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B Physics at CDF

Vaia Papadimitriou[a]
(for the CDF Collaboration)

[a] Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, Illinois, 60510, U.S.A.

We present the latest measurements on production, spectroscopy, lifetimes and branching fractions for b-mesons, b-baryons and quarkonia. We also discuss recent results on B_s^0 mixing as well as on CP violation for the B_s^0 meson and for b-baryons. These results were obtained by analyzing data collected by the CDF II detector at Fermilab.

1. Introduction

In this paper we are reviewing recent results on the properties of b-mesons and b-baryons and for quarkonia. These include mass, lifetime, production cross section and branching fraction measurements as well as mixing and CP violation. The results reported in this review are based on data collected by the CDF II detector [1] at Fermilab recording $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV. By the end of June 2008, the Tevatron delivered 4.4 fb^{-1} per experiment during Run II, with a peak luminosity record of 3.15 x 10^{32} cm^{-2}s^{-1} in March 2008 and a monthly delivered luminosity record of 221.5 pb^{-1} in May 2008. The data taking efficiency for CDF is approximately equal to 82%. The results reported here utilize up to 2.4 fb^{-1} of the recorded data.

This paper is organized as follows. In section 2 we discuss orbitally excited b-mesons and in section 3 new results on the lifetime, mixing, CP violation and rare decays for the B_s^0 meson. In section 4 we discuss mass and lifetime measurements for the $B_c^\pm$ meson and in section 5 we discuss lifetime, branching ratios and CP violation for the Λ_b^0 baryon as well as the observation and mass measurements of the $\Sigma_b^{(*)\pm}$ and $\Xi_b^\pm$ baryons. In section 6 we briefly discuss $\psi(2S)$ production and in section 7 conclusions and prospects.

2. Orbitally excited b-mesons.

The b-hadron production cross section $\sigma(p\overline{p} \to H_b X)$ has been measured by CDF to be $17.6 \pm 0.4(stat)^{+2.5}_{-2.3}(syst)\,\mu b$ [1]. The large production together with the excellent CDF vertex and mass resolution has allowed for very accurate measurements of the masses of b-mesons and b-baryons [2]. The corresponding systematic uncertainties are of the order of 1

MeV/c^2 or below. Recently CDF has observed as well and measured the masses and widths of the neutral orbitally excited (L=1) mesons B_2^{*0} and B_1^0 in decays to $B^{(*)+}\pi^-$ using 1.7 fb^{-1} of data [3]. The mass and width of the narrow B_2^{*0} state are measured to be

$m(B_2^{*0}) = 5740.2^{+1.7}_{-1.8}(stat)^{+0.9}_{-0.8}(sys)\ MeV/c^2$

and

$\Gamma(B_2^{*0}) = 22.7^{+3.8}_{-3.2}(stat)^{+3.2}_{-10.2}(sys) MeV/c^2$

respectively. The B_1^0 mass, resulting from the mass difference we measure between the narrow B_2^{*0} and B_1^0 states, is equal to $5725.3^{+1.6}_{-2.2}(stat)^{+1.4}_{-1.5}(sys)\ MeV/c^2$. This is the most precise measurement of the masses of these states to date and the first measurement of the B_2^{*0} width. Using 1 fb^{-1} of data CDF reported as well [4] the observation of two narrow resonances consistent with states of orbitally excited (L=1) B_s^0 mesons. The states were reconstructed using their two-body decays into K$^-$ and B$^+$ mesons and their masses were measured to be

$m(B_{s1}) = 5829.4 \pm 0.7\, MeV/c^2$ and

$m(B_{s2}^*) = 5839.6 \pm 0.7\, MeV/c^2$. This is the first observation of the B$_{s1}$ state.

3. The B_s^0 meson.

CDF has recently measured the lifetime of the B_s^0 meson using fully and partially reconstructed hadronic decays $B_s^0 \to D_s^-\pi^+(X)$ followed by $D_s^- \to \phi\pi^-$ and $\phi \to K^+K^-$. Using an 1.3 fb^{-1} data sample, the lifetime was measured to be equal to

$\tau(B_s^0) = 1.518 \pm 0.041(stat) \pm 0.025(sys)$ ps.

