic decays $\bar{B}^0\to\Lambda_c^+\bar{p}$, $B^-\to\Lambda_c^+\pi^-\bar{p}$, and $B^-\to\Lambda_c^+\pi^0\bar{p}$. Except for the results presented in the sections II, III and IV, all the given numbers are preliminary.

I. TESTS OF QCD FACTORIZATION

Weak decays of hadrons provide a straight access to the parameters of the CKM matrix and thus to the study of the CP violation. Gluon scattering in the final state, related with the confinement of quarks and gluons into hadrons, can modify the decay dynamics and so must be well understood. In the factorization model [1, 2], the non-factorizable interactions in the final state by soft gluons are neglected. The matrix element in the effective weak Hamiltonian of the B decay is then factorized into a product of independent hadronic currents.

A. Measurement of the branching fractions (BF) of the decays $B\to\chi_{c0}K^*$ [3]

In the factorization model of the decay $b\to c\bar{c}s$, the charge conjugation invariance of the current-current operator forbids the hadronization of $c\bar{c}$ into χ_{c0}. The branching fractions (BF) of the decays $B^0\to\chi_{c0}K^{*0}$ and $B^+\to\chi_{c0}K^{*+}$ are measured from exclusive reconstruction using a data sample of 454×10^6 $B\bar{B}$ pairs in units of 10^{-4}: $BF(B^0\to\chi_{c0}K^{*0})=1.7\pm0.3\pm0.2$ and $BF(B^+\to\chi_{c0}K^{*+})=1.4\pm0.5\pm0.2$, where the quoted first errors are statistical and the second are systematic. The decay $B^0\to\chi_{c0}K^{*0}$ is observed with a 8.9 standard deviation (quoted as σ) significance and an evidence is found for $B^+\to\chi_{c0}K^{*+}$ with a 3.6σ significance. An upper limit is set for $BF(B^+\to\chi_{c0}K^{*+})<2.1$ at 90 % confidence level (quoted as CL). The $B^0\to\chi_{c0}K^{*0}$ BF does not agree with the zero value expected from factorization and is about half of the favored mode $B^0\to\chi_{c1}K^{*0}$ ($(3.2\pm0.6)\times10^{-4}$ [4]).

B. Measurement of the BFs of the decays $B\to\chi_{c1,2}K^{(*)}$ [5]

In the factorization model, no operators exist for the hadronization of $c\bar{c}$ into χ_{c2}, while the hadronization to χ_{c1} is favored. The BFs of the decays $B\to\chi_{c1}K^{(*)}$ and $B\to\chi_{c2}K^{(*)}$ are measured from exclusive reconstruction using a data sample of 465×10^6 $B\bar{B}$ pairs in units of 10^{-5}: $BF(B^+\to\chi_{c1}K^+)=46\pm2\pm3$, $BF(B^0\to\chi_{c1}K^0)=41\pm3\pm3$, $BF(B^+\to\chi_{c1}K^{*+})=27\pm5\pm4$, $BF(B^0\to\chi_{c1}K^{*0})=25\pm2\pm2$, $BF(B^+\to\chi_{c2}K^+)<1.8$ @90 % CL, $BF(B^0\to\chi_{c2}K^0)<2.8$ @90 % CL, $BF(B^+\to\chi_{c2}K^{*+})<12$ @90 % CL, and $BF(B^0\to\chi_{c2}K^{*0})=6.4\pm1.7\pm0.5$, where the first quoted errors are statistical and the second are systematic. The measured values of $BF(B^+\to\chi_{c1}K^+)$, $BF(B^0\to\chi_{c1}K^0)$, and $BF(B^+\to\chi_{c1}K^{*+})$ are the most precise to date. The upper limit on $BF(B^+\to\chi_{c2}K^+)$ is

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improved and evidence for the decay $B^0 \to \chi_{c2} K^{*0}$ is seen for the first time.