This is word's best flavor-specific measurement for the B_s^0.

With the currently available data samples CDF can measure accurately several observables related to the phenomenology of flavor mixing and decay of the B_s^0 meson like the mass and width difference between the mass (lifetime) eigenstates, the mixing phase φ$_s$, the mean lifetime, etc. For the B_s^0 meson, the quantities Δm$_s$, ΔΓ and φ$_s$ are sensitive to new physics processes. While the standard model (SM) expectation for φ$_s$, $\varphi_s^{SM} = 4\times10^{-3}$ [5] is small, contributions from new physics processes to B_s^0 mixing can lead to a significantly different value of the phase, $\varphi_s = \varphi_s^{SM} + \varphi_s^{NP}$. Such new physics contribution would be also accessible in $B_s^0 \to J/\psi\phi$ decays where one can measure the CP-violating phase β_s and access the new physics contributions from $2\beta_s = 2\beta_s^{SM} - \varphi_s^{NP}$. In terms of the CKM matrix elements β_s^{SM} can be expressed as $\beta_s^{SM} = \arg(-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*) \approx 0.02$ [5].

Using 5600 fully reconstructed and 3100 partially reconstructed hadronic B_s^0 decays, and 61500 partially reconstructed semileptonic B_s^0 decays in 1fb^{-1} of data, CDF observed $B_s^0 - \overline{B}_s^0$ oscillations and measured Δm$_s$ as well as $|V_{td}/V_{ts}|$ [6]. Using ~2500 untagged $B_s^0 \to J/\psi\phi$ signal events in 1.7 fb^{-1} of data CDF has recently updated as well the measurement of the lifetime and decay width difference in $B_s^0 \to J/\psi\phi$ decays [7]. Assuming CP conservation, a good approximation for the B_s^0 system in the SM, we obtain from an un-binned likelihood fit in the space of mass, decay time and angles of the final state particles:

$$\Delta\Gamma = 0.076^{+0.059}_{-0.063}(stat) \pm 0.006(sys)\ \text{ps}^{-1}$$

and $\tau = 1.52 \pm 0.04(stat) \pm 0.02(sys)$ ps.

The CP-violation phase β_s in $B_s^0 \to J/\psi\phi$ decays was measured by CDF using ~ 2000 tagged signal events in 1.35 fb^{-1} of data [8]. Fig. 1 shows the frequentist confidence region in the $2\beta_s - \Delta\Gamma$ plane. Assuming the SM predictions of the CP-violation parameter $2\beta_s$ and the decay width difference $\Delta\Gamma$, the probability for a deviation as large as the level of the observed data (p-value) is 15%, corresponding to 1.5 Gaussian standard deviations. Additionally, we find that the frequentist confidence interval for $2\beta_s$, where $\Delta\Gamma$ is treated as a nuisance parameter, is $2\beta_s \in [0.32, 2.82]$ at the 68% confidence level (CL). Preliminary updated results [9] using 2.8 fb^{-1} of data are consistent with the measurement reported above and indicate a p-value of 7% at the SM favoured point. If $\beta_s \geq 0.4(0.5)$, then the probability for a 5σ observation of new physics processes at the Tevatron is greater than 20(65)%, assuming 6 fb^{-1} of data recorded per experiment and no improvement over the present analysis.

Exploiting the two-track trigger sample ($p_{T1,2} > 2$ GeV/c) [10] CDF reconstructed about 6500 $B^0_{(s)} \to h^+h'^-$ (h, h' = K or π) decays in 1 fb^{-1} of data with a collective Gaussian mass standard

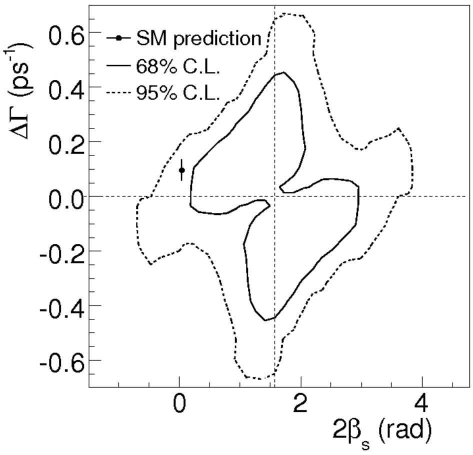

Fig.1. Frequentist confidence region in the $2\beta_s - \Delta\Gamma$ plane where the SM favored point is shown with error bars [5].

deviation of σ=39±0.8 MeV/c^2. Combining mass, kinematics and particle ID in an unbinned maximum likelihood fit we extract the fraction of each of the expected components and measure the corresponding branching ratios [11]. We report the first observation of the self-tagging mode $B_s^0 \to K^-\pi^+$ with a yield of 230±34(stat)± 16(sys) events (8.2σ) and measure the corresponding branching fraction with respect to the $B^0 \to K^+\pi^-$ decay. With this sample, we perform the first measurement of a direct CP asymmetry in the B_s^0 meson and find

$A_{CP}(B_s^0 \to K^-\pi^+)$ = 0.39±0.15(stat)±0.08(sys)

which is different from 0 by 2.5σ and is consistent with the SM prediction of ≈0.37 [12]. The measurement of the direct CP asymmetry for the B^0 meson is $A_{CP}(B^0 \to K^+\pi^-)$ = -0.086±0.023(stat) ±0.009(sys), its uncertainties competitive with the ones from the latest measurements of the B-factories [13]. Such measurements are very essential in testing the validity of the SM prediction for the equality of

$|A(\overline{B}^0 \to K^-\pi^+)|^2 - |A(B^0 \to K^+\pi^-|^2$ and

$|A(B_s^0 \to K^-\pi^+)|^2 - |A(\overline{B}_s^0 \to K^+\pi^-|^2$ as

suggested in [12,14]. We also observe for the first time two charmless decays of the Λ_b^0 baryon, $\Lambda_b^0 \to p\pi^-$ and $\Lambda_b^0 \to pK^-$ with significances of 6σ (110±18(stat)±16(sys)) events and 11.5σ (156±20(stat)±11(sys)) events respectively. In addition we measure the rate of the decays $B_s^0 \to K^+K^-$ and $B^0 \to \pi^+\pi^-$ and set upper limits for the rate of the decays $B^0 \to K^+K^-$ and $B_s^0 \to \pi^+\pi^-$.

Using 1.2 fb-1 of data CDF observed for the first time the decay $\overline{B}_s^0 \to D_s^{\pm}K^{\mp}$ where $D_s^{\pm} \to \phi\pi ; \phi \to K^+K^-$. This decay is interesting in the context of studying the interference between $\overline{B}_s^0 \to D_s^+K^-$ and $\overline{B}_s^0 \to D_s^-K^+$ as well as for the study of the angle γ through a time dependent, flavor-tagged analysis. The signal is 109±19(stat) events and the statistical significance of the observation 7.9σ. We use this sample to measure

$Br(\overline{B}_s^0 \to D_s^{\pm}K^{\mp}) / Br(\overline{B}_s^0 \to D_s^+\pi^-) =$ 0.107±0.019(stat)±0.008(sys). This result is statistically consistent with the measurement of the analogous B^0 branching fractions.