C. Measurement of the BFs of the color-suppressed decays $\bar{B}^0 \to D^{(*)0} h^0$, $h^0 = \pi^0, \eta, \omega, \eta'$ [6]

Previous measurements of the BFs of the color-suppressed decays $\bar{B}^0 \to D^{(*)0} h^0$ invalidated the factorization model [7–9]. However more precise measurements are needed to confirm that result and to constrain the different QCD models: SCET (Soft Collinear Effective Theory) and pQCD (perturbative QCD). The BFs are measured from exclusive reconstruction using a data sample of 454×10^6 $B\bar{B}$ pairs, the measured values are given in the Table I.

TABLE I: BFs of the decays $\bar{B}^0 \to D^{(*)0} h^0$ measured in data.

$\bar{B}^0$ mode	$(BF \pm \text{stat.} \pm \text{syst.}) \times 10^{-4}$	Signif.
$D^0 \pi^0$	$2.78 \pm 0.08 \pm 0.20$	35.5σ
$D^0 \eta(\gamma\gamma)$	$2.34 \pm 0.11 \pm 0.17$	26.1σ
$D^0 \eta(\pi\pi\pi^0)$	$2.51 \pm 0.16 \pm 0.17$	20.3σ
$D^0 \eta$	$2.41 \pm 0.09 \pm 0.17$	-
$D^0 \omega$	$2.77 \pm 0.13 \pm 0.22$	29.4σ
$D^0 \eta'(\pi\pi\eta(\gamma\gamma))$	$1.29 \pm 0.14 \pm 0.09$	14.7σ
$D^0 \eta'(\rho^0\gamma)$	$1.95 \pm 0.29 \pm 0.30$	7.2σ
$D^0 \eta'$	$1.38 \pm 0.12 \pm 0.22$	-
$D^{*0} \pi^0$	$1.78 \pm 0.13 \pm 0.23$	15.1σ
$D^{*0} \eta(\gamma\gamma)$	$2.37 \pm 0.15 \pm 0.24$	19.4σ
$D^{*0} \eta(\pi\pi\pi^0)$	$2.27 \pm 0.23 \pm 0.18$	12.2σ
$D^{*0} \eta$	$2.32 \pm 0.13 \pm 0.22$	-
$D^{*0} \omega$	$4.44 \pm 0.23 \pm 0.61$	22.3σ
$D^{*0} \eta'(\pi\pi\eta)$	$1.12 \pm 0.26 \pm 0.27$	8.0σ
$D^{*0}(D^0\pi^0)\eta'(\rho^0\gamma)$	$1.64 \pm 0.53 \pm 0.20$	3.3σ
$D^{*0} \eta'$	$1.29 \pm 0.23 \pm 0.23$	-

These results are consistent with the prediction by SCET: $BF(D^{*0}h^0)/BF(D^0h^0) \sim 1$ for $h^0 \neq \omega$, but marginally consistent with the predictions by pQCD on the BFs. The measurements are 3 to 7 times higher than the predictions by the naive factorization model.