Using 2 fb^{-1} of integrated luminosity CDF has searched for the decays $B_s^0 \to \mu^+\mu^-$ and $B^0 \to \mu^+\mu^-$. The SM predictions for the branching ratios of these flavor-changing neutral current (FCNC) processes are small, (3.6±0.4) x 10^{-9} for the B_s^0 [15], while new physics

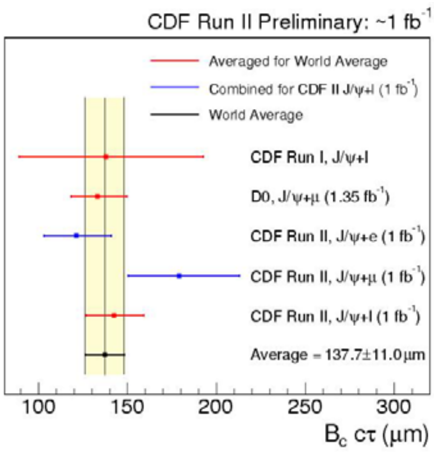

Fig.2. Summary of the experimental results on the $B_c^{\pm}$ lifetime.

contributions can provide significant enhancements. Normalization is provided by the decay $B^{\pm} \to J/\psi K^{\pm}$ and the resulting upper limits on the branching fractions are:

$Br(B_s^0 \to \mu^+\mu^-) < 5.8\text{x}10^{-8}$ and

$Br(B^0 \to \mu^+\mu^-) < 1.8\text{x}10^{-8}$ at 95% CL [16].

CDF sensitivity studies show that a $2\text{x}10^{-8}$ 95% CL limit could be reachable with 8 fb^{-1} of data.

4. The $B_c^{\pm}$ meson.

The $B_c^{\pm}$ meson, the ground state of a b-quark and a c-antiquark, contains two heavy quarks and decays weakly, providing a unique system for studying weak decay properties in the context of NRQCD.

A very precise measurement of the $B_c^{\pm}$ mass was recently performed by CDF using 2.4 fb^{-1} of data and reconstructing the $B_c^{\pm}$ in the $B_c^{\pm} \to J/\psi\,\pi^{\pm}$ decay [17]. The analysis was optimized on a $B^{\pm} \to J/\psi\, K^{\pm}$ control sample consisting of ~ 21 K events after all selection requirements. We observe 108±15 signal events with a significance that exceeds 8σ. The mass was measured to be

$$M(B_c^{\pm}) = 6275.6 \pm 2.9(stat) \pm 2.5(sys)$$

MeV/c^2, in relatively good agreement with theoretical predictions [18].

The decay of the $B_c^{\pm}$ meson takes place through either a b-quark or a c-quark decaying weakly through a W boson or through annihilation of the two (anti)quarks into a lepton and neutrino final state. The lifetime is expected to be approximately equal to 0.5 ps [19]. Using 1 fb^{-1} of data CDF measured the $B_c^{\pm}$ lifetime reconstructing its semileptonic decays to $J/\psi l^{\pm}\nu_l$, where $J/\psi \to \mu^+\mu^-$ and l stands for an electron or a muon. The CDF combined measurement for the electron and muon channels is $\tau(B_c^{\pm}) = 0.476^{+0.053}_{-0.049}(stat) \pm 0.018(sys)$ ps. Fig. 2 shows a summary of the experimental results for the $B_c^{\pm}$ lifetime.

5. b-baryons.

The measurement of the lifetimes of b-baryons provides an excellent test of the accuracy of the Heavy Quark Expansion theoretical approach. CDF has currently the largest available sample of Λ_b^0 baryons with decays to J/ψ mesons or charged hadrons. Using 1 fb^{-1} of data we extracted the Λ_b^0 lifetime from the decay channel $\Lambda_b^0 \to J/\psi\Lambda^0$ where $J/\psi \to \mu^+\mu^-$ and $\Lambda^0 \to p\pi^-$. We find that $\tau(\Lambda_b^0)$ is 1.580±0.077(stat)±0.012(sys) ps and that $\tau(\Lambda_b^0)/\tau(B^0)$ is equal to 1.018±0.062(stat)± 0.007(sys). The theoretical expectation for $\tau(\Lambda_b^0)/\tau(B^0)$ is ~0.9 [20]. New CDF results [21] using ~3000 fully reconstructed $\Lambda_b^0 \to \Lambda_c^+\pi^-$ decays in 1 fb^{-1} of data report that $\tau(\Lambda_b^0)$ is 1.410±0.046(stat)±0.029(sys) ps and that $\tau(\Lambda_b^0)/\tau(B^0)$ is equal to 0.922±0.039.