II. STUDY OF THE B-MESON DECAYS TO $\eta_C K^{(*)}$, $\eta_C(2S) K^{(*)}$, AND $H_C \gamma K^{(*)}$ [10]

The B decays to charmonium singlet states h_c and η_c are still poorly known. A better knowledge of the relative abundances of the various charmonium states allows a deeper understanding of the underlying strong processes. In the non-relativistic QCD model, the productions of χ_{cJ} $(J = 0, 1, 2)$ and h_c are predicted to be comparable in magnitude, however $BF(B \to \chi_{c1} K) \sim 3 \times 10^{-4}$ and $BF(B^+ \to h_c K^+) < 3.8 \times 10^{-5}$. Similarly no exclusive measurements of the BF of $\eta_c(2S)$ production have been performed. The knowledge of the mass parameters of the charmonium state η_c is pivotal for the models of $c\bar{c}$ spectrum, but the measurements available so far are in poor agreement with one another. The large uncertainties on $BF(\eta_c \to K\bar{K}\pi)$ and on $BF(\eta_c(2S) \to K\bar{K}\pi)$ are cancelled by measuring the ratio by respect to $BF(B^+ \to \eta_c K^+)$ and $BF(B^+ \to \eta_c(2S) K^+)$. The measured BF of the h_c and η_c productions are measured using 384×10^6 $B\bar{B}$ pairs (with $BF(B^+ \to \eta_c K^+) = (9.1 \pm 1.3) \times 10^{-4}$): $BF(B^0 \to \eta_c K^{*0}) = (5.7 \pm 0.6(\text{stat.}) \pm 0.4(\text{syst.}) \pm 0.8(\text{bf.})) \times 10^{-4}$, $BF(B^+ \to h_c K^+) \times BF(h_c \to \eta_c \gamma) < 4.8 \times 10^{-5}$ @90 % CL, and $BF(B^0 \to h_c K^{*0}) \times BF(h_c \to \eta_c \gamma) < 2.2 \times 10^{-4}$ @90 % CL. The uncertainty noted bf. is related the error on $BF(B^+ \to \eta_c K^+)$. These are the first upper limits and confirm the h_c suppression. Using $BF(B^+ \to \eta_c(2S) K^+) = (3.4 \pm 1.8) \times 10^{-4}$, the upper limit on BF for $\eta_c(2S)$ production is $BF(B^0 \to \eta_c(2S) K^{*0}) < 3.9 \times 10^{-4}$ @90 % CL. Using $BF(B^+ \to \eta_c K^+) \times BF(\eta_c \to K\bar{K}\pi) = (6.88 \pm 0.77^{+0.55}_{-0.66}) \times 10^{-4}$, the first measurement is reported for

$BF(\eta_c(2S) \to K\bar{K}\pi) = (1.9 \pm 0.4(\text{stat.}) \pm 0.5(\text{syst.}) \pm 1.0(\text{bf.}))$. Both the mean and width of the η_c mass distribution are extracted: $m(\eta_c) = (2985.8 \pm 1.5(\text{stat.}) \pm 3.1(\text{syst.}))$ MeV/c^2, $\Gamma(\eta_c) = (36.3^{+3.7}_{-3.6}(\text{stat.}) \pm 4.4(\text{syst.}))$ MeV, which are in agreement with the previous *BABAR* measurements.

III. MEASUREMENT OF THE MASS DIFFERENCE $M(B^0) - M(B^+)$ [11]

The measurement of the mass difference $\Delta m_B = m(B^0) - m(B^+)$ probes the Coulomb contributions to the quark structure, which affect the relative production rates of $\Upsilon(4S) \to B^0\bar{B}^0$ and $\Upsilon(4S) \to B^+B^-$. The decay modes $B^0 \to J/\psi K^+\pi^-$ and $B^+ \to J/\psi K^+$ with $J/\psi \to e^+e^-$, $\mu^+\mu^-$, are reconstructed exclusively using 230 million$\times 10^6$ $B\bar{B}$ pairs. The mass difference Δm_B is then computed as:

$$\Delta m_B = -\Delta p^* \times \frac{p^*(B^0) + p^*(B^+)}{(m(B^0) + m(B^+)) \cdot c^2}, \tag{1}$$

where p^* is the momentum in the $\Upsilon(4S)$ rest frame. The measured value is $\Delta m_B = (0.33 \pm 0.05(\text{stat.}) \pm 0.03(\text{syst.}))$ MeV/c^2, which excludes the null value at the 5σ level.

IV. MEASUREMENT OF THE BFS OF $B^0 \to D_s^{(*)+}\pi^-$, $B^0 \to D_s^{(*)+}\rho^-$, AND $B^0 \to D_s^{(*)-}K^+$ [12]

The quantity $\sin(2\beta+\gamma)$, with the CKM parameters β and γ, can be measured from the study of the time evolution of the doubly-Cabibbo and CKM-suppressed decays $B^0 \to D^{(*)-}\pi^+$ and $B^0 \to D^{(*)-}\rho^+$. That study requires the knowledge of the ratios of the decay amplitudes $r(D^{(*)}\pi) = |A(B^0 \to D^{(*)+}\pi^-)/A(B^0 \to D^{(*)-}\pi^+)|$, which cannot be directly measured. Assuming $SU(3)$ flavor symmetry, $r(D^{(*)}\pi)$ can be related to the decay $B^0 \to D_s^{(*)+}\pi^-$:

$$r(D^{(*)}\pi) = \tan(\theta_c)\frac{f_{D^{(*)}}}{f_{D_s^{(*)}}}\sqrt{\frac{BF(B^0 \to D_s^{(*)+}\pi^-)}{BF(B^0 \to D^{(*)-}\pi^+)}}, \tag{2}$$

where θ_c is the Cabibbo angle, and $f_{D^{(*)}}/f_{D_s^{(*)}}$ is the ratio of $D^{(*)}$ and $D_s^{(*)}$ meson decay constants.