As discussed in section 3, using 1 fb^{-1} of data CDF observed for the first time the decays $\Lambda_b^0 \to p\pi^-$ and $\Lambda_b^0 \to pK^-$ and measured [22] their branching ratios to be equal to

$$Br(\Lambda_b^0 \to pK) = (5.0 \pm 0.7(stat) \pm 1.0(sys)) \times 10^{-6}$$

and

$$Br(\Lambda_b^0 \to p\pi) = (3.1 \pm 0.6(stat) \pm 0.7(sys)) \times 10^{-6}$$

respectively, in agreement with SM expectations. CDF has also reported the first measurement of CP-violating asymmetries in these decays:

$A_{CP}(\Lambda_b^0 \to p\pi^-)$ =0.03±0.17(stat)±0.05(sys)

and

$A_{CP}(\Lambda_b^0 \to pK^-)$ = 0.37±0.17(stat)±0.03(sys).

In the latter the measured value of the asymmetry deviates from zero at the 2.1σ level. The statistical uncertainty currently dominates the resolution but it will be improved with more data.

Using 1.1 fb^{-1} of data CDF has observed [23] for the first time four $\Lambda_b^0\pi^{\pm}$ resonances in the fully reconstructed decay mode $\Lambda_b^0 \to \Lambda_c^+\pi^-$, where $\Lambda_c^+ \to pK^-\pi^+$, whose masses and widths are consistent with those expected for the lowest-lying, charged $\Sigma_b^{(*)}$ baryons. We measure the following masses:

$m_{\Sigma_b^+} = 5807.8^{+2.0}_{-2.2}(stat) \pm 1.7(sys)$ MeV/c^2,

$m_{\Sigma_b^-} = 5815.2 \pm 1.0(stat) \pm 1.7(sys)$ MeV/c^2,

$m(\Sigma_b^*) - m(\Sigma_b) = 21.2^{+2.0}_{-1.9}(stat)^{+0.4}_{-0.3}(sys)$ MeV/c^2.

CDF searched as well for the bottom, strange baryon Ξ_b^- through the decay chain $\Xi_b^- \to J/\psi\,\Xi^-$, $J/\psi \to \mu^+\mu^-$, $\Xi^- \to \Lambda^0\pi^-$ and $\Lambda^0 \to p\pi^-$. A signal of 17.5±4.3 events (7.7σ) is observed [24] and the Ξ_b^- mass is measured to be 5792.9±2.5(stat)± 1.7(sys) MeV/c^2. Fig. 3 shows the comparison with theoretical predictions and the corresponding measurement from the D0 experiment [25].

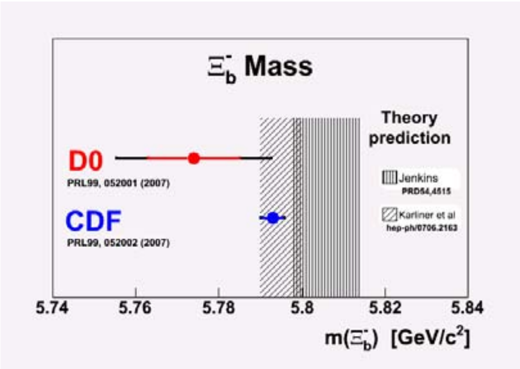

Fig.3. Comparison of Ξ_b^- mass measurements and theoretical predictions.

6. Production of the ψ(2S) meson.

In an attempt to understand better the production of heavy vector mesons in $p\bar{p}$ collisions CDF has used recently 1.1 fb^{-1} of data to measure the differential cross section for the inclusive production of ψ(2S) mesons in both prompt and B-decay processes up to p_T of 30 GeV/c. We find that for $p_T(\psi(2S)) > 2$ GeV/c and $|y(\psi(2S))| < 0.6$ the integrated inclusive cross section multiplied by the branching ratio for dimuon decay is 3.17±0.04(stat)±0.28(sys) nb. These new measurements provide an important input for the update of the matrix elements in the NRQCD factorization approach.

7. Conclusions and prospects.

More than 4.4 fb^{-1} of $p\bar{p}$ collisions has been delivered by the Tevatron and many new B physics results have been recently produced by the CDF experiment. As the Tevatron is expected to provide between 5.8 to 6.7 fb^{-1} by October 2009 and 7.3 to 8.8 fb^{-1} by October 2010, a lot of answers to explored and yet unexplored questions and a lot of surprises are awaiting.

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REFERENCES

1. D. Acosta et al., Phys. Rev. D **71**, 032001 (2005).
2. D. Acosta et al., Phys. Rev. Lett. **96**, 202001 (2006).
3. The CDF Collaboration, http://www-cdf.fnal.gov/physics/new/bottom/070726.blessed-bss/, public note 8945.
4. T. Aaltonen et al., Phys. Rev. Lett. **100**, 082001 (2008).
5. A. Lenz and U. Nierste, J. High Energy Phys. **06**, 072 (2007).
6. A. Abulencia et al., Phys. Rev. Lett. **97**, 242003 (2006).
7. T. Aaltonen et al., Phys. Rev. Lett. **100**, 121803 (2008).
8. T. Aaltonen et al., Phys. Rev. Lett. **100**, 121802 (2008).
9. The CDF Collaboration, http://www-cdf.fnal.gov/physics/new/bottom/080724.blesse

d-tagged_BsJPsiPhi_update_prelim/, public note 9458.

10. W. Ashmanskas et al., Nucl. Instrum. Methods A**518**, 532 (2004).

11. The CDF Collaboration, http://www-cdf.fnal.gov/physics/new/bottom/060921.blessed-bhh_1fb/, public note 8579.

12. H.J. Lipkin, Phys. Lett. B **621**, 126 (2005).

13. E. Barberio et al., HFAG, arXiv:hep-ex/0607021.

14. X.G. He, Eur. Phys. J. **C** 9 443 (1999); N.G. Deshpande et al., Phys. Rev. D **62**, 034018 (2000).

15. M. Blanke et al., arXiv:hep-ph/0805.4393.

16. T. Aaltonen et al., Phys. Rev. Lett. **100**, 101802 (2008).

17. T. Aaltonen et al., Phys. Rev. Lett. **100**, 182002 (2008).

18. I.F. Allison et al., Phys. Rev. Lett. **94**, 172001 (2005); N. Brambilla et al., Phys. Rev. D **65**, 034001 (2002); S. Godfrey, Phys. Rev. D **70**, 054017 and references therein.

19. V.V. Kiselev et al., Nucl. Phys. B **585**, 353 (2000); M. Beneke and G. Buchalla, Phys. Rev. D **53**, 4991 (1996); I. Bigi, Nucl. Instrum. Methods A351, 240 (1994).

20. C. Tarantino, Eur. Phys. J. **C** 33 S895 (2004); F. Gabbiani et al., Phys. Rev. D **70**, 094031 (2004); D. Pirjol and N. Uraltsev, Phys. Rev. D **59**, 034012 (1999).

21. The CDF Collaboration, http://www-cdf.fnal.gov/physics/new/bottom/080703.blessed-lblcpi-ct/, public note 9408.

22. The CDF Collaboration, http://www-cdf.fnal.gov/physics/new/bottom/071018.blessed-ACP_Lambdab_ph/, public note 9092.

23. T. Aaltonen et al., Phys. Rev. Lett. **99**, 202001 (2007).

24. T. Aaltonen et al., Phys. Rev. Lett. **99**, 052002 (2007).

25. V.M. Abazov et al., Phys. Rev. Lett. **99**, 052001 (2007).