The contribution from W-exchange diagrams are evaluated from the study of $B^0 \to D_s^{(*)-}K^+$, which proceeds through a W-exchange diagram only.

Using 381×10^6 $B\bar{B}$ pairs, the measured BFs are (in units of 10^{-5}): $BF(D_s^+\pi^-) = 2.5 \pm 0.4 \pm 0.2$, $BF(D_s^{*+}\pi^-) = 2.6^{+0.5}_{-0.4} \pm 0.2$, $BF(D_s^+\rho^-) < 2.4$ @90 % CL, $BF(D_s^{*+}\rho^-) = 4.1^{+1.3}_{-1.2} \pm 0.4$, $BF(D_s^-K^-) = 2.9 \pm 0.4 \pm 0.2$, $BF(D_s^{*-}K^+) = 2.4 \pm 0.4 \pm 0.2$, $BF(D_s^-K^{*+}) = 3.5^{+1.0}_{-0.9} \pm 0.4$, and $BF(D_s^{*-}K^{*+}) = 3.2^{+1.4}_{-1.2} \pm 0.4$.

The measured longitudinal fractions are: $f_L(D_s^{*+}\rho^-) = 0.84^{+0.26}_{-0.28} \pm 0.13$ and $f_L(D_s^{*-}K^{*+}) = 0.92^{+0.37}_{-0.31} \pm 0.07$. The values of $r(D^{(*)}\pi)$ are computed with Equation (2): $r(D\pi) = (1.78^{+0.14}_{-0.13} \pm 0.08 \pm 0.10(\text{th.}))$ %, $r(D^*\pi) = (1.81^{+0.16}_{-0.15} \pm 0.09 \pm 0.10(\text{th.}))$ %, $r(D\rho) = (0.71^{+0.29}_{-0.27} \pm 0.10 \pm 0.04(\text{th.}))$ %, and $r(D^*\rho) = (1.45^{+0.23}_{-0.22} \pm 0.12 \pm 0.08(\text{th.}))$ %. The quoted first errors are statistical and the second are systematic. The errors denoted th. are related to the theoretical uncertainties.

V. MEASUREMENT OF THE BFS OF THE RARE DECAYS $B \to J/\psi\phi K$ [13]

Many charmonium-like resonances were discovered recently and more are expected in the $J/\psi\phi$ decay channel. The decays $B^0 \to J/\psi\phi K^0$ and $B^+ \to J/\psi\phi K^+$ were exclusively reconstructed using 433×10^6 $B\bar{B}$ pairs. The measured BFs are: $BF(B^0 \to J/\psi\phi K^0) = (5.40 \pm 1.20(\text{stat.}) \pm 0.40(\text{syst.})) \times 10^{-5}$ and $BF(B^+ \to J/\psi\phi K^+) = (5.81 \pm 0.73(\text{stat.}) \pm 0.29(\text{syst.})) \times 10^{-5}$. The study of the $J/\psi\phi$ mass spectrum is on-going.

VI. STUDY OF BARYONIC B DECAYS

Baryonic decays of B mesons provide a laboratory for searches for excited charm baryon states and for the investigation of the dynamics of 3-body decays.

A. Study of the decays $\bar{B}^0 \to \Lambda_c^+ \bar{p}$ and $B^- \to \Lambda_c^+ \pi^- \bar{p}$ [14]

The BFs of the decay channels $\bar{B}^0 \to \Lambda_c^+ \bar{p}$ and $B^- \to \Lambda_c^+ \pi^- \bar{p}$ are measured from exclusive reconstruction using 383×10^6 $B\bar{B}$ pairs: $BF(\bar{B}^0 \to \Lambda_c^+ \bar{p}) = (1.89 \pm 0.21(\text{stat.}) \pm 0.06(\text{syst.}) \pm 0.49(\text{bf.})) \times 10^{-5}$ and $BF(B^- \to \Lambda_c^+ \pi^- \bar{p}) = (3.38 \pm 0.12(\text{stat.}) \pm 0.12(\text{syst.}) \pm 0.88(\text{bf.})) \times 10^{-4}$, where the error denoted bf. is related to the uncertainty on $BF(\Lambda_c^+ \to pK^-\pi^+)$. One notices an enhancement of the 3-body channel by a factor 15 by respect to the 2-body channel. An enhancement is seen in the Dalitz plot of $B^- \to \Lambda_c^+ \pi^- \bar{p}$ at the threshold of the phase space in $m^2(\Lambda_c \bar{p})$. Such threshold enhancement has been seen in other baryon-antibaryon decay modes and is thus expected to be a dynamical effect rather than a resonance. Three resonances are investigated in the $\Lambda_c \pi$ mass spectrum: $\Sigma_c(2455)^0$, $\Sigma_c(2520)^0$ and $\Sigma_c(2800)^0$. The relative BFs measured are: $BF(B^- \to \Sigma_c(2455)^0 \bar{p})/BF(\bar{B}^0 \to \Lambda_c^+ \pi^- \bar{p}) = (12.3 \pm 1.2(\text{stat.}) \pm 0.8(\text{syst.})) \times 10^{-2}$, $BF(B^- \to \Sigma_c(2800)^0 \bar{p})/BF(\bar{B}^0 \to \Lambda_c^+ \pi^- \bar{p}) = (11.7 \pm 2.3(\text{stat.}) \pm 2.4(\text{syst.})) \times 10^{-2}$, and $BF(B^- \to \Sigma_c(2520)^0 \bar{p})/BF(\bar{B}^0 \to \Lambda_c^+ \pi^- \bar{p}) < 0.9 \times 10^{-2}$ @90 % CL. No signal is seen for $\Sigma_c(2520)^0$.

The parameters of the mass distributions of these resonances are extracted: $m(\Sigma_c(2455)^0) = 2454.0 \pm 0.2$ MeV/c^2, $\Gamma(\Sigma_c(2455)^0) = 2.6 \pm 0.5$ MeV, $m(\Sigma_c(2800)^0) = 2846.0 \pm 8.0$ MeV/c^2, and $\Gamma(\Sigma_c(2800)^0) = 86^{+33}_{-22}$ MeV. The measured mass for $\Sigma_c(2800)^0$ is 3σ higher than the resonance seen by Belle [15], which may indicate a new $J = 1/2$ state. The angular distribution of $B^- \to \Sigma_c(2455)^0 \bar{p}$ is consistent with a spin of $J = 1/2$ for $\Sigma_c(2455)^0$ and the hypothesis $J = 3/2$ is rejected at the $> 4\sigma$ level.

B. Study of the decay $\bar{B}^0 \to \Lambda_c^+ \pi^0 \bar{p}$

This channel is the isospin counterpart of $B^- \to \Lambda_c^+ \pi^- \bar{p}$ and has never been observed. The BF is measured in the restrictive phase space $m(\Lambda_c^+ \pi^0) > 3.0$ GeV/c^2 and so does not include contributions from $\Sigma_c(2455, 2520, 2800)^0$ resonances. An enhancement, similar to the one seen for $B^- \to \Lambda_c^+ \pi^- \bar{p}$, is seen at the threshold of the phase space of the $\Lambda_c^+ \bar{p}$ mass spectrum. Using 467×10^6 $B\bar{B}$ pairs the measured BF is: $BF(\bar{B}^0 \to \Lambda_c^+ \pi^0 \bar{p}) = (1.61 \pm 0.26(\text{stat.}) \pm 0.13(\text{syst.}) \pm 0.42(\text{bf.})) \times 10^{-4}$, where the error denoted bf. is related to the uncertainty on $BF(\Lambda_c^+ \to pK^-\pi^+)$.

